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GIS-Based Water Balance Modeling for Estimating Regional Specific Yield and Distributed Recharge in Data-Scarce Hard-Rock Regions

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Abstract

In this study, a methodology is presented and demonstrated for combined estimation of regional specific yield and distributed recharge using double water-table fluctuation (DWTF) technique and geographical information system (GIS) in a hard-rock aquifer system of semi-arid regions. The study area was divided into 25 zones and groundwater budget components were computed for both wet and dry seasons using 11-year period (1996-2006) data. In each zone, the regional specific yield was estimated by applying the WTF technique for dry seasons and the rainfall recharge was estimated by applying the WTF technique for wet seasons. Zone-wise rainfall-recharge relationships were established using regression technique. Thereafter, the specific yield and recharge estimates were used with GIS to generate their maps. Surface-water bodies were found to significantly contribute to groundwater recharge. This finding underscores the need for adopting rainwater harvesting in the study area to enhance recharge. The regional specific yields were found to range from 0.038 to 0.002, whereas the mean rainfall recharge was found to vary from 0.5 to 10.9 cm. The box-whisker plots of z-scale transformed specific yield revealed the greatest spatial variation. The spatial and temporal variations of the rainfall recharge in the study area are statistically significant ($p<0.05$ and $CV>30\%$). The developed rainfall-recharge relationships were found to be ‘highly significant’ ($r^2 \geq 0.54$, $p<0.05$) in four zones, ‘moderately significant’ ($0.54>r^2 \geq 0.36$, $p<0.01$) in ten zones and ‘insignificant’ ($r^2<0.36$) in the remaining zones.

Keywords: *Double water-table fluctuation technique, Water balance modeling, Regional specific yield, Distributed recharge, Hard-rock aquifer system, Semi-arid region.*

1. INTRODUCTION

Quantification of natural and human-induced recharge is a basic requisite for efficient groundwater management, and is especially of great significance in arid and semi-arid regions of the world where groundwater resources are often key to socio-economic development. In arid and semi-arid regions, recharge rates are highly variable in space and time, recharge mechanisms vary throughout the basin and several approaches exist for measuring groundwater recharge (Yair and Lavee, 1985; de Vries and Simmers, 2002). Important considerations in choosing a recharge estimation technique include spatial and temporal scales, range, and reliability of recharge estimates by different techniques (Scanlon et al., 2002).

Although there are various well-established techniques for the quantitative evaluation of groundwater recharge, none of them are free from uncertainties (Sharma, 1989; Scanlon et al., 2002). Direct determination of recharge by a lysimeter and seepage meter is of local value and is not a representative of the entire aquifer. Darcian approaches based on field measurement and numerical methods are used under conditions of full or partial saturation (Samper, 1997). Methods based on the use of natural tracers, whether chemical (chloride balance) or isotopic (^{18}O, ^{2}H, ^{3}H and ^{14}C), or the use of artificial tracers (organic and inorganic colorants) constitute an alternative to hydrodynamic methods (Allison et al., 1985; Wood and Sanford, 1995; Scanlon et al., 2002). The hydro-chemical and isotopic methods require representative samples of rainfall and groundwater. In the water-balance method, only a few components of groundwater-balance equation are measured directly (e.g., precipitation) and the remaining components are estimated indirectly using semi-empirical formulae (Andreo et al., 2008). The water-balance method has several advantages like straightforward implementation, relatively low cost, and its applicability to all types of recharge and aquifer media. Among the different recharge estimation techniques, those based on groundwater data have the capability to estimate actual recharge as they compute actual change in groundwater storage. Such techniques (e.g., water-table fluctuation technique) are amongst the widely applied methods for estimating recharge rates (Sophocleous, 1991; Healy and Cook, 2002; Crosbie et al., 2005).

In semi-arid areas, water-table fluctuation (WTF) technique is considered to be one of the most promising and attractive due to its accuracy, ease of use and cost-effectiveness (Beekman and Xu, 2003). The accurate application of the WTF technique requires reliable specific yield data of the aquifer at a suitable scale as well as reliable and representative water-table fluctuation data (Healy and Cook, 2002; Beekman and Xu, 2003). In hard-rock areas, the specific-yield values are highly site-specific and vary significantly over small distances. This wide variation in the specific-yield values of the aquifer suggests strong heterogeneity, which is most likely in fractured subsurface formations (NABARD, 2006). Therefore, specific-yield values determined by analyzing time-drawdown pumping test data may not be reliable and useful for regional recharge estimation (Naik and Awasthi, 2003; Machiwal, 2009). Under this situation, double water-table fluctuation (DWTF) technique, which is a combination of groundwater budget and water-table fluctuation methods, can be employed to determine regional specific yield and regional recharge. The review of literature revealed that the studies dealing with the DWTF technique is very limited (Naik and Awasthi, 2003; Maréchal et al., 2006; Saha and Agrawal, 2006). In the past studies on the DWTF technique, the specific yield and the recharge rate were determined for the aquifer systems as a whole neglecting their heterogeneity. In reality, however, the specific yield and recharge rate exhibit significant variations from one location to another in most hydrogeological settings.

Therefore, in the present study, which is the first of its kind in the study area, an attempt has been made to determine regional specific yield and distributed natural recharge under data-scarce conditions by using DWTF technique and geographical information system (GIS). Unlike earlier studies on the DWTF technique, this study takes into account spatial and temporal variability of natural recharge as well as the spatial variability of specific yield over a groundwater basin. Since adequate data are not available in the study area, which is a common problem in most developing nations, it is not possible in this study to apply other methods of recharge estimation for comparative assessment.

2. DESCRIPTION OF THE STUDY AREA

2.1 Location and Hydrometeorology

The study area chosen for this study (Udaipur district) is located in the southern part of Rajasthan, western India (Fig. 1) and covers a geographical area of about 12698 km^2. It lies between latitude 23°45′ and 25°10′ N and longitude 73°0′ and 74°35′ E. The Udaipur district has 11 blocks (Badgaon, Bhinder, Dhariawad, Girwa, Gogunda, Jhadol, Kherwara, Kotra, Mavli, Salumber, and Sarada). In India, for the administration purpose, a state is divided into districts, districts into blocks and blocks into *Gram Panchayats*; a *Gram Panchayat* consists of several villages.

The Udaipur district has a tropical, semi-arid climate with temperature rising to a maximum of 42.3 °C and dipping to a minimum of 28.8 °C in summers. In winters, temperature varies between 28.8 °C (maximum) and 2.5 °C (minimum). The average annual rainfall is 625 mm, of which more than 80% precipitates during June through September. The rainy season (i.e., wet season) has a span of about four months and it normally starts around mid-June and lasts until the end of October. The non-rainy (i.e., dry season) is spread over November to May months. The main rivers of the district are Berach, Jhakham, Sabarmati, Sei, Som and Wakal, which have intermittent flow. In addition, there are several surface reservoirs and lakes in the district, which supply water mainly for drinking, irrigation and industrial needs. Surface irrigation is mostly confined to canal commands situated in the southern and southeast portions of the study area (Fig. 1).

2.2 Hydrogeologic Conditions

The geologic formations available in the area are phyllite-schist, gneiss, granite, schist, and quartzite (Fig. 2). The dominating phyllite-schist geology, located in western portion and as a localized pocket near Mavli, covers about half of the area. The gneiss geology covers the eastern part of the area. The granite formation occupies the western periphery of Kotra block, while the quartzite is present in Jhadol block. The schist geology exists in very small parts of Gogunda and Kotra blocks. The hillocks or small hills present in the area have negligible groundwater potential. However, foothills of the hillocks appear as valley fills and buried pediment, and are effective in recharging shallow and deep aquifers. Both shallow and deep aquifers are present in the area though the deep aquifers are available at deeper than 100 m from the land surface and little is known about these aquifers (GWD, 2008). The shallow aquifers are mainly under unconfined conditions in the saturated zone of the weathered rock formations and they constitute the major source of groundwater in the area. The occurrence of groundwater is largely controlled by the topography, physiography and structural features present in the geological formations (CGWB, 2010). The hydraulic conductivity of the shallow aquifer system varies from 1.33 to 41.65 m/day as determined by field pumping tests conducted by the first author (Machiwal, 2009).

3. CONCEPT OF REGIONAL SPECIFIC YIELD AND DWTF TECHNIQUE

The specific yield can be determined by field pumping test, soil moisture measurements, water-balance method or water table fluctuation (WTF) technique (Healy and Cook, 2002). Unlike the pumping test, the water-balance method provides a regional estimate of the specific yield (CGWB, 1997; Naik and Awasthi, 2003). The water-balance method is a widely used technique for estimating specific yield in fractured-rock systems, probably because it does not require any assumptions concerning flow processes (Healy and Cook, 2002). The Central Ground Water Board (CGWB), the apex body involved in the planning and monitoring of groundwater resources in India, has suggested the application of water-balance method for determining specific yield in hard-rock regions of the country due to several practical constraints in conducting pumping tests (CGWB, 1997; NABARD, 2006).

The WTF method is best applied to shallow water tables that display sharp seasonal water level rises and declines (Maréchal et al., 2006). Deep aquifers may not display sharp rises because wetting fronts tend to disperse over long distances (Healy and Cook, 2002). In the fractured-rock aquifer systems of semi-arid regions, the rainy season during which the water table rises several meters due to rainfall recharge, is followed by the dry season during which the water table drops due mainly to groundwater pumping. Therefore, the hydrological year can be divided into two distinct seasons: (i) recharge (wet season), and (ii) no recharge (dry season) that permits for a double use of the WTF method. First during the dry season, the WTF method can be used to estimate specific yield, and second during the wet season, the WTF method can be used to estimate groundwater recharge, along with due consideration of the other water balance components. It is worth to mention that a successful application of the WTF method requires a proper network of groundwater-level monitoring in order to ensure a large number of water level measurements before and after each season. The advantage of the method is that specific yield and recharge are estimated at the scale of interest to basin hydrologic studies and that the method requires no extensive *in situ* instrumentation network (Maréchal et al., 2006).

The groundwater-balance method focuses on the various components contributing to groundwater inflow and outflow, and groundwater storage changes as shown in the following equation:

$$R + R_i + Q_{in} = ET + GWD + Q_{out} + Q_{bf} + \Delta S \qquad (1)$$

Where, R = total groundwater recharge (sum of direct recharge through unsaturated zone and indirect recharge from surface bodies and canals), R_i = recharge due to irrigation return flow, Q_{in} and Q_{out} = groundwater flow into and out of the area, ET = evapotranspiration from water table, GWD = groundwater draft/abstraction, Q_{bf} = baseflow (groundwater discharge to streams or rivers), and ΔS = change in groundwater storage.

In the study area, the water table remains much below the ground surface (more than 3.5 m below ground level) and hence, ET is insignificant and can be neglected. Similarly, baseflow is zero because there is no contribution from groundwater to streams and rivers. In addition, the change in groundwater storage is taken care by Eqn. 3 and groundwater inflow and outflow components are considered negligible for the regional scale and annual time step. Thus, for the study area, Eqn. (1) reduces to the following:

$$R + R_i = GWD + \Delta S \qquad (2)$$

The groundwater is withdrawn for both domestic and irrigation purposes. Similarly, return flow originates from both surface-water irrigation and groundwater irrigation. The total recharge in the study area includes recharge due to rainfall, surface-water bodies, canal seepage, and return flow. Change in groundwater storage (ΔS) can be determined by the WTF method, which links the ΔS with resulting water-table fluctuation (WL_f) as:

$$\Delta S = S_y \ WL_f \tag{3}$$

Where, S_y = specific yield of the unconfined aquifer.

Combining Eqn. (2) with Eqn. (3), we have:

$$R + R_i = GWD + S_y \ WL_f \tag{4}$$

By applying Eqn. (4) separately to the dry and wet seasons, we obtain the following two seasonal groundwater-balance equations:

Dry Season:

$$R_r^{dry} + R_{swb}^{dry} + R_{canal}^{dry} + R_{swi}^{dry} + R_{gwi}^{dry} = GWD_{irigation}^{dry} + GWD_{domestic}^{dry} - S_y \ WL_d \tag{5}$$

Wet Season:

$$R_r^{wet} + R_{swb}^{wet} + R_{canal}^{wet} + R_{swi}^{wet} + R_{gwi}^{wet} = GWD_{irrigation}^{wet} + GWD_{domestic}^{wet} + S_y \ WL_r \tag{6}$$

Where, R_r^{dry} and R_r^{wet} = recharge due to rainfall, R_{swb}^{dry} and R_{swb}^{wet} = recharge due to surface-water bodies, R_{canal}^{dry} and R_{canal}^{wet} = recharge due to canal seepage, R_{swi}^{dry} and R_{swi}^{wet} = recharge due to return flow from surface-water irrigation, R_{gwi}^{dry} and R_{gwi}^{wet} = recharge due to return flow from groundwater irrigation, $GWD_{irrigation}^{dry}$ and $GWD_{irrigation}^{wet}$ = groundwater drafts for irrigation, $GWD_{domestic}^{dry}$ and $GWD_{domestic}^{wet}$ = groundwater drafts for domestic purpose, WL_d = groundwater level decline during dry season, and WL_r = groundwater level rise during wet season. The superscripts dry and wet indicate dry and wet seasons, respectively.

4. METHODOLOGY

4.1 Data Collection

Monthly rainfall data of ten rainfall gauging stations for the period 1996-2006 were collected from the Land Record Section of Collectorate, Udaipur, Rajasthan. Pre- and post-monsoon groundwater level records of 251 monitoring wells for the 19 years (1988-2006) were collected from the Ground Water Department, Udaipur, Rajasthan (India). In general, pre-monsoon groundwater levels are monitored at the end of May, while the post-monsoon groundwater-level monitoring is done at the end of October month. All the collected groundwater-level records were processed and checked for anomalies and consistency. The locations of the rainfall stations and groundwater monitoring sites are shown in Fig. 1. Also, data of crop acreage, irrigation water supply from different sources were obtained from the Land Record Section of Collectorate of Udaipur, Rajasthan. The well census and discharge data were acquired from the Public Health Engineering Department, Udaipur, Rajasthan (India). Moreover, the data on lake storage were collected for 11-year period (1996-2006) from the Irrigation Department, Udaipur, Rajasthan. The unavailability of adequate data required for the water balance modeling at a desired regional scale is common for many hard-rock regions and the study area of the present study is no exception. Therefore, recommendations provided by the Central Ground Water Board (CGWB, 1997) and the local Ground Water Department (GWD, 2008) are adopted in this study for making a reasonable estimation of water balance components.

4.2 Zoning of the Study Area

In this study, a zone-based approach was adopted to account for the spatial variability of specific yield and rainfall recharge. The study area was subdivided into 25 zones according to the type of geology, excluding hillocks, and land (command or non-command) as shown in Fig. 3. The command land refers to the area where canal water is available for irrigation. Details of the 25 zones are given in Table 1. The phyllite-schist geology covering 28% of the total area exists in 12 zones and gneiss type of geology covers 25% area in 9 zones followed by schist (6%) in 2 zones, and granite (3%) and quartzite (1%) in one zone.

4.3 Computation of Groundwater Budget Components

A schematic of water-balance components for command and non-command areas of the study area is shown in Fig. 4. All the groundwater budget components were estimated separately for wet (rainy) and dry (non-rainy) seasons of the 11-year period (1996-2006) for the 25 zones.

4.3.1 Estimation of Groundwater Abstraction

The annual groundwater abstractions for the domestic purpose for the 11-year period (1996-2006) were estimated based on the information about number of annual operation days, average well yield, and the total number of operational wells for the domestic purpose.

Similarly, the annual abstractions for irrigation during dry seasons were estimated based on well census data. The groundwater abstractions for irrigation purposes were considered as 25% and 75% of the annual abstractions in wet and dry seasons, respectively (GWD, 2008).

4.3.2 Estimation of Groundwater Recharge from Irrigation Return Flow and Surface-Water Bodies

The recharge due to return flow from irrigation was estimated based on the source of irrigation (groundwater or surface water), type of crop (paddy, non-paddy) and depth of water table below the ground surface as suggested by CGWB (1997) (Table 2). Total annual irrigation water volumes applied were estimated based on the total crop acreage and average depth of irrigation.

Recharge due to canal seepage was estimated following the guidelines of CGWB (1997) and the recharge due to the seepage of water from tanks/lakes and ponds was estimated by considering a seepage factor (GWD, 2008). It was experienced that usually the water in the lakes can be stored at most for eight months in a year.

4.4 Estimation of Regional Specific Yield by the Water-Balance Method

During the dry season, there is negligible rainfall and hence, recharge due to rainfall is zero. After rearranging terms, Eqn. (5) can be written as follows to compute S_y:

$$S_y = (GWD_{irrigation}^{dry} + GWD_{domestic}^{dry} - R_{canal}^{dry} - R_{swb}^{dry} - R_{swi}^{dry} - R_{gwi}^{dry}) / WL_d \tag{7}$$

Eqn. (7), the ‘water-balance method’ for estimating S_y (Healy and Cook, 2002), was used to determine regional S_y in the 25 zones. A GIS- classified S_y map was prepared and statistical techniques were employed to depict its spatial variation.

Moreover, the relative spatial variability of the S_y was compared with that of the wet season water-balance components by drawing box-whisker plots of the mean z-scale transformed values of all the parameters.

4.5 Estimation of Recharge and Development of Rainfall-Recharge Relationship

Solving the wet-season water-balance equation [Eqn. (7)] in terms of rainfall recharge, the following expression can be obtained:

$$R_r^{wet} = GWD_{irrigation}^{wet} + GWD_{domestic}^{wet} - R_{swb}^{wet} - R_{canal}^{wet} - R_{swi}^{wet} - R_{gwi}^{wet} + S_y\ WL_r \tag{9}$$

The above water-balance equation was used to estimate rainfall recharge in 25 zones for 11-year period. Finally, distributed recharge map was prepared by GIS technique.

Moreover, an empirical rainfall-recharge relationship for the 25 zones was developed by the linear regression technique. The developed relationships (i.e., rainfall-recharge models) were evaluated based on the coefficient of determination (r^2). The evaluation criteria based on correlation measures such as r^2 are considered to be over-sensitive to extreme values and insensitive to additive and proportional differences between observations and regression-based predictions (Moore, 1991). Therefore, two additional criteria namely, modified Nash-Sutcliffe efficiency, MNSE (Legates and McCabe, 1999), and modified index of agreement, MIA (Willmott et al., 1985) were also employed to ensure better evaluation. These three evaluation criteria are summarized in Table 3.

5. RESULTS AND DISCUSSION

5.1 Groundwater Abstraction for Domestic and Irrigation Purposes

The mean seasonal domestic and irrigation groundwater abstractions in the 25 zones are shown in Figs. 5(a,b). It is apparent that there is no significant temporal variation of domestic groundwater abstractions in both wet and dry seasons, except for the 5th zone (i.e., phyllite-schist non-command of Girwa block) (Fig. 5a). In this zone, mean domestic abstraction is considerably high (i.e., 1.44×10^6 and 2.94×10^6 m^3 in wet and dry seasons, respectively), which sustains a large proportion of human and livestock population.

On the other hand, the highest mean groundwater abstractions for irrigation purpose are in the 2nd (gneiss non-command of Bhinder block), 5th (phyllite-schist non-command of Girwa block), and 17th (gneiss non-command of Mavli) zones (Fig. 5b), which are located in the non-command land and hence are deprived of canal water supply. However, topographic and soil conditions of these zones are favorable for agriculture. Thus, farmers of the area withdraw groundwater indiscriminately for irrigating their fields. It is seen that the groundwater abstraction for irrigation in the wet season is considerably less than that in the dry season (Fig. 5b).

5.2 Recharge due to Return Flows from Irrigation

The mean seasonal recharge due to return flows from irrigations is shown in Figs. 5(c,d). The amount of the dry season recharge from surface-water irrigation is not significant in most zones of the area (Fig. 5c). In the wet season, canals are not operated and the only source of surface-water irrigation is small ponds or lakes. Consequently, the return flow from surface-water irrigation is negligible in all the zones. However, considerable recharge during the dry season occurs for the 3rd and 4th zones (i.e., gneiss non-command and command of Dhariawad block), which is attributed to the significant application of surface-water irrigation in the 3rd zone and the largest command size (i.e., 385.69 km^2) of the 4th zone. The large standard error bars indicate the significant temporal variations of the return flow in both 3rd and 4th zones (Fig. 5c). It is obvious from Fig. 5d that the recharge due to the return flows from groundwater irrigation is substantially higher during dry seasons than those during wet seasons. Relatively large recharge from groundwater irrigation during dry seasons occurs for the 1st, 2nd, 3rd, 4th, 5th, 6th, 9th, 11th, 17th, 20th, and 22nd zones of the area, which is due to the greater groundwater withdrawals for irrigation.

It is revealed that the mean seasonal return flow from groundwater irrigation dominates over that from surface-water irrigation except for the 4th, 21st, and 23rd zones [Figs. 5(c,d)]. These three zones (gneiss command of Dhariawad block, gneiss command of Salumber, and phyllite-schist command of Sarada) have well-designed canal network and hence, the mean return flow is almost the same for both types of irrigation.

5.3 Recharge from Surface-Water Bodies

It is seen from Fig. 5e that relatively high recharge from surface-water bodies occurs for the 11th (phyllite-schist non-command of Kherwara block), 20th (gneiss non-command of Salumber), and 24th (gneiss non-command of Sarada) zones of the area. Of these three high recharge zones, the 20th and 24th zones share the Jaisamand lake, which is the largest artificial lake of the Asian continent and 11th zone has a big irrigation dam (Som Kagdar). These large surface-water bodies appreciably contribute to recharge in both wet and dry seasons, with significant temporal variation (Fig. 5e).

5.4 Regional Groundwater Budget Components for Dry Seasons

Details about the components of the groundwater budget for the dry seasons of 1996, 1999, and 2003 are presented in Table 4. The groundwater budget components for the dry season could be estimated for these three years only because of non-availability of the adequate data for rest of the years. The data required for estimating groundwater budget components such as canal seepage and recharge from surface water bodies could be available for these years. for It is apparent that the maximum decline of dry season groundwater levels occurred in the 16th zone (phyllite-schist non-command of Mavli) in 1996. However, in the years 1999 and 2003, the maximum decline was observed in the 1st zone (phyllite-schist non-command of Badgaon). It is also evident that a large amount of groundwater is withdrawn from the 5th zone (phyllite-schist non-command of Girwa) for domestic uses in 1996, 1999 and 2003 (Table 4). However, the 2nd zone (gneiss non-command of Bhinder) abstracted the maximum groundwater for irrigation during 1996 and 1999, because this zone is quite favorable for agricultural production. However, in 2003, the abstraction for domestic and irrigation purposes was the highest from the 5th zone (Table 4).

It is obvious from Table 4 that the recharge from canal seepage was the greatest in 1996 for 12th zone (phyllite-schist command of Kherwara). The maximum canal recharge in the 4th zone (gneiss command of Dhariawad) occurred in the years 1996 and 2003. It is also apparent that the 4th zone (gneiss command of Dhariawad) contributed the highest recharge due to return flow from surface-water irrigation in the years 1996 and 1999 (Table 4). However, in 2003, the 3rd zone (gneiss non-command of Dhariawad) contributed the highest recharge due to return flow from surface-water irrigation. On the other hand, the 2nd zone (gneiss non-command of Bhinder) contributed the maximum of recharge from groundwater irrigation in 1996 and 1999. In 2003, the 5th zone (phyllite-schist non-command of Girwa) contributed the maximum recharge from groundwater irrigation. Moreover, the maximum recharge from surface-water bodies in the year 1996 was from the 24th (gneiss non-command of Sarada) and 11th zones (phyllite-schist non-command of Kherwara) in 1999 and 2003, which are due to the Jaisamand lake and Som Kagdar dam, respectively.

5.5 Regional Specific Yield and Its Spatial Variation

The representative regional values of the specific yield obtained for the individual zones are presented in Table 5. The regional specific yield (S_y) values range from 0.038 to 0.002, which are reasonable and reliable for the type of subsurface formations present in the area (CGWB, 1997). The estimated regional S_y reveal an effective regional process; they are insensitive to local heterogeneity in the hard-rock aquifer system, in contrast with S_y values locally obtained from pumping test which are highly variable and somewhat unreliable (Machiwal, 2009). It is apparent that the regional S_y values in the study area vary appreciably with the types of geology and land (Fig. 6 and Table 5) due to heterogeneity of the aquifer system. The value of regional S_y is the highest (0.038) for the non-command land and phyllite-schist geologic setting encompassing a small southern portion (56.27 km^2). On the other hand, the command land and gneiss geologic setting has the lowest regional S_y (0.002). A close perusal of Table 5 reveals that the non-command land and gneiss geology (15th and 24th zones) has a regional S_y of 0.0028, which is more or less similar to that of phyllite-schist geology and non-command land (11th and 14th zones), and command land and gneiss geology (4th zone). Similarly, the regional S_y values of the non-command land and phyllite-schist geology (8th and 9th zones) are more or less similar to those of non-command land and schist geology (7th and 13th zones), and command land and phyllite-schist geology (23rd zone). Also, the regional S_y of the non-command land and phyllite-schist geology (16th zone) is essentially similar to those of the non-command land and gneiss geology (2nd, 6th and 20th zones). These findings clearly suggest that it is not proper to assign one value of S_y or hydraulic conductivity to a particular geologic formation in a groundwater basin, which is a common belief of many practicing hydrogeologists, especially in developing nations.

Moreover, in a major portion (54% of the entire area excluding hillocks), the S_y value ranges from 0.002-0.006 (Fig. 6). The mean of the regional S_y is 0.007 with a standard deviation of 0.007 and a coefficient of variation (CV) of 97%, which strongly suggest a significant spatial variation of regional S_y. In the past, some researchers (e.g., Naik and Awasthi, 2003) used the DWTF technique for estimating a single value of regional S_y for the entire aquifer system without considering geology and land types. Such an approach is not appropriate or realistic bearing in mind the heterogeneity of real-world aquifer systems. Therefore, it is emphasized that a range of S_y values should be determined for an aquifer system instead of a single value.

5.6 Spatial and Temporal Variations of Groundwater Recharge

The temporal and spatial variations of wet-season recharge are illustrated in Figs. 7(a,b) and Fig. 8. It is apparent that the maximum mean monsoon recharge occurs in the 18th zone (phyllite-schist non-command of Salumber), while little groundwater recharge occurred over the entire area in 1999, 2000, and 2002 [Figs. 7(a,b], which is attributed to the scanty rainfall in these three years (Fig. 9). Similarly, the significant recharge in two years (2005 and 2006) also reflects high rainfall in these years (Fig. 9). Thus, it is inferred that the wet season recharge responds well to the significant rainfall events. The mean monsoon recharge in the area varies from 0.5 to 12.9 cm during normal rainfall years (with a mean annual rainfall of

69.7 cm), while it varies from 0.15 to 5.73 cm during below average rainfall years (1999, 2000, and 2002). Moreover, standard errors range from 0.09 to 2.16 cm with large errors for the zones having high recharge (Fig. 8), thereby indicating a significant temporal variation in the groundwater recharge.

Moreover, Fig. 10 reveals that the rainfall recharge of 10-11 cm/year occurs only in a small southern portion, which is attributed to relatively high regional S_y value. Relatively high recharge (4-6 cm/year) occurs in the northeast, eastern and central portions of the study area where gneiss type of geology having S_y of 0.008-0.01 prevails. In the northeast portion, high recharge is also attributed to the relatively low topographic relief (0-3%) and the presence of pediment and buried pediment landforms. On the other hand, the recharge is relatively low in the western, southwest, southern and southeast portions (Fig. 10) where mainly phyllite-schist and schist types of geology exist with S_y ranging from 0.002 to 0.006. In the western and southwest portions, low rainfall recharge is also due to relative high land slope (10-30%) and presence of structural hills which generate more runoff than recharge. The low recharge in the southeast is due to low S_y of gneiss formation. Furthermore, results of the F-test (p-value<0.05) and CV (30 to 76%) revealed the significant spatial and temporal variations of the rainfall recharge at $\alpha = 0.05$. As a result, there is a need to formulate an efficient and resilient water management plan to cope with frequent droughts in the region.

The comparison of recharge from different sources in the 25 zones (Table 5) reveals that the surface-water irrigation is the least contributor to the total recharge, whereas rainfall has a major contribution (>80%) in 24 zones. The total mean monsoon recharge in the study area varies from 0.96 to 11.58 cm. The mean recharge due to rainfall ranges from as high as 10.9

cm in the 18th zone (phyllite-schist non-command of Salumber) to as low as 0.50 cm in the 24th zone (gneiss non- command of Sarada).

5.7 Comparative Spatial Variability of Specific Yield and Water-Balance Components

It is evident from Fig. 11 that the specific yield (S_y) is the most spatially variable parameter ($z \approx -0.72$ to 4.28). However, the values of S_y in most of the zones lie below the median value. Further, the rainfall recharge is the third highly-variable parameter ($z \approx -1.1$ to 3.41) after the domestic groundwater abstraction. Large variation of S_y, rainfall recharge and other water-balance components justifies the distributed approach followed in this study, i.e., dividing the entire area into different zones and then applying the water budget equation to each zone. It is worth mentioning that the spatial variation of specific yield in the study area is due to the aquifer heterogeneity (common characteristics of real-world subsurface formations) and it should not be considered as the variation owing to administrative zones.

5.8 Rainfall-Recharge Relationship

Based on the r^2 values at $\alpha = 0.01$ and 0.05, the rainfall-recharge relationship was classified as: (i) 'highly significant' at $p<0.05$ ($r^2 \geq 0.54$), (ii) 'moderately significant' at $p<0.01$ ($0.54>r^2\geq 0.36$), and (iii) 'insignificant' ($r^2<0.36$) as shown in Table 6. Results of the regression analysis are shown for some of the zones in Figs. 12(a-f) as an example, which indicate that the zones 9 and 13 have a strong rainfall-recharge relationship, zones 1 and 2 have a moderate, and zones 5 and 4 have an insignificant relationship. The two parallel dashed lines show the standard error of estimate. The values of MNSE and MIA evaluation criteria support the r^2-based classification (Table 6). The MNSE and MIA values are ≥ 0.40 and 0.62, respectively for the zones having 'highly significant' relationship and less than 0.20 and 0.50, respectively for the zones having 'insignificant' relationship. Thus, a 'highly significant' relationship exists in four zones [phyllite-schist non-command of Jhadol (Fig. 12a), schist non-command of Kotra (Fig. 12b), phyllite-schist non-command of Mavli, and gneiss non-command of Mavli block]. However, the relationship is found 'moderately significant' in ten and 'insignificant' in eleven zones (Table 6). Thus, the developed rainfall-recharge models of only 14 zones encompassing an area of 4934 km^2 (61% of the area excluding hillocks) can be reliably used for predicting rainfall recharge.

Moreover, the relatively low r^2 values (0.43-0.48) in six zones (gneiss non-command of Dhariawad, schist and phyllite-schist non-commands of Gogunda, phyllite-schist non-command of Kotra, granite non-command of Kotra, and gneiss non-command of Salumber) and very low r^2 values (0.20-0.30) in four zones (phyllite-schist non-command of Girwa, phyllite-schist command of Salumber, gneiss command of Salumber, and phyllite-schist non-command of Sarada) are due to the high intensity and short duration rainstorms in 2006. The r^2 values for these ten zones considerably improved on removing the 2006 data from the analysis. However, 'insignificant' relationship for the six zones (gneiss command of Dhariawad, phyllite-schist command and non-command of Kherwara, phyllite-schist command of Sarada, gneiss command and non-commands of Sarada) indicates their inadequate potential for natural recharge. This finding is in agreement with the lowest mean monsoon rainfall recharge estimates in these six zones (Table 5). Based on the above discussion, it can be inferred that proper utilization of rainfall through rainwater harvesting and the augmentation of groundwater resource by artificial recharge techniques are indispensable in the study area, particularly in the low recharge potential zones so as to ensure sustainable water supply for the present generation as well as for future generations. Further field investigation in this direction is required in order to select suitable sites for rainwater harvesting and artificial recharge structures.

6. CONCLUSIONS

Based on the results of this study following conclusions could be drawn:

- The major sources of groundwater recharge in the study area in the decreasing order of their contribution are direct rainfall, recharge from return flow of groundwater irrigation and the recharge from surface-water bodies.
- The recharge due to return flow from groundwater irrigation was higher during the dry period than that during the wet period.
- The regional specific yields were found to range between 0.038 and 0.002, with a significant spatial variation compared to other groundwater-balance components.
- The spatial and temporal variations of rainfall recharge were found to be significant ($p<0.05$ and $CV>30\%$). Total recharge in the study area varies from 0.96 to 11.58 cm. However, the mean monsoon rainfall recharge in the study area ranges from as high as 10.9 cm for the phyllite-schist non-command to as low as 0.50 cm in the gneiss non-command.
- The developed rainfall-recharge relationships were found to be ‘highly significant’ in four zones (constituting 23% of the study area), ‘moderately significant’ in ten zones (38% of the study area) and ‘insignificant’ in the remaining eleven zones (39% of the study area). Consequently, proper utilization of rainfall through rainwater harvesting and the augmentation of groundwater recharge by suitable artificial recharge techniques are essential for sustainable utilization of groundwater in the study area.

On the whole, it can be concluded that the DWTF technique is a promising tool for estimating regional specific yield as well as groundwater recharge in a groundwater basin, which can help prepare an efficient groundwater management plan for the basin. The proposed methodology, which is easy to use, cost-effective and based on scientific reasoning, can also be applicable to other semi-arid/arid regions of the world. Finally, it is recommended that the estimates of recharge and specific yield obtained in this study be compared with those obtained by other appropriate methods in the future when required field data are made available.

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Table 1. Details of the 25 zones of the study area

Zone	**Location (Block Name)**	**Type of Geology**	**Type of Land**	**Area (km^2)**
1	Badgaon	Phyllite-Schist	Non-Command	314.33
2	Bhinder	Gneiss	Non-Command	846.63
3	Dhariawad	Gneiss	Non-Command	249.77
4	Dhariawad	Gneiss	Command	385.69
5	Girwa	Phyllite-Schist	Non-Command	580.77
6	Girwa	Gneiss	Non-Command	328.80
7	Gogunda	Schist	Non-Command	431.33
8	Gogunda	Phyllite-Schist	Non-Command	183.71
9	Jhadol	Phyllite-Schist	Non-Command	696.58
10	Jhadol	Quartzite	Non-Command	171.24
11	Kherwara	Phyllite-Schist	Non-Command	729.69
12	Kherwara	Phyllite-Schist	Command	77.88
13	Kotra	Schist	Non-Command	376.62
14	Kotra	Phyllite-Schist	Non-Command	103.63
15	Kotra	Granite	Non-Command	417.72
16	Mavli	Phyllite-Schist	Non-Command	152.89
17	Mavli	Gneiss	Non-Command	619.78
18	Salumber	Phyllite-Schist	Non-Command	56.27
19	Salumber	Phyllite-Schist	Command	254.35
20	Salumber	Gneiss	Non-Command	313.14
21	Salumber	Gneiss	Command	53.25
22	Sarada	Phyllite-Schist	Non-Command	320.62
23	Sarada	Phyllite-Schist	Command	95.10
24	Sarada	Gneiss	Non-Command	280.02
25	Sarada	Gneiss	Command	80.21

Table 2. Guidelines for estimating groundwater recharge in the agricultural land due to return flows from irrigation (CGWB, 1997)

Source of Irrigation	**Type of Crop**	**Recharge as Percentage of Irrigation Water Applied under Different Water Table Depth Conditions**		
		<10 m Depth	**10-25 m Depth**	**>25 m Depth**
Groundwater	Paddy	45	35	20
Groundwater	Non-paddy	25	15	5
Surface Water	Paddy	50	40	25
Surface Water	Non-paddy	30	20	10

Table 3. Summary of the evaluation criteria used in the study

Evaluation Criteria	**Mathematical Expression**	**Range of Values**		
		Worst	**Best**	**Acceptable**
Coefficient of Determination (r^2)	$r^2 = \left\{ \frac{\sum_{i=1}^{N} (O_i - \overline{O})(P_i - \overline{P})}{\left[\sum_{i=1}^{N} (O_i - \overline{O})^2\right]^{0.5} \left[\sum_{i=1}^{N} (P_i - \overline{P})^2\right]^{0.5}} \right\}^2$	0	1.0	0.5 – 1.0
Modified Nash-Sutcliffe Efficiency (MNSE)	$\mathrm{MNSE} = 1.0 - \frac{\sum_{i=1}^{N} \lvert O_i - P_i \rvert}{\sum_{i=1}^{N} \lvert O_i - \overline{O} \rvert}$	- ∞	1.0	0.0 – 1.0
Modified Index of Agreement (MIA)	$\mathrm{MIA} = 1.0 - \frac{\sum_{i=1}^{N} (O_i - P_i)}{\sum_{i=1}^{N} \left(\lvert P_i - \overline{O} \rvert + \lvert O_i - \overline{O} \rvert \right)}$	0	1.0	0.5 – 1.0

Note: O_i = Computed/observed recharge; P_i = Predicted recharge; $\overline{O}$ = Mean observed recharge; N = Number of observations.

Table 4. Groundwater budget components for the dry (non-rainy) season of three years in 25 zones of the study area

Zone	**Groundwater Level Decline (m)**			**Groundwater Abstraction for Domestic Purpose (10^6 m^3)**			**Groundwater Abstraction for Irrigation Purpose (10^6 m^3)**			**Recharge due to Canal Seepage (10^6 m^3)**		
	1996	**1999**	**2003**	**1996**	**1999**	**2003**	**1996**	**1999**	**2003**	**1996**	**1999**	**2003**
1	4.36	4.01$^{\#}$	7.37$^{\#}$	0.84	1.05	1.29	13.48	10.55	9.60	0	0	0
2	6.23	3.08	2.76	1.41	1.42	1.23	55.05$^{\#}$	29.90$^{\#}$	22.24	0.37	0	0
3	3.11	2.51	1.68	0.36	0.41	0.55	10.33	11.15	13.98	1.73	0	0
4	2.19	1.97	3.93	0.27	0.40	0.41	7.71	8.45	10.45	0.15	0.96$^{\#}$	0.90$^{\#}$
5	4.86	3.75	4.83	4.11$^{\#}$	4.30$^{\#}$	1.97$^{\#}$	20.77	28.76	25.41$^{\#}$	0.12	0	0
6	5.77	2.03	2.41	0.38	1.11	0.58	7.23	10.08	8.93	0.12	0	0
7	5.69	2.87	5.73	0.72	0.70	0.44	9.20	8.95	10.72	1.18	0	0
8	5.88	2.69	6.33	0.24	0.24	0.20	5.46	2.68	4.83	0.04	0	0
9	3.13	2.36	4.77	0.74	0.97	0.81	11.41	12.03	12.46	0.25	0	0
10	2.47	0.95	2.95	0.17	0.22	0.17	1.56	2.69	2.78	0	0	0
11	3.14	2.30	3.73	1.59	1.76	1.28	8.55	10.41	14.83	1.09	0	0
12	1.27	1.15	0.90	0.17	0.28	0.14	0.97	1.00	0.60	2.98$^{\#}$	0.22	0.52
13	2.79	1.59	2.93	0.25	0.32	0.39	4.53	4.12	6.45	0	0	0
14	4.60	2.41	5.40	0.11	0.11	0.09	1.27	1.30	1.60	0	0	0
15	2.64	1.40	3.16	0.16	0.19	0.26	3.60	3.69	5.39	1.33	0	0
16	9.01$^{\#}$	1.92	4.52	0.47	0.65	0.39	7.79	4.75	3.86	0.44	0	0
17	5.63	1.90	2.92	1.40	1.50	1.16	27.99	20.00	16.53	0	0	0
18	0.30	1.12	2.40	0.12	0.15	0.11	2.46	1.56	5.01	0.16	0	0
19	1.73	2.19	3.20	0.48	0.54	0.38	6.36	3.74	5.11	0.01	0	0
20	6.02	2.26	3.54	0.60	0.66	0.53	12.09	12.46	13.38	0.10	0	0
21	2.53	2.11	2.33	0.06	0.08	0.06	1.29	1.05	1.28	0	0	0
22	1.48	1.21	1.56	0.51	0.54	0.67	9.29	9.91	11.54	0.39	0	0
23	1.51	2.58	0.50	0.03	0.04	0.09	1.13	1.21	0.43	0.12	0	0
24	1.50	1.70	2.33	0.24	0.27	0.28	2.45	2.08	3.51	2.55	0	0
25	2.10	2.93	3.67	0.02	0.03	0.06	1.28	1.37	1.05	0.16	0	0

Note: $^{\#}$ Highest value.

Table 4. Continued

Zone	**Return Flow from Surface Water Irrigation (10^6 m^3)**			**Return Flow from Groundwater Irrigation (10^6 m^3)**			**Recharge from Surface Water Bodies (10^6 m^3)**		
	1996	**1999**	**2003**	**1996**	**1999**	**2003**	**1996**	**1999**	**2003**
1	0.47	0.06	0.01	3.37	2.64	2.40	1.84	0.03	0.07
2	0.02	0.01	0	13.76[#]	7.48[#]	5.56	1.31	0	0
3	2.26	3.95	3.23[#]	2.58	2.79	3.50	0.15	0.13	0.13
4	10.81[#]	10.11[#]	2.42	1.93	2.11	2.61	0.07	0.06	0.06
5	0.15	0.03	0.04	5.19	7.19	6.35[#]	1.38	0.02	0.09
6	0.07	0	0	1.81	2.52	2.23	0.02	0	0
7	0.11	0.02	0.17	2.30	2.24	2.68	0.06	0.05	0.06
8	0.12	0.01	0	1.37	0.67	1.21	0.03	0	0.09
9	0.52	0.18	0.45	2.85	3.01	3.11	0.89	0.32	0.21
10	0.13	0.01	0.11	0.39	0.67	0.69	0	0	0
11	1.28	0.23	1.08	2.14	2.60	3.71	1.76	1.63[#]	1.73[#]
12	0.39	0	0.20	0.24	0.25	0.15	0	0	0
13	0.13	0	0.06	1.13	1.03	1.61	0.53	0.04	0.06
14	0	0.02	0.01	0.32	0.33	0.40	0.08	0.01	0.02
15	0.03	0.02	0.04	0.90	0.92	1.35	1.15	0.08	0.03
16	0.04	0	0	1.95	1.19	0.96	0.09	0	0.06
17	0.14	0	0	7.00	5.00	4.13	1.04	0	0
18	0.66	0.13	0.13	0.62	0.39	1.25	0	0	0.13
19	2.65	0.56	0.56	1.59	0.94	1.28	3.63	0	0
20	1.66	0.15	0.62	3.02	3.11	3.34	5.68	0.12	0.16
21	3.04	0.04	0.11	0.32	0.26	0.32	0.31	0.08	0.13
22	1.40	0.14	0.56	2.32	2.48	2.89	0.16	0.05	0.06
23	2.80	0.11	0.11	0.28	0.30	0.11	0.09	0.01	0.09
24	0.67	0.09	0.14	0.61	0.52	0.88	6.13[#]	0.29	1.16
25	0.59	0.28	0.12	0.32	0.34	0.26	0.02	0.06	0.01

Note: [#] Highest value.

Table 5. Zone-wise regional specific yields and wet season mean groundwater recharge from different sources

Zone No.	Regional Specific Yield	Recharge from Surface Water Irrigation (cm)	Recharge from Groundwater Irrigation (cm)	Recharge from Surface Water Bodies (cm)	Rainfall Recharge (cm)	Total Recharge (cm)	Rainfall Recharge as Percentage of Total Recharge
1	0.0057	0	0.15	0.09	3.29	3.53	93
2	0.0082	0	0.18	0.03	4.35	4.55	95
3	0.0103	0.01	0.37	0.03	4.36	4.77	91
4	0.0032	0.01	0.17	0.01	1.39[#]	**1.57**	88
5	0.0086	0	0.19	0.05	5.33	5.57	96
6	0.0084	0	0.13	0.00	4.53	4.66	97
7	0.0040	0	0.11	0.01	2.40	2.52	95
8	0.0039	0	0.12	0.02	2.40	2.54	95
9	0.0040	0	0.10	0.03	1.83	1.97	93
10	0.0069	0	0.07	0.00	2.06	2.13	96
11	0.0033	0.01	0.12	0.12	1.44[#]	**1.69**	85
12	0.0090	0.01	0.11	0.03	1.41[#]	**1.55**	91
13	0.0044	0	0.09	0.02	1.61	1.71	94
14	0.0029	0	0.07	0.02	1.37	1.46	94
15	0.0028	0	0.07	0.03	0.97	1.07	90
16	0.0077	0	0.18	0.03	5.42	5.64	96
17	0.0092	0	0.16	0.03	5.82	6.01	97
18	0.0380	0.08	0.53	0.06	10.91	11.58	94
19	0.0048	0.01	0.14	0.18	1.54	1.87	82
20	0.0079	0.02	0.23	0.27	4.29	4.81	89
21	0.0065	0.02	0.15	0.11	2.15	2.44	88
22	0.0164	0.02	0.27	0.02	4.36	4.66	93
23	0.0039	0.01	0.09	0.11	0.97[#]	**1.19**	82
24	0.0028	0.01	0.08	0.38	0.50[#]	**0.96**	51
25	0.0022	0.01	0.10	0.03	1.02[#]	**1.16**	88

Note: [#] Zones having low potential for natural groundwater recharge; the coefficient of determination (r^2) values did not improve significantly even after excluding the rainfall and recharge data of 2006.

Table 6. Goodness-of-fit statistics for the rainfall-recharge models of the 25 zones

Sl. No.	Name of Zone	r^2	MNSE	MIA	Extent of Rainfall-Recharge Relationship
1	Phyllite-schist non-command of Jhadol	0.56	0.38	0.64	Highly Significant ($r^2 \geq 0.54$; MNSE≥0.40; MIA≥0.62)
2	Schist non-command of Kotra	0.91	0.67	0.82	
3	Phyllite-schist non-command of Mavli	0.62	0.57	0.74	
4	Gneiss non-command of Mavli	0.67	0.41	0.66	
5	Phyllite-schist non-command of Badgaon	0.50	0.29	0.57	Moderately Significant ($0.54 > r^2 \geq 0.36$; 0.40>MNSE≥0.20; 0.62>MIA≥0.50)
6	Gneiss non-command of Bhinder	0.36	0.26	0.53	
7	Gneiss non-command of Dhariawad	0.48	0.37	0.61	
8	Schist non-command of Gogunda	0.45	0.29	0.53	
9	Phyllite-schist non-command of Gogunda	0.44	0.26	0.51	
10	Quartzite non-command of Jhadol	0.37	0.30	0.56	
11	Phyllite-schist non-command of Kotra	0.43	0.29	0.55	
12	Granite non-command of Kotra	0.45	0.31	0.57	
13	Phyllite-schist non-command of Salumber	0.42	0.20	0.50	
14	Gneiss non-command of Salumber	0.43	0.27	0.55	
15	Phyllite-schist non-command of Girwa	0.30	0.18	0.44	Insignificant ($r^2 < 0.36$; MNSE<0.20; MIA<0.50)
16	Gneiss command area of Dhariawad	0.16	0.09	0.37	
17	Gneiss non-command of Girwa	0.20	0.17	0.40	
18	Phyllite-schist non-command of Kherwara	0.26	0.10	0.35	
19	Phyllite-schist command of Kherwara	0.03	-0.06	0.07	
20	Phyllite-schist command of Salumber	0.27	0.18	0.44	
21	Gneiss command of Salumber	0.20	0.15	0.41	
22	Phyllite-schist non-command of Sarada	0.27	0.14	0.38	
23	Phyllite-schist command of Sarada	0.09	-0.01	0.19	
24	Gneiss non-command of Sarada	0.08	0.05	0.23	
25	Gneiss command of Sarada	0.02	-0.01	0.08	

Note: r^2 = Coefficient of Determination; MNSE = Modified Nash-Sutcliffe Efficiency; MIA = Modified Index of Agreement

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Figure Captions

Fig. 1. Location map of the study area showing groundwater monitoring sites

Fig. 2. Geology map of the study area

Fig. 3. Division of the study area into 25 zones. NC = non-command; C = command; PhSc = phyllite-schist; Sc = schist; Gn = gneiