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Estimation of groundwater recharge from water storage structures in a semi-arid climate of India

V.N. Sharda [a,*], R.S. Kurothe [b], D.R. Sena [b], V.C. Pande [b], S.P. Tiwari [b]

[a] *Central Soil and Water Conservation Research and Training Institute, 218, Kaulagarh Road, Dehradun 248195, Uttaranchal, India*
[b] *Central Soil and Water Conservation Research and Training Institute, Research Centre, Vasad 388306, Anand District, Gujarat, India*

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Water storage structures;
Recharge function;
Water table fluctuation

Summary Groundwater recharge from water storage structures under semi-arid conditions of western India has been estimated by employing water table fluctuation (WTF) and chloride mass balance (CMB) methods. Groundwater recharge was estimated as 7.3% and 9.7% of the annual rainfall by WTF method for the years 2003 and 2004, respectively while the two years average recharge was estimated as 7.5% using CMB method. A Recharge function depicting the relationship between potential recharge from storage structures and successive day averaged storage depths was better exhibited by a power function. A diagnostic relationship correlating the rainfall to the potential recharge from water storage structures has been developed to explain the characteristics of the storage structures for a given geographical location. The study has revealed that a minimum of 104.3 mm cumulative rainfall is required to generate 1 mm of recharge from the water storage structures. It was also inferred that the storage structures have limited capacity to induce maximum recharge irrespective of the amount of rainfall and maximum recharge to rainfall ratio is achieved at a lower rainfall than the average annual rainfall of the area. An empirical linear relationship was found to reasonably correlate the changes in chloride concentration with water table rise or fall in the study area.

Introduction

Groundwater is an important source of irrigation in India accounting for more than half of the net irrigated area in the country (Deb Roy and Shah, 2002). It is estimated that 70–80% of the total production from irrigated areas in India may ultimately depend on groundwater utilization (Dains and Pawar, 1987). According to the World Bank (1998) and

* Corresponding author. Tel.: +91 135 2758564; fax: +91 135 2754213.
E-mail addresses: vnsharda1@rediffmail.com, vnsharda@stpd.soft.net (V.N. Sharda).

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Nomenclature

a,b,c	arbitrary constants in regression analysis (.)
A_s	average planar area of submergence (L^2)
A_w	area of the watershed (L^2)
Cl_d	Dry deposition rate of chloride (ML^{-3})
Cl_{gw}	chloride concentrations of groundwater (ML^{-3})
Cl_p	chloride concentrations of the rainfall (ML^{-3})
CN	curve number (.)
ET_a	actual evapotranspiration (L)
EV	evaporation (L)
h_{av}	average of consecutive days storage depths (L)
h_t	absolute depth of water impounding (m) on tth day (L)
I	interception of rainfall by vegetation (L)
O_f	outflow (L^3)
P	rainfall (L)
P_{year}	annual average rainfall (L)
R_e	cumulative potential recharge (L)
$R_{e(WB)}$	recharge component in the water balance equation (L)
R_{ep}	potential recharge (L^3)
R_{gw}	actual groundwater recharge (L, L^3)
R_{max}	maximum cumulative potential recharge (L)
RO	runoff (L)
S	storativity (.)
S_T	maximum potential storage of the watershed (L)
Δh	change in depth in water level in the structure (L)
ΔCl	change in chloride concentration in groundwater (ML^{-3})
ΔWT	change in water table (L)
$\Delta\theta$	change in soil moisture storage (L)
N	Number of data pairs (.)

Ministry of Water Resources, Government of India estimates (1998) the contribution of groundwater to India's GDP is about 9%. The great significance of groundwater in the agrarian economy of India is ascribed to the fact that crop yields are generally high in areas irrigated with groundwater than irrigated from other sources (Dhawan, 1995).

On an average, about 32% of the annual utilizable groundwater potential of 452.2 km^3 has been actually exploited in India, out of which 8% of the groundwater resource has been exploited beyond 85% of its potential. In the state of Gujarat, where this study has been undertaken, 25% of the groundwater sources have been exploited by more than 85% of their potential resulting in sharp decline of water table. In Gujarat, water table in over 90% of the wells monitored by Central Groundwater Board has dropped by 0.5 m to as high as 9.5 m in the recent past (Bose et al., 1998).

Water storage structures play a vital role in augmenting the groundwater recharge as they constitute one of the major interventions in the massive watershed development programmes undertaken in the country. It calls for studying the interaction between surface and groundwater (SW—GW) resource systems which include surface water storage structures, artificial recharge systems and addressing the concerns about the quantity and quality of the water being recharged to the aquifer. The concepts of hydrology, geology and ecology need to be combined for comprehensive conceptualization of SW—GW interactions related with groundwater recharge (Sophocleous, 2002).

Estimation of recharge has been a daunting task for the researchers, due to the complexity of the geohydrological settings and the uncertainty associated with the meteorological data of a given location. The groundwater recharge is quantified by employing surface water, unsaturated, and saturated-zone techniques. Identification of an appropriate technique in a given location partly depends on the recharge rate (Scanlon et al., 2002). However, limitations and uncertainty associated with each of the methods sometimes warrants application of multiple methods to authenticate the estimation.

Analysis of water table fluctuations (WTF) is a useful tool for determining the magnitude of both short- and long-term changes in groundwater recharge and has been widely applied under varying climatic conditions (Gerhart, 1986; Hall and Risser, 1993; Healy and Cook, 2002). Groundwater Estimation Committee (India) constituted in 1982 to improve the existing methodologies for estimation of groundwater resource potential has also recommended this method for estimation of groundwater recharge. However, in areas, where groundwater level monitoring is not carried out regularly, or where adequate data about groundwater level fluctuations is not available, ad hoc norms of rainfall infiltration have been recommended. As per guidelines, recharge in hard rock areas with geological formation predominantly representing basaltic rocks varies from 3% to 15% (Kumar, 1996).

In the process of estimating ground-water recharge of fresh-water lenses, it has been observed that the chloride ion can be considered as a tracer for estimating recharge which is concentrated by the processes of evapotranspiration (Vacher and Ayers, 1980; Ayers, 1981). This method is independent of the fact whether the recharge is focused or diffused and integrates spatial data over the watershed. The chloride mass balance method with certain conditions and assumptions has been found to provide reasonable estimates of groundwater recharge in semi-arid areas well comparable to those obtained by physically based methods (Wood and Sanford, 1995).

The estimation of recharge related to surface-water bodies depends on the extent of connectivity between surface water and groundwater systems (Sophocleous, 2002). The impact of water storage structures on groundwater recharge in different agro-ecological situations has not been properly understood except through crude methods based upon fluctuations in water level in the surrounding open or tube wells. No generalized approach or solution is available to decide the location and size of the water storage structure in a micro-watershed and its efficacy in augmenting groundwater table in a quantifiable manner. Arid or semi-arid regions are generally characterized by the lack of surface-water bodies due to thick unsaturated sections frequently separating surface and groundwater systems. Therefore, surface-water bodies generally form localized recharge zones from which recharge can be estimated using surface-water data. It is estimated that seepage from surface water bodies vis-à-vis water storage tanks may vary from 9% to 20% of their live storage capacity (Kumar, 1996). The seepage from percolation tanks is higher and may be up to 50% of their gross storage capacity.

In the present study, an attempt has been made to analyze this broader, multidisciplinary perspective of GW—SW interaction in the context of water storage structures in two adjacent micro-watersheds in a semi-arid region of India. The characteristics of water storage structures have been critically examined in relation to their position and size to study their impact on inducing the potential groundwater recharge by employing both direct and indirect (surrogate) recharge techniques. A regional based surrogate method for estimation of groundwater recharge in the absence of requisite database has also been attempted.

Study area description

The study area is located at 73°10′ E Longitude and 23°0′ N Latitude and 100 m above mean sea level in district Kheda of Gujarat State in India (Fig. 1). It consists of two micro-watersheds (WS-I and WS-II) adjacent to each other and covering an area of 612 ha and 200 ha, respectively. The micro-watersheds in general, have gentle to moderate slope (1—5%) and are characterized by the problems of soil erosion varying in intensity from sheet and rill erosion in crop lands to gully erosion in the community wastelands. The physiographic details of the watersheds are presented in Table 1.

Soils and geomorphology

Based upon the surface heterogeneity, soil profiles were studied in the fields and soil samples were collected from 71 sites at equidistant grid configuration (362 m) in the study area. Dominant soils in the watershed are generally very deep (>90 cm), well drained, and moderately coarse (sandy clay loam) in texture. Black soils having swelling and shrinkage characteristics also exist in patches. The presence of calcareous layer ($CaCO_3$) of varying thickness and depth is a common feature of the pedons which gets exposed at some places due to severe water erosion. Table 2 describes the physico-chemical characteristics of the soils in the two watersheds.

Hydrogeological setting

The study area represents semi-arid region of India with an average annual rainfall of 835 mm. Rainy season lasts for about three and a half months (mid June to end of September) and most of the annual rainfall (78%) is received between June and September. Winter rains are generally intermittent and mild. The mean annual temperature varies from 26°C to 28 °C with the summer temperatures varying between 37 °C and 42 °C and winter temperatures between 10°C and 18 °C.

The geologic history of the area's bedrock materials, their structure, and the tectonic forces and processes that formed them is part of the history of Kathiawar peninsula. Tectonic processes created many fractures, faults, and voids and, at the same time, locally sealed some of these structures. The geological formation is of recent Pleistocene sedimentation with pocketed presence of eocene basaltic flows having trappean characteristics (Sharma et al., 1994). Despite a complex history of sedimentation and multiple events of deformation, metamorphism, and intrusion, if viewed from a broad hydrologic perspective, water moves through, and is stored in open fractures. The size, number, distribution, and degree of interconnection of fractures are highly variable. However, in general, fractures are presumed to decrease in size and number with depth. Thus the overall storage capacity of bedrock is small and tends to decrease with depth. Wells that penetrate bedrock commonly yield dependable supplies of water for irrigation.

Water storage/artificial recharge structures

There are seven major water storage structures in the area. Besides these structures, 23 recharge filtering units and 16 check dams have also been constructed during 1997—2002 (Fig. 1). The specifications of the water storage structures are presented in Table 3.

Methodology

Storage balance equation for water storage structures

The potential recharge from a water storage structure has been defined as the volume of water percolated from the structure (Scanlon et al., 2002). The potential recharge was calculated using simple storage balance equation considering the pertinent components of hydrologic cycle. The schematic diagram of the recharge process has been shown in Fig. 2. The generic form of the storage balance equations may be given as follows:

$$\text{Rainfall } (P) - \text{Infiltration } (I_f) - \text{Evapotranspiration } (\text{ET}) = \text{Runoff } (\text{RO}) \quad (1)$$

$$\text{Runoff } (\text{RO}) = A_s \cdot \Delta h + \text{Evaporation } (\text{EV}) + \text{Recharge } (R_{ep}) + \text{Outflow } (O_f) \quad (2)$$

where A_S is the average planar area (m^2) of submergence $= A_{s,t} + A_{s,t-1} + \sqrt{A_{s,t}A_{s,t-1}}/3$, Δh is the change in depth (m) in water level in the structure = $(h_t - h_{t-1})$, h_t is the absolute depth of water impounding (m) on tth day, and h_{t-1} is the absolute depth of water impounding (m) on $(t-1)$th day.

The application of the storage balance equation is based on the non-event days when rainfall is non-existent. The net loss in storage depth is functionally equated with the potential recharge taking into account the free surface evaporation and outflow (O_f), if any. Therefore, potential recharge from water storage structure is expressed as:

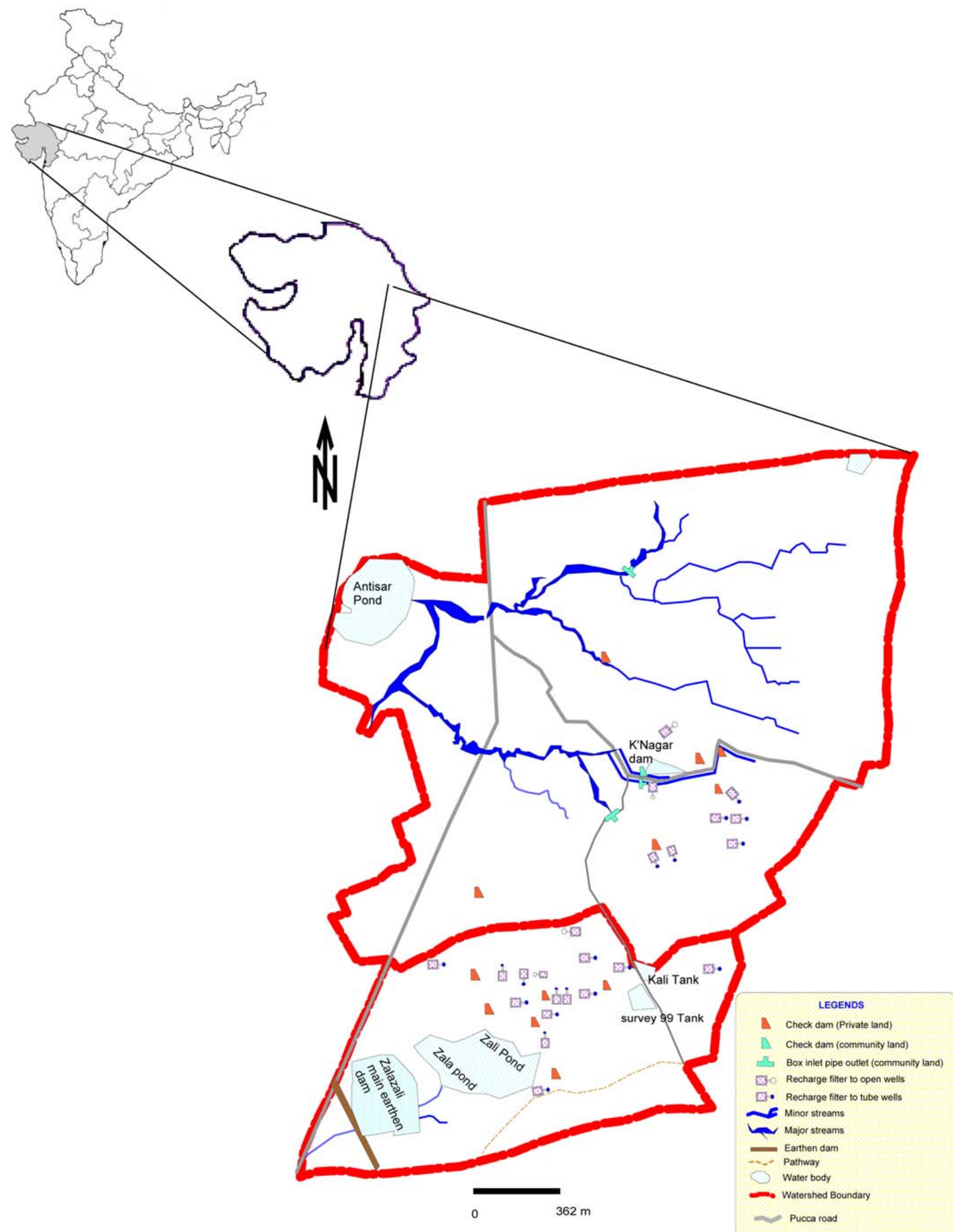


Figure 1 Details of the location and water storage structures in the study area.

Table 1 Physiographic characteristics of two watersheds of the study area

Particulars	WS-I	WS-II
Area (ha)	612	200
Soil depth (cm)	>90	>90
Slope (%)	1—5	1—5
Drainage	Fairly well drained	Well to moderately well drained
Major land use	Agriculture	Community land + agriculture

$$R_{ep} = -A_s \cdot \Delta h - EV - O_f \tag{3}$$

Eq. (3) is difficult to account for the event days when rainfall is occurring and the storage depth in an un-gauged reservoir is increasing due to runoff. To ascertain the potential recharge under these circumstances, a functional relationship between potential recharge and the consecutive days average storage depth was developed and would hereafter be referred as the recharge function from percolation structures. The functional fitting is based on the trend of the data pairs of recharge and average successive days' maximum depth of ponding in the structure. The general form may be expressed as:

Table 2 Physical and chemical properties (top 30 cm) of the soils of two watersheds of the study area

Particulars	WS-I	WS-II
Sand (%)	66.1 (24.3–87.2)	57.3 (15.0–79.4)
Silt (%)	9.3 (2.6–20.0)	10.4 (2.5–48.9)
Clay (%)	24.7 (5.8–60.5)	32.3 (15.5–75.0)
Texture	Sandy loam	Sandy loam
	Sandy clay loam	Sandy clay loam
Bulk density (g/cc)	1.42	1.37
Water holding capacity (%)	46	48
Field capacity[a] (%)	27	28
Permanent wilting point[a] (%)	15	18
Saturated hydraulic conductivity[a] (cm/day)	9.36	5.52
pH	6.4–9.0 (neutral–alkaline)	6.7–9.3 (neutral–alkaline)
EC (dsm^{-1})	<1.0	<1.0
Organic carbon (%)	0.3 (0.1–0.5)	0.3 (0.2–0.5)
P_2O_5 (kg/ha)	36.7 (3.0–176.9)	47.8 (13.0–142.3)
K_2O (kg/ha)	260.7 (117.2–652.3)	262.2 (114.4–967.0)

Figures in parentheses denote range.
[a] Saxton et al. (1986) (software: SSWATER).

Table 3 Specifications of water storage structures in the study area

Sl. no.	Structure	Catchment area (ha)	Ponding area (ha)	Capacity ($\times 10^4$ m^3)
1	Zalazali E/D	163.00	9.40	10.13
2	Zali pond	100.80	6.42	10.33
3	Zala pond	43.20	8.99	10.80
4	Antisar*	612.00	4.50	11.27
5	Khodiar nagar E/D*	7.48	0.83	0.41
6	Kali tank[#]	2.38	1.37	3.73
7	Survey 99[#]	1.06	0.61	0.58

* The watershed area denoted for water storage structures at serial no. 4 and 5 are modified due to diversion of part of the runoff water to other areas and the study was under taken for these structures for developing recharge function only.
[#] Water storage structures at Sl. nos. 6 and 7 were introduced during 2003 and 2004 and are used for recharge function development.

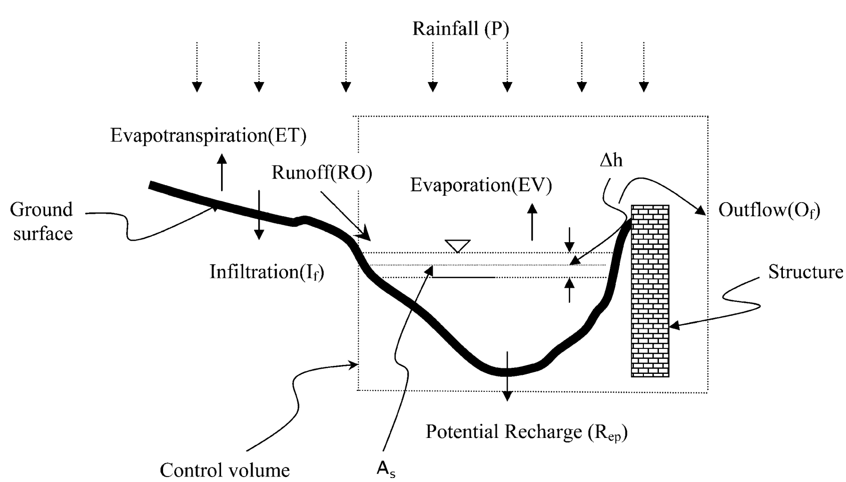


Figure 2 Schematic of the control volume for calculations of potential recharge from a water storage structure.

$$R_{ep} = f(\text{average}(h_t + h_{t-1})) \quad (4)$$

Inclusion of recharge estimates using recharge function among those computed for non-event days breaks the continuity of the estimates. Therefore, the recharge function thus developed was used to estimate recharge over the whole period when water is available in the storage structures. A correction factor was applied to equate the total observed potential recharge during the non-event days with the recharge computed by the recharge function.

Water table fluctuation method

The Water Table Fluctuation (WTF) method is based on the principle that rise in groundwater level in any aquifer is proportional to the water reaching the water table. The recharge component contributed to groundwater (R_{gw}) may be expressed as:

$$R_{gw} = S\Delta WT A_w \tag{5}$$

where, S is the storativity, ΔWT is the change in water-table depth and A_w is the area of the watershed. To calculate the volume of water recharged to the groundwater, both the watersheds WS-I and WS-II were combined together to find out the cumulative recharge. It was also assumed that the water table aquifer is in dynamic equilibrium with the surrounding aquifer area. Groundwater table maps for the consecutive time intervals were constructed using mapping software SURFER version 8.02. The recharge between two-successive time intervals was calculated by super-imposing the maps and considering the positive component of the change in water table. The kriging interpolation technique was used to plot the water table contours. The effect of instantaneous groundwater table rise or fall was taken into account by geostatistical analyses that helped in smoothening the antecedent water level recession or accession beneath a well while plotting the groundwater table maps. It was necessitated to account for the sudden change in water table due to instantaneous recharge from recharge filters or discharge due to pumping. Difficulties in applying WTF method arise in determining a representative value of storativity (S) for the whole watershed. At any given location, the storativity of the formation remains essentially constant, but the volume of water in storage, and all the aquifer parameters vary with changes in saturated thickness (water table elevation). Some of this variation can be explained (and quantitatively predicted) on the basis of straight forward physical principles, but some of it is attributed to local variations in the aquifer structure. It is difficult to accurately predict or measure hydrologic variability in storativity. Pumping test data analysis provides a more accurate estimation of this parameter. But uncertainty, poor reliability in extrapolating the point information to the whole watershed and presence of multiple aquifers with varying characteristics warrants a more reliable, cost effective and approximate technique for estimation of storativity. Therefore, the storativity was estimated using the seasonal water balance analysis. The seasonal recharge computed from water balance was then equated to the seasonal groundwater recharge due to observed rise in groundwater table.

In the water balance model, the recharge is estimated as the residual of all the other fluxes in the hydrological cycle. The principle being that all these fluxes (i.e., precipitation, evapotranspiration, runoff, interception and soil moisture changes) can relatively be more easily measured or estimated than recharge. The whole watershed was assumed to be a one-dimensional vertical element with the root zone as the control volume. No other losses of water occur below the root zone, such as lateral flows due to the bedding plane pattern of the geologic strata or absorption due to capillarity action above the water table. Therefore, considering a volume balance of water in the root zone (assumed to be 1 m from the soil surface), the recharge ($R_{e(WB)}$) is estimated as:

$$R_{e(WB)} = P - I - RO - ET_a \pm \Delta\theta \tag{6}$$

where, P is rainfall (mm), I is interception of rainfall by vegetation (mm), RO is runoff (mm), ET_a is actual evapotranspiration (mm), and $\Delta\theta$ is change in soil moisture storage (mm).

ET_a was estimated by Thornthwaite and Mather (1955) method based upon monthly average temperature, P and $\Delta\theta$. The runoff (RO) was estimated using SCS curve number method (SCS, 1972) modified for Indian conditions (Dhruvanarayana, 1993) as:

$$RO = \frac{(P - 0.3S_T)^2}{(P + 0.7S_T)} \tag{7}$$

where, S_T is the maximum potential storage of the watershed (mm) given as

$$S_T = \frac{25,400}{CN} - 254 \tag{8}$$

and CN is the weighted curve number for the watershed depending upon antecedent moisture conditions (SCS, 1972).

$\Delta\theta$ is assumed as maximum plant available water beyond which the gravitational water contributes to recharge and is defined as:

$$\Delta\theta = 10 * (FC - PWP) * RDZ \tag{9}$$

where, FC is the weighted average field capacity (%) of the watershed, PWP is the weighted average permanent wilting point (%) and RDZ is the root zone depth (m).

Interception is assumed as negligible in the absence of major vegetation and particularly in the rainy season where it gets satisfied in the few initial storms. Therefore, Eq. (6) reduces to:

$$R_{e(WB)} = P - RO - ET_a - \Delta\theta \tag{10}$$

It may be noted that, ET_a values are calculated on monthly basis, whereas the recharge period taken in the watershed for calculation of water balance is based on the wet cycle of the year starting with the onset of the monsoon. Therefore, the values of the hydrologic components used in the water balance equation, not covering the full month in the recharge period, are taken on *pro-rata* basis.

Since it was assumed that $R_{e(WB)}A_w = R_{gw}$, therefore, the storativity S may be calculated as:

$$S = \frac{R_{e(WB)}}{\Delta WT} \tag{11}$$

where, ΔWT is the change in weighted average of the groundwater table depth for the duration of water balance calculation in the entire watershed.

The estimated storativity, however, represents an approximate weighted value for the entire watershed and considering entire geological formation constituting the multiple aquifer system.

Chloride mass balance method

The basic equation applicable for estimation of recharge using chloride mass balance method (Wood and Sanford, 1995) is defined as:

$$R_{gw} = P_{year}\frac{Cl_p}{Cl_{gw}} \tag{12}$$

where, R_{gw} is the annual recharge rate (mm), P_{year} is the average annual rainfall (mm), and Cl_p and Cl_{gw} are the chloride concentrations of the rainfall and groundwater (mg l^{-1}), respectively. The chloride concentration of the water samples was computed and mapped as per data collection schedule of the water table. The iso-concentration map was constructed and utilized to compute the average weighted chloride concentration of the entire area covering the two watersheds.

Database

Meteorological data

Daily rainfall data was recorded from both recording and non-recording type rain gauges installed in the Antisar watershed. The evaporation data was collected from open pan evaporimeter installed in the nearby meteorological observatory of Central Soil and Water Conservation Research and Training Institute, Regional Research Centre, Vasad, Gujarat (India) having identical climatic conditions.

Stage level of water storage structures

Daily water level records of five major water storage structures, viz; Zalazali (WHS_1), Zali (WHS_2), Zala (WHS_3), Antisar (WHS_4) and Khodiyarnagar (WHS_5) were collected regularly from January 2001 to December 2004. Two more water storage structures, viz.; Kali tank (WHS_6) and Survey 99 (WHS_7) were also included during the years 2003 and 2004 for the purpose of studying their impact on groundwater recharge. Water is generally harvested and stored into these structures during 2nd week of June to 1st week of December. The stage versus storage capacity relationships of the individual storage structures was established. The stage level gauges were installed inside the storage structures to measure daily fluctuations in the water level of the storage structures during the water availability period.

Well network for monitoring groundwater fluctuations and collection of samples

A large number of tube wells/open wells (139) are available around the water storage structures for providing irrigation to agricultural crops. In addition to the existing wells, three more piezometers were also installed in the study area. The details of the spatial distribution of wells/piezometers are shown in Fig. 3. The water samples were collected periodically for chemical analysis to estimate chloride concentration in the water. The number of samples was based upon the active bore wells being managed by the farmers during a particular season. However, the number of wells for sample collection varied between 40 and 70 comprising of a network adequately representing the entire watershed area. For water table data, the numbers varied from 32 to 45. The data was collected during September 2002 to December 2004 and the interval of data collection varied from a maximum of 15 days to a minimum of seven days depending upon the fluctuations in the water table. During the period from June to December, which experiences intense recharge and extraction activities with higher fluctuations in water table, a minimum interval of 7 days was adopted. To study the time taken for the water percolated from a storage structure to reach the groundwater aquifer, daily data were recorded from three piezometers/observation wells installed on the upstream and downstream side of the structures in the watershed WS-II (Fig. 3).

Bore well logging data

Samples (95 numbers) at appropriate depths spanning the geological formations up to 93 m were collected during drilling and installation of three piezometers (well nos. 85, 86 and 89). The salient geological features of the representative formation based on analysis of above samples have been shown in Fig. 4. It is evident that the phreatic or unconfined aquifer mainly comprises of weathered basalt with topsoil layer predominantly consisting of trap wash with lime flakes. The subsequent layers are constituted of fractured or weathered basalt with vesicles and fractures. The depth of this aquifer is approximately 12 m. The second water bearing formation (13.7—24.4 m) is a leaky semi-confined aquifer with predominant lithology of amygdaloidal basalt in a fractured configuration. This particular layer is a better water transmitting zone than the other two subsequent water bearing strata i.e. inter-trappean semi-confined to confined aquifer (29.0—38.1 m) and the aquifer with intermittent mud layers (48.8 m onwards).

Results and discussion

Hydrological framework

The average annual rainfall of the area has been recorded as 835.4 mm (1983—2004) with erratic and uneven distribution in the last five years (Table 4). The water storage and recharge structures are effective mostly during the high intensity and large size rainfall events. The distribution of rainfall events since 1999 exhibit a drought like situation except during the years 2003 and 2004.

Estimation of potential recharge from storage structures

An empirical equation conforming to power function was found to best describe the relationship between depth of storage and potential recharge expressed as:

$$R_{ep} = ah_{av}^{b} \tag{13}$$

where, R_{ep} is the potential recharge from water storage structures (m^3), $h_{av} = \frac{h_t + h_{t-1}}{2}$ is the average of consecutive days absolute storage depths (h_t and h_{t-1}) of the water

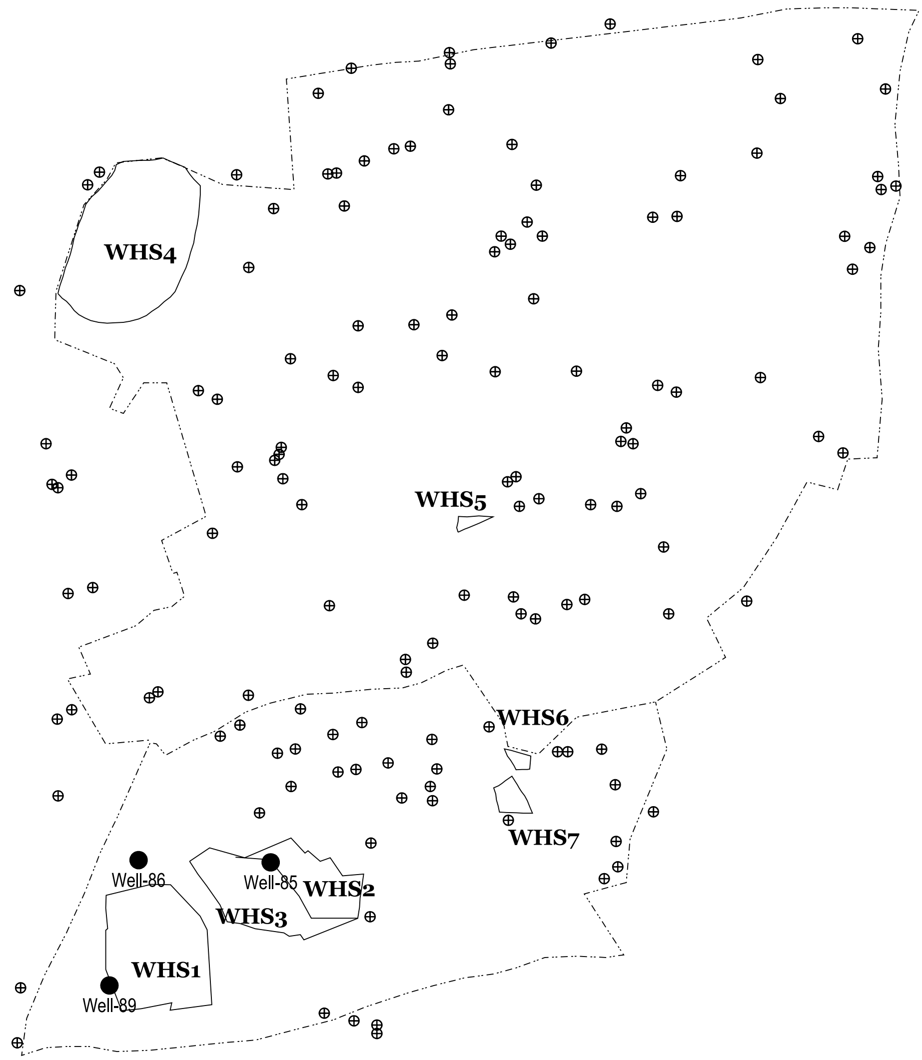


Figure 3 Network of open and tubewells in the study area (dark dots refer to additional three piezometers installed).

storage structures (m), and 'a' and 'b' are curve fitting parameters.

The relationship in Eq. (13) is specific to a water storage structure for which the empirical constants have been computed. The previous day storage depth (h_{t-1}) in the calculation of potential recharge volume (R_{ep}) is included so that the instantaneous rise or fall in the storage depth due to runoff resulting from high intensity storms may not cause any abrupt change in the recharge volume and is averaged with 'h_t' to account for variable antecedent storage depth on a given day.

The fitting of the equation was done by using non-linear estimation technique instead of conventional log transformation technique due to strong non-linearity which existed between R_{ep} and h_{av} as evident from Fig. 5(a)–(g). In doing so, significant fluctuations in the random error (residual error) around the fitted curve could be minimized. Table 5 presents the fitted parameters of the recharge functions for the seven structures. Temporal variations in potential recharge volume from different water storage structures as influenced by rainfall patterns are depicted in Fig. 6(a)–(g). It is evident that the water storage structures get filled up during high intensity events as discussed earlier.

Potential recharge and rainfall relationship

After computing the potential recharge from water storage structures during 2001–2004 (Table 6), a functional relationship between the cumulative recharge depth to cumulative rainfall depth was developed. A detailed study of three structures (Zalazali, Zala and Zali ponds) was carried out to find out their characteristics individually as well as in combination. The diagnostic equation fitted to obtain the relationship between cumulative recharge (R_e) and rainfall (P) is of the form:

$$\log_{10}(R_e) = a[b - e^{-cP}] \quad (14)$$

The equation is fitted using non-linear regression technique involving Rosenbrock–Quasi-Newton method (R–QN). R–QN method is a combination of non-linear estimation techniques such as Rosenbrock and Quasi-Newton method and can be advantageously used where appropriate

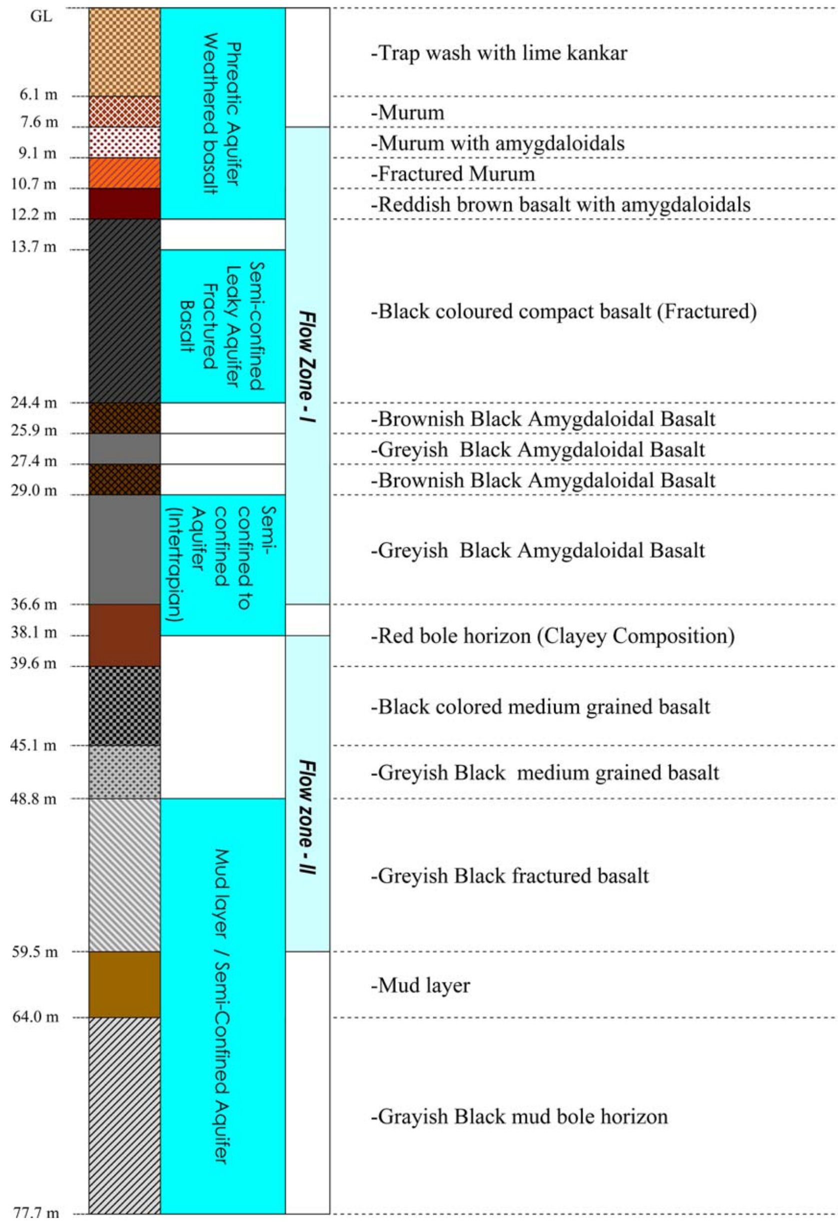


Figure 4 Well log information of the representative geological profile of the study area.

Table 4 Distribution of rainfall in the watershed

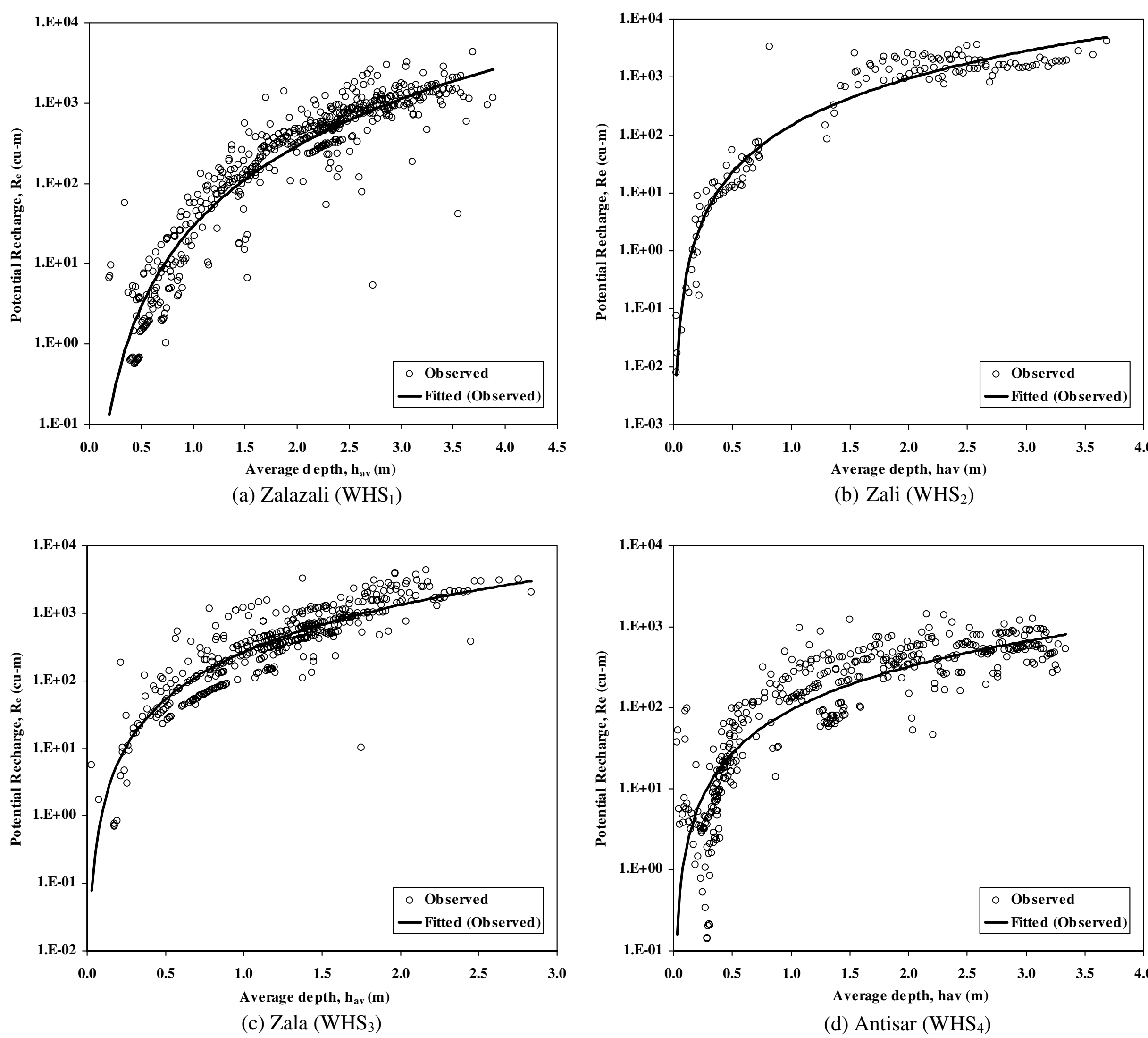
Rainfall interval (mm)	Distribution of rainfall (days)					
	1999	2000	2001	2002	2003	2004
<2.5	0	2	11	12	18	6
>2.5–5.0	0	2	7	1	6	7
>5.0–10.0	5	3	4	3	12	7
>10.0–25.0	2	5	5	9	9	7
>25–50	3	5	4	5	4	8
>50–100	3	1	2	1	5	3
>100–150	2	0	0	1	0	1
>150–200	0	1	0	0	1	0
>200	0	0	0	0	0	0
Rainfall (mm)	626	505	421	538	864	826
Rainy days	15	17	22	20	37	33

start values of the fitting parameters are not known. This is the fastest method of convergence and is less sensitive to local minima. The statistical details of the regression analysis are given in Table 7.

It was observed that with increasing cumulative rainfall depth, the cumulative potential recharge increases for all the structures but at a decreasing rate (Fig. 7(a)–(d)). The relationship to correlate cumulative potential recharge, R_e (mm) to cumulative rainfall, P (mm) explicates the exact situation of the water storage structures in the watershed, their storage area, contributing catchment area, the temporal rainfall distribution pattern in a year and others. The complexities of these interrelationships were addressed by simplification through a diagnostic empirical equation so that their performance may be compared with respect to each other.

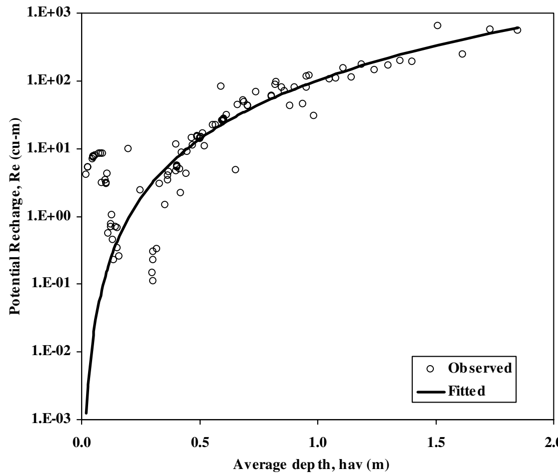
As can be deduced from Eq. (14), when $P \to \infty$, R_e attains the maximum value of potential recharge ($R_{max} = 10^{ab}$) that the structure can deliver considering the shape, size, and other agro-ecological features. The optimum value of recharge, however, is less than R_{max} as beyond this particular value if rainfall increases, the potential recharge will decrease the R_e/P ratio, representing the recession limb of the $R_e/P \sim P$ curve (Fig. 7(a)–(d)). The rainfall, P representing this peak $[d(R_e/P)/dP = 0]$ is the value inducing maximum fraction of the recharge. In a physical sense, when runoff corresponding to an excess rainfall exceeds the capacity of the storage structure, the same would flow out of it limiting its recharge to a maximum value (R_{max}). Whereas, in the condition pertaining to $P = 0$, the right hand side of Eq. (14) assumes a negative value resulting in R_e value greater than zero, which is an imaginary case with the proposed equation and, therefore, a minimum limit of 1 mm has been described in this equation. With increase in rainfall the percentage of potential recharge increases during the accession limb of the $R_e/P \sim P$ relationship until it attains a peak value.

It can also be observed that the threshold rainfall amount (i.e P_{thres} at $[d(R_e/P)/dP = 0]$) which can induce maximum potential recharge is still lower as compared to the average rainfall of the area (835.4 mm) for individual structures as well as their combination, or more succinctly, considering

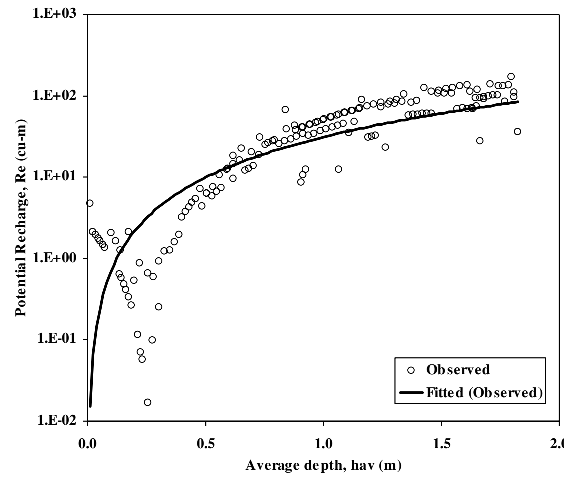


(a) Zalazali (WHS_1)
(b) Zali (WHS_2)
(c) Zala (WHS_3)
(d) Antisar (WHS_4)

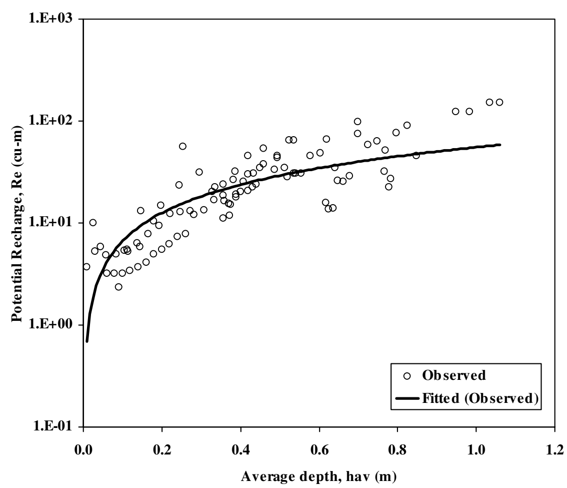
Figure 5 Regression fitting of the recharge function for the seven water storage structures.



(e) Khodiyarnagar (WHS_5)



(f) Kali Tank (WHS_6)



(g) Survey 99 (WHS_7)

Figure 5 (*continued*)

Table 5 Statistical parameter details of the recharge/seepage function for event days of form $R_e = ah_{av}^b$

Sl. no.	Water storage structure/pond	Coefficients[b]		
		a	*b*	R^2
1	Khodiyarnagar pond	101.84	2.894	0.857 (N^c = 103)
2	Zali pond	146.80	2.691	0.942 (N = 141)
3	Zala pond	264.37	2.321	0.786 (N = 423)
4	Zalazali earthen dam	29.25	3.323	0.866 (N = 519)
5	Antisar main pond	93.67	1.775	0.732 (N = 435)
6	Kali Tank[a]	31.035	1.654	0.649 (N = 204)
7	Survey 99[a]	76.33	1.072	0.668 (N = 97)

Where R_e = Recharge (m^3) and h_{av} = successive days average depth of impounding in m.
[a] Data for years 2003 and 2004 only.
[b] (Pooled data from year 2001–2004).
[c] N = number of data pairs.

the average rainfall of the area, the structures are seemed to be of lower capacity to accommodate the runoff resulting from the average rainfall pattern and inducing potential recharge as a maximum fraction of it. A set of criteria evolved for comparing the potential recharge in different structures of the study area is presented in Table 8. These criteria can

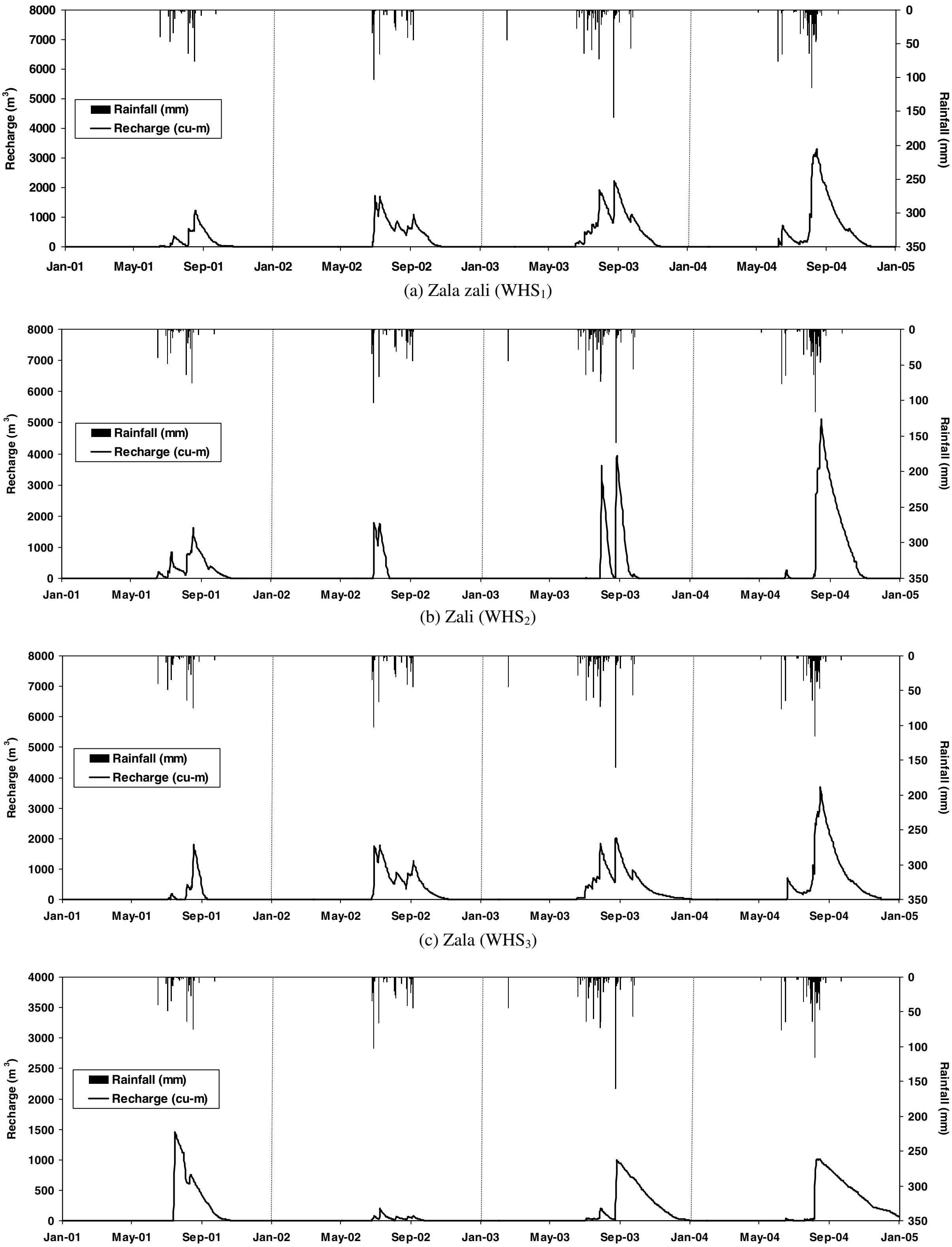
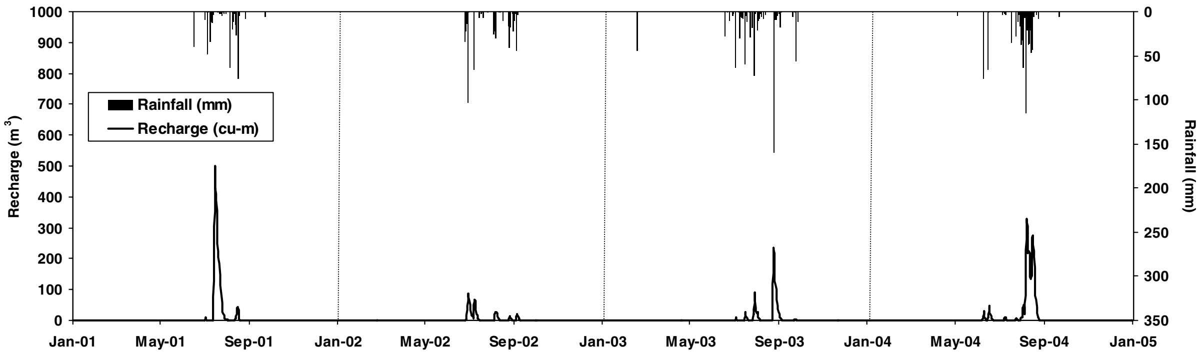


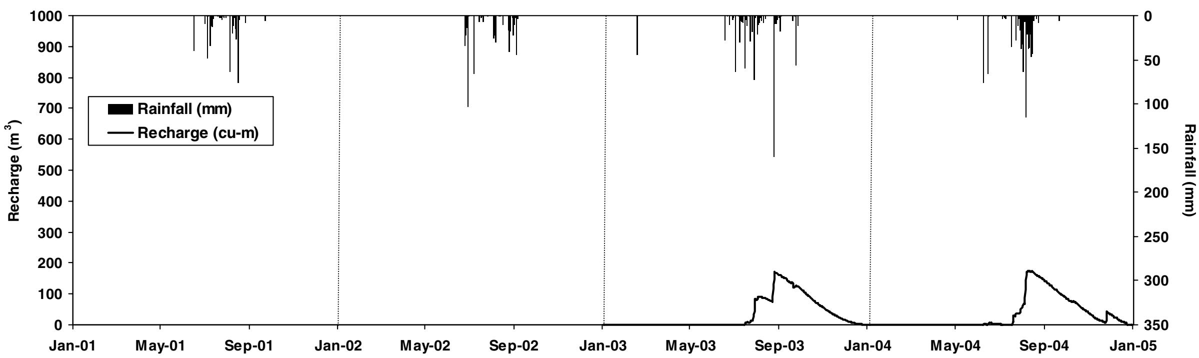
Figure 6 Temporal potential recharge and rainfall pattern in different water storage structures.

serve as indicators for comparing different water storage structures in a given agro-climatic situation and can also help in designing the storage structures efficiently.

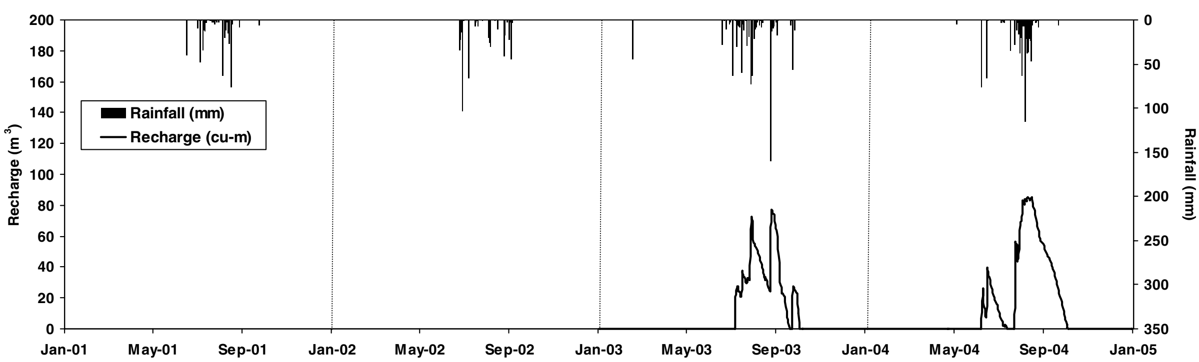
For the three water storage structures considered together in the sub-watershed WS-II, a minimum of 104.3 mm rainfall is required to induce 1 mm recharge into



(e) Khodiyar nagar earthen dam (WHS_5)



(f) Kali pond (WHS_6) (Recharge not measured in 2001 and 2002)



(g) Survey 99 (WHS_7) (Recharge not measured in 2001 and 2002)

Figure 6 (*continued*)

Table 6 Computed potential recharge (R_e in m^3) due to percolation from water storage structures/ponds from 2001 to 2004

Sl. No.	Water storage structure/pond	R_e (m^3)				
		2001	2002	2003	2004	Average[a]
1	Zalazali earthen dam	33,919	77,646	120,803	139,832	104,163
2	Zali pond	51,932	28,562	83,273	178,828	96,976
3	Zala pond	32,833	80,611	107,065	162,970	107,327
4	Antisar main pond	48,999	4673	53,606	72,726	48,898
5	Khodiyarnagar pond	3210	795	1307	3290	2124
6	Kali Tank	–	–	11,617	11,554	11,602
7	Survey 99	–	–	3048	4318	3355
Total (m^3)		170,893	192,287	380,719	572,582	374,444
Rainfall (mm)		421	538	864	826	835[b]

[a] The average R_e is rainfall weighted value.
[b] Long term average (1983–2004) (4 years' average 662 mm).

Table 7 Regression summary of the curve fitting of cumulative recharge (R_e in mm) to rainfall (P in mm) relationship

Storage structure	Regression summary			
	a	*b*	*c*	R^2
Zalazali (N[a] = 568)	3.067	0.594	4.82×10^{-3}	0.894
Zali (N = 333)	3.018	0.677	3.61×10^{-3}	0.608
Zala (N = 554)	4.081	0.582	5.11×10^{-3}	0.857
Combined (N = 599)	3.322	0.611	4.72×10^{-3}	0.889

[a] N = number of data pairs.

the aquifer. The rainfall that induces maximum recharge (11.5%) in the watershed amounts to 676.4 mm. Corresponding to average annual rainfall of the area (835.4 mm), the potential recharge from water storage structures works out to be 11%.

Estimation of aquifer recharge using water table fluctuation technique

The groundwater table maps of the whole area (watersheds WS-I and WS-II) were constructed and weighted area average depth to water table is shown in Fig. 8 for the years 2003 and 2004.

Water balance method was used to estimate storativity of the watershed during the period representing that part of the wet cycle when no instances of water withdrawal from the watersheds are reported i.e. between June 17 and September 26 in the year 2003 and from June 8 to August 31 in the year 2004. The storativity values estimated for individual years were averaged and adopted for computation of groundwater recharge by WTF method.

The field capacity (FC) and permanent wilting point (PWP) of the soil for the whole area were computed as 27.2% and 15.7%, respectively on volumetric basis. These parameters have been estimated as the weighted area average of the two watersheds; WS-I and WS-II (see Table 2). The values of FC and PWP for individual watersheds have been estimated from generalized soil textural data (Saxton et al., 1986) collected from 71 grid samples in the area.

In the absence of soil moisture information during the study period, the maximum storage in the soil profile was assumed to be equivalent to field capacity (FC) and the excess was assumed to contribute to the recharge component. The initial moisture content was taken equal to the permanent wilting point (PWP).

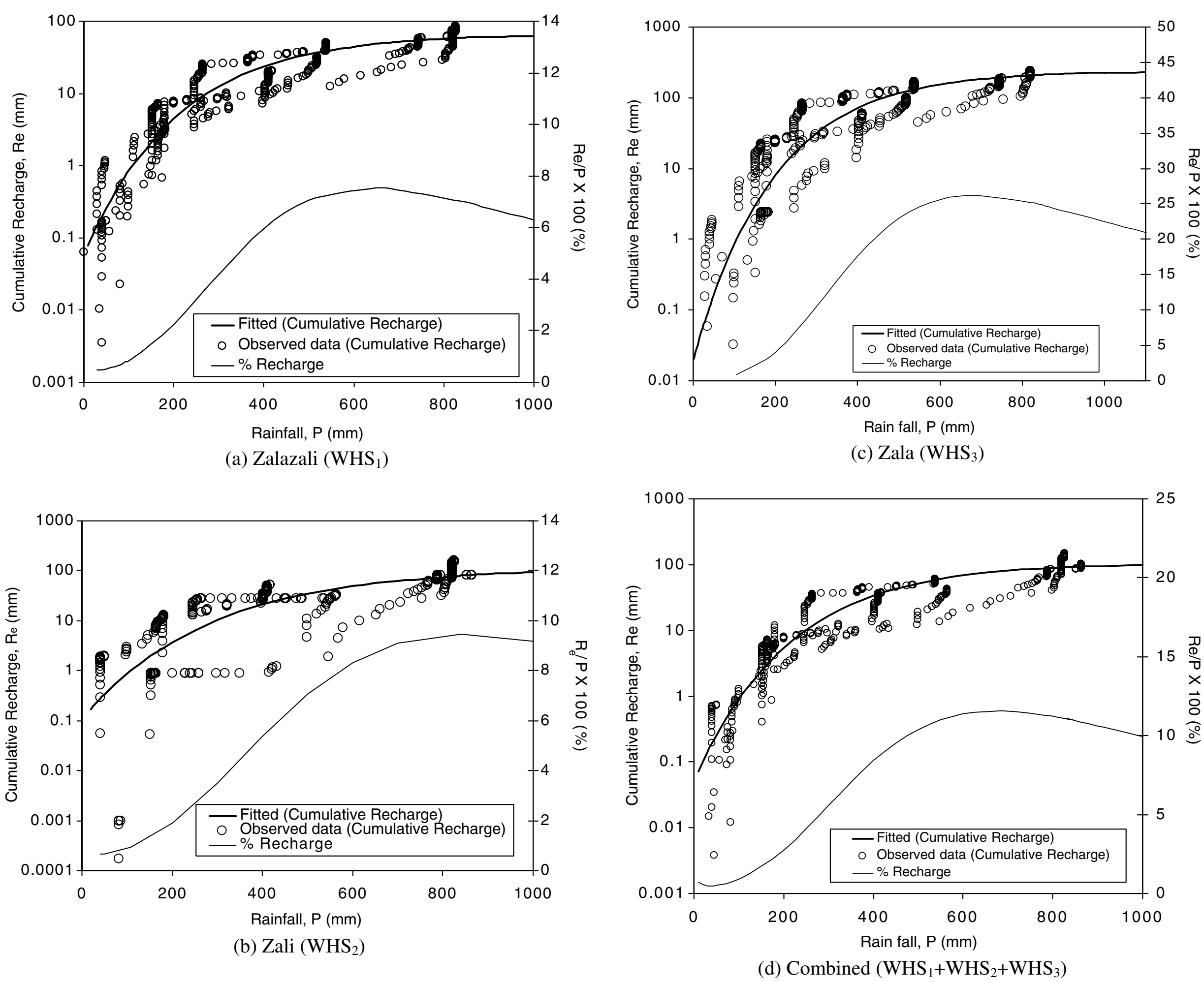


Figure 7 Cumulative potential recharge and cumulative rainfall and curve showing the trend of change of recharge as a percentage of rainfall for different water storage structures.

Table 8 Comparison of positional characteristics of the water storage structures in watershed WS-II against the chosen criteria

Criteria	Zalazali			Zala			Zali			Combined		
	P (mm)	Re (mm)	% Re	*P* (mm)	Re (mm)	% Re	*P* (mm)	Re (mm)	% Re	*P* (mm)	Re (mm)	% Re
To induce 1 mm potential recharge	107.9	1.0	1.0	105.7	1.0	1.0	107.8	1.0	1.0	104.3	1.0	1.0
Maximum % of rainfall recharged	638.9	48.1	7.5	682.8	178.8	26.2	846.3	79.9	9.4	676.4	82.3	11.5
Corresponding to average rainfall	835.4	58.6	7.0	835.4	208.9	25.0	835.4	78.9	9.4	835.4	92.3	11.0
Maximum capacity to recharge	—	66.5	—	—	238.2	—	—	110.8	—	—	106.9	—

P = Rainfall (mm), Re = Potential recharge from water storage structure (mm), %Re = Re/*P* $\times$ 100.

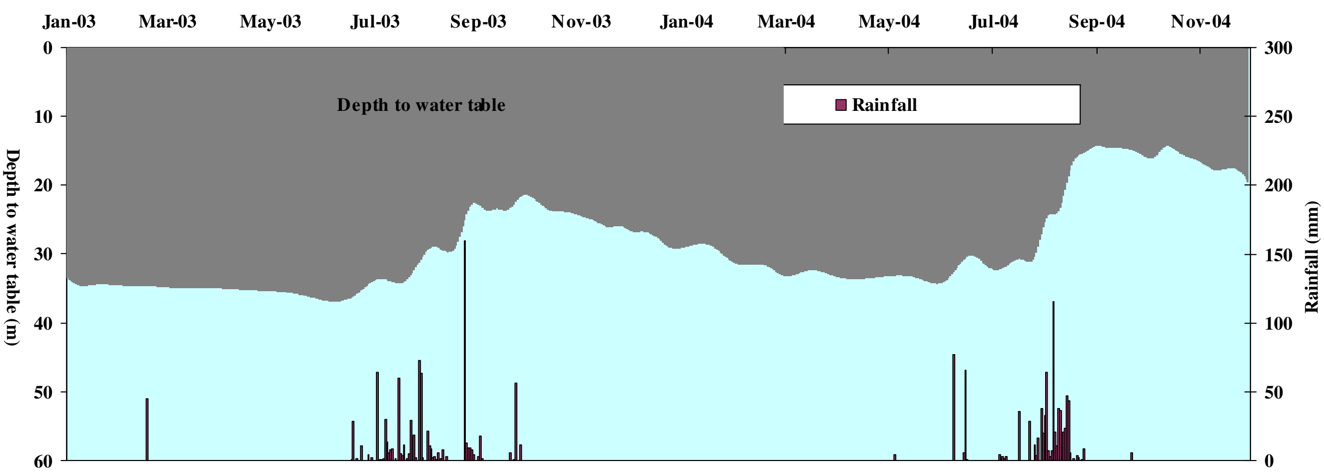


Figure 8 Water table fluctuation in the study area (weighted area average value of depth to water table considering both the watersheds WS-I and WS-II) year 2003—2004.

The Curve Number (CN) values were estimated based on the land use and cropping patterns of both the watersheds. Out of 812 ha area of watersheds WS-I and WS-II, an area of 736 ha is under agriculture with small grain crops such as pearlmillet, maize and sunflower (CN = 83) while 76 ha is under pasture and wasteland (CN = 79). The weighted value of CN was computed as 83 (AMC = II) (SCS, 1972). The curve number (CN) values of 69 and 91 were estimated for antecedent moisture conditions (AMC) I and III, respectively following standard procedure. Consequently, the surface runoff for the years 2003 and 2004 was computed as 166.7 and 243.5 mm, respectively (Dhruvanarayana, 1993; SCS, 1972).

The actual evapotranspiration values for the years 2003 and 2004 were calculated as 453.9 and 420.8 mm, respectively. When compared to a cumulative groundwater table rise during the period of water balance calculation i.e. 18.01 m in 2003 and 17.7 m in 2004, the average storativity for the years 2003 and 2004 worked out to be 3.39×10^{-3}.

The rise in water table was 18.5 m during the recharging period from June 17, 2003 to December 31, 2003. Hence, the cumulative recharge to the groundwater table was estimated as 5.107×10^5 m^3 which is 7.3% of the annual rainfall during the year. Similarly, in the year 2004, the groundwater recharge was estimated as 6.769×10^5 m^3 (9.7% of the annual rainfall). Considering both the years, the average recharge worked out to be 8.5% of the annual rainfall.

Influence of potential recharge on groundwater table

The interaction of potential recharge from surface water bodies to the groundwater aquifer was specifically studied, both under natural and artificial recharging systems. The objective of the first approach was to study the influence of all the surface water bodies on the groundwater table rise under artificial recharge methods while the second aimed at ascertaining the time required for a drop of water percolated from the storage structures under natural recharge conditions to reach the groundwater aquifer. The pre- and post- monsoon water table maps (Fig. 9(a) and (b)) indicate that in the areas having both natural storage structures and artificial recharge filters, the groundwater table increased significantly.

Based on the water table data collected during July 20, 2003 to August 5, 2003 (rainfall during the period is

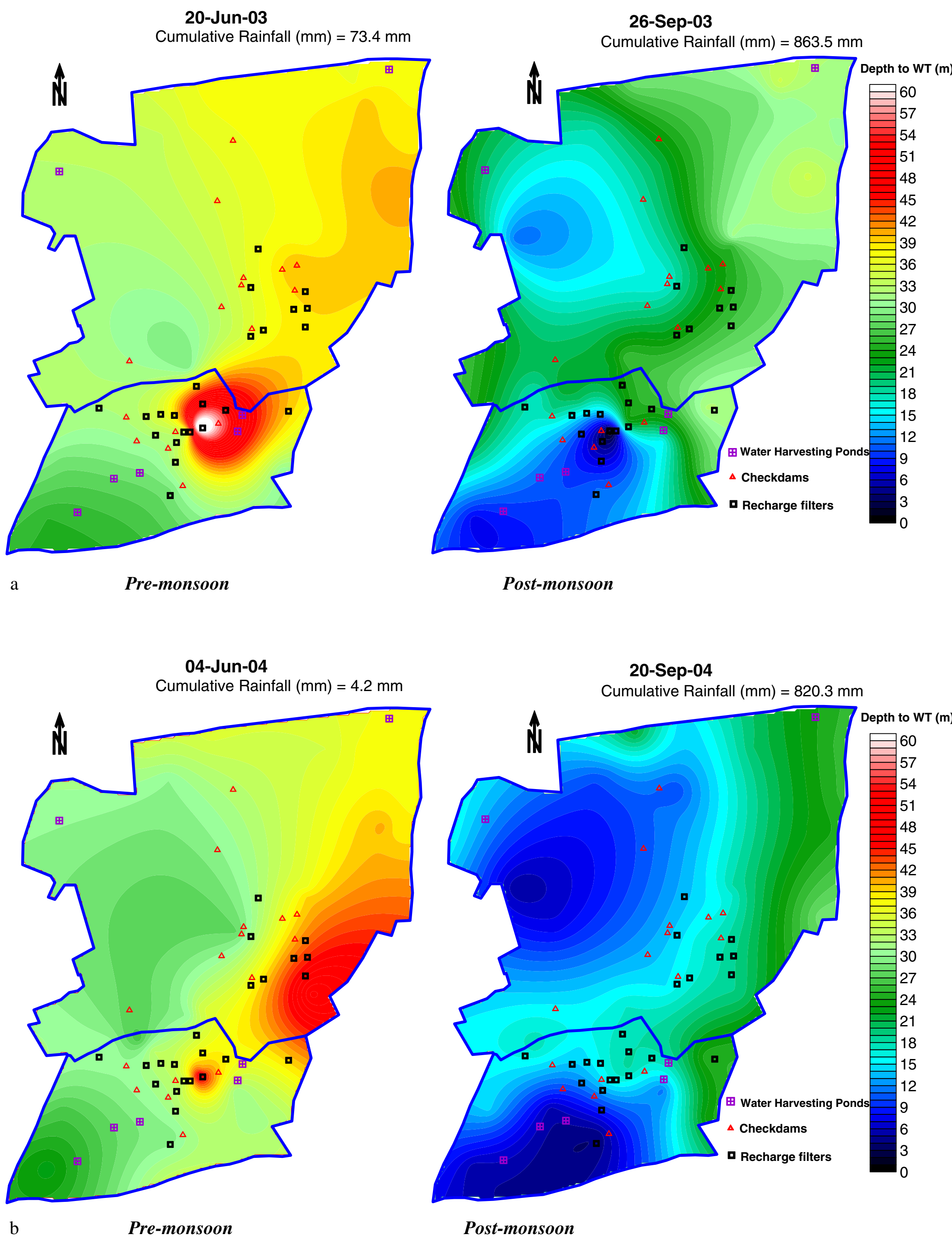


Figure 9 Pre-monsoon and post-monsoon groundwater table scenario of the watersheds for year (a) 2003 and (b) 2004.

234 mm), it was established that 101 tube wells/open wells (73%) out of the designated 139 tube wells and open wells get influenced by the recharged water (Fig. 10(a)). The net rise in water table during this period was 4.99 m.

In the successive fortnight (August 5, 2003 to August 20, 2003), there was no rainfall. Therefore, the net rise in water table was only 0.69 m which is ascribed to percolation of water from water storage structures coupled with internal redistribution of water table in the aquifer and gradual recession of the mounds formed under different water storage structures (Fig. 10(b)).

Practically, at all places in a ground-water reservoir, the water table fluctuates up and down in response to additions to or withdrawals from the reservoir. When a well or surface storage structure (a feeder zone) begins to recharge water to an aquifer, the water table adjacent to the well is raised, establishing a hydraulic gradient away from the feeder zone. For a short period, most of the water recharged from

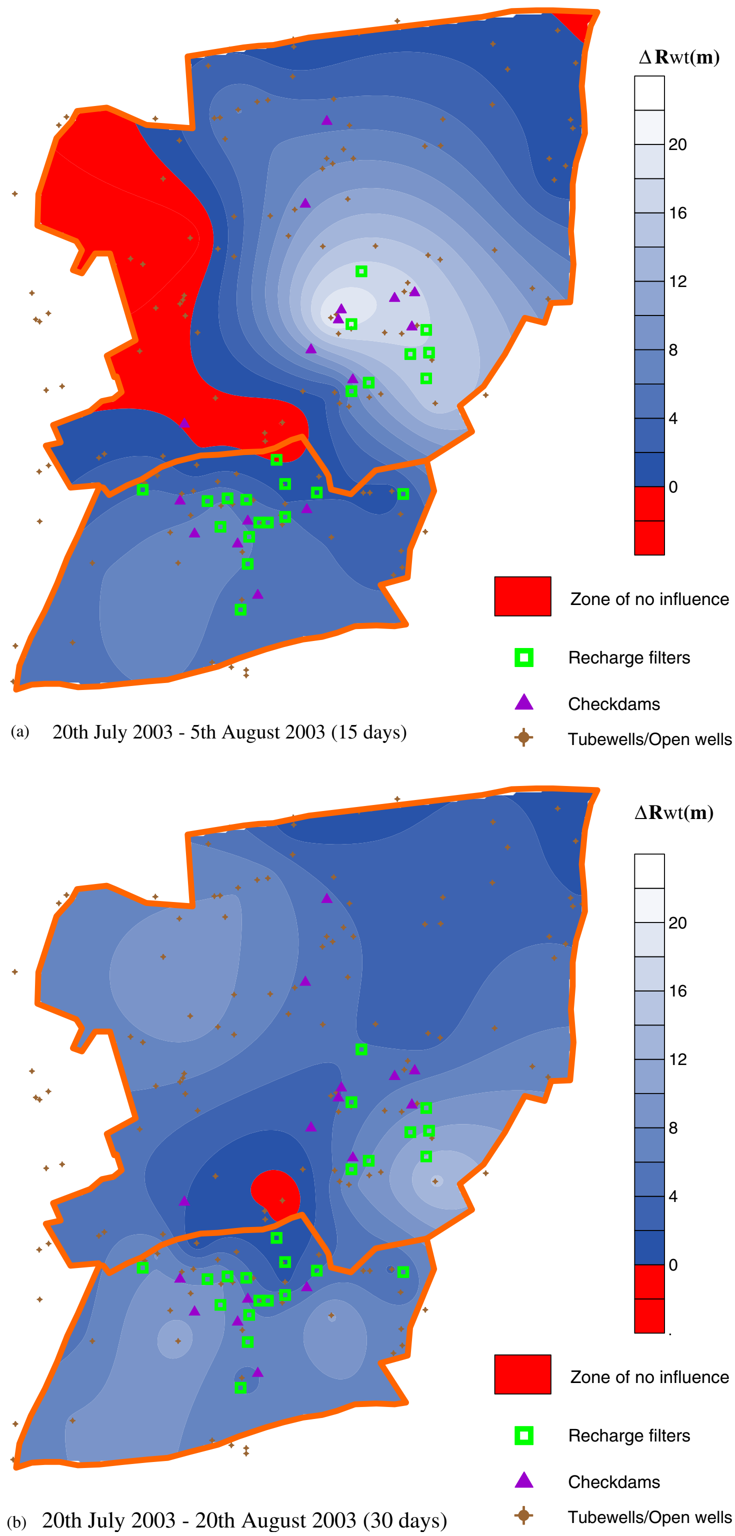


Figure 10 Influence of recharge on ground water table rise over a period of time.

these feeder zones forms a mound that results in increase in water table of the surrounding well derived from the internal recession of these mounds close to the well. When considered over an interval (a fortnight or a month), the gain in water table at any place is associated with a consequential recession of water table in the feeder zone. The cone of recession around the recharge structure continues to decrease in size until sufficient recharge is added to the receiving zone compensating the hydraulic gradient. It is quite evident from Fig. 10(a) and (b) that the negative water table change is attributed to the feeder zones from the previous recharge instances.

Data were analyzed from three observation wells (numbered as 85, 86 and 89) to study the fluctuations in water table due to potential recharge from water storage structures. It is evident from Fig. 11 that water table responds quickly to the recharge from the storage structures. Fluctuations in potential recharge and water table were plotted on a same time scale (Fig. 11) and the difference between the peaks were taken as the base for determining the period taken by the water percolated from ponds to reach the groundwater table. It was estimated that the percolated water from the structures takes about 6 days to reach the groundwater table.

Further, it was estimated that during the data years (2003–2004), the storage structures in the watershed WS-II alone contributed 11% of the annual rainfall as potential recharge; whereas 8.5% of the annual rainfall actually recharged the groundwater table in the entire area covering WS-I and WS-II. Considering the loss of water in the thick unsaturated section of the aquifer, it can be deduced that 77% of the potential recharge contributes to groundwater aquifer through natural translatory process. However, the amount of water contributed by the individual recharging filter directly to the aquifer still remains unpredicted.

Hydro-geochemical framework

Fig. 12 presents the fluctuations in water table vis-à-vis the chloride concentration in the entire study area. It may be concluded that with the increase in water table, the weighted average chloride concentration decreases, thus conforming to an inverse relationship between the change in chloride concentrations and the water table fluctuations.

The chloride concentration maps were analyzed to find out the area where there was an increase in chloride concentration, which were then compared to those where water table declined and vice versa Fig. 13 shows the relation between the changes in chloride concentration (ΔCl) to the changes in water table depth (ΔWT). Accordingly, a diagnostic empirical relationship was developed as under:

$$\Delta WT = -0.0169 * \Delta Cl, \; R^2 = 0.608 \; (N = 132) \qquad (15)$$

During peak irrigation season, most of the tube wells/bore wells are not available for measurement of water table fluctuations due to installation of pumping units, though water samples can be easily collected. By analyzing the water samples for chloride concentration during such periods, Eq. (15) can be used to generate the missing water

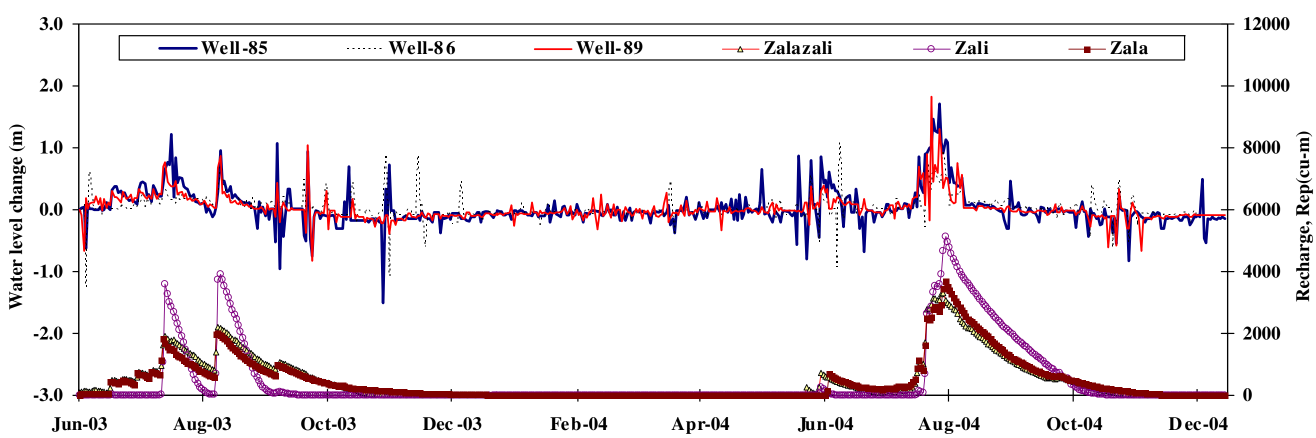


Figure 11 Response of water table in three installed piezometers to potential recharge from three water storage structures in the sub-watershed WS-II.

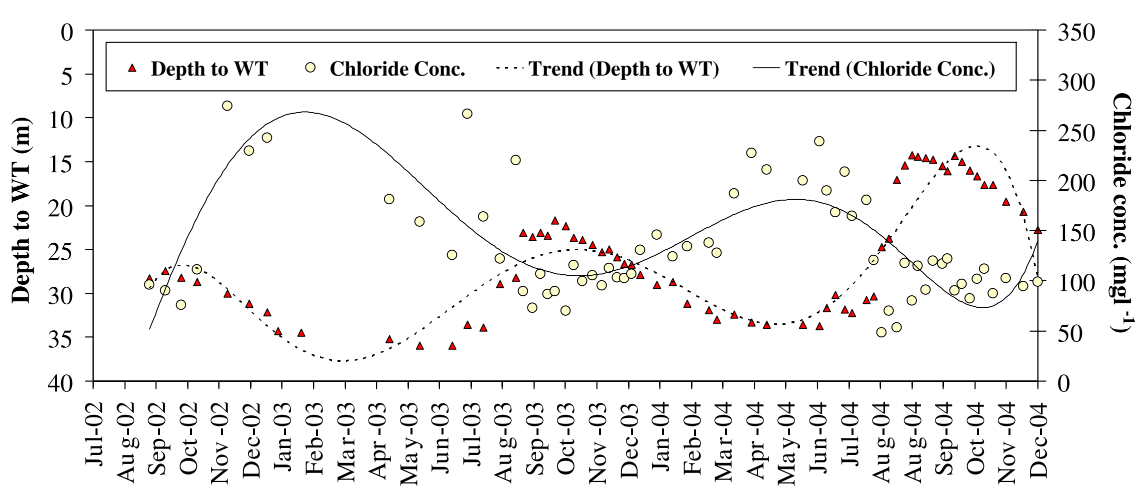


Figure 12 Trend of chloride concentration to water table fluctuation in the study area.

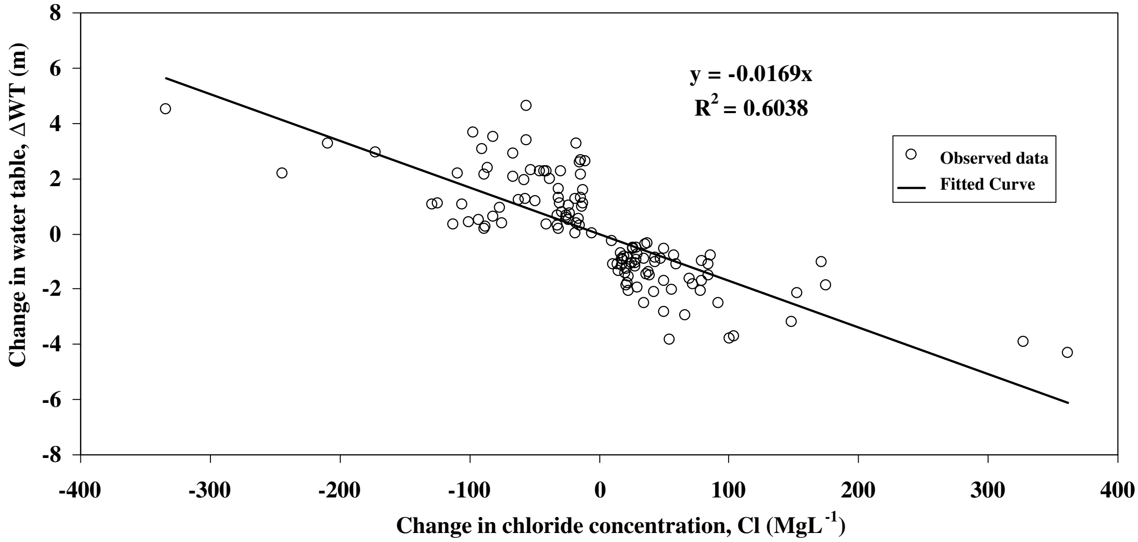


Figure 13 Change in chloride concentration to water table rise or fall in the study area.

table data. The second hypothesis was to develop a surrogate method for estimating recharge in the watershed based on changes in chloride concentration over successive periods. A reduction in chloride concentration indicates a rise in the water table in the study area and consequently the recharge volume can be estimated from the changes in the water table. The relationship developed is not the best-fit equation but reasonably represents the trend over a period spanning from September 2002 to December 2004. However, a physical concept of chloride mass balance can be used to refine the relationship with more time series data and can be coupled to a most physically sound empirical model comprising the saturated and unsaturated sections of the flow domain.

To find out the annual recharge, the average chloride concentration of the groundwater samples for the years 2003 and 2004 was calculated as 132.97 mg l^{-1}. The Average weighted chloride concentration of the rainfall was found out to be 9.94 mg l^{-1}. Using Eq. (11), the average recharge rate for the years 2003 and 2004 was computed as 7.5% of the annual rainfall (835.4 mm) which is well comparable to the average recharge estimated by water table fluctuation method (7.55%).

Summary and conclusions

An attempt has been made to examine the effect of water storage structures on groundwater recharge in a semi-arid agro-climatic setting. The interaction between potential recharge and the actual groundwater recharge was studied in a situation when a large unsaturated section divides the surface and groundwater body. To start with, potential recharge was computed from storage structures using a recharge function developed for each storage structure. These functions estimated the potential recharge reasonably well. A diagnostic relationship developed between cumulative recharge and rainfall for a small watershed (WS-II) served as a base to determine the characteristics of the water storage structures based on their geographical position. The analysis revealed that a minimum of 104.3 mm cumulative rainfall is needed to trigger 1 mm of potential recharge in this agroclimatic setting. Further, critical appraisal of this relationship indicated that individual storage structure in the watershed has a limiting capacity to induce a maximum recharge irrespective of the amount of rainfall. It was also inferred that the maximum potential recharge from a structure can be achieved at a rainfall lower than the existing average rainfall in a given area. This finding would help in designing the storage structures more efficiently for inducing ground water recharge and can serve as a parameter to compare the water harvesting structures in a given agro-ecological situation.

The chloride mass balance (CMB) method was used to assess its efficiency in estimating the annual recharge in comparison to WTF method. Both the methods were found to yield comparable results for estimation of actual groundwater recharge. The storativity estimated by the water balance approach was in conformity with the recharge estimates of CMB method and can be used as a weighted parameter representing the whole watershed.

It was observed that there exists a definite relationship between the changes in chloride concentration and the rise or fall in the water table. A diagnostic linear relationship was found to fit the data reasonably well. However, a sound database is needed to further improve this relationship in conjunction with physical concepts of chloride mass balance.

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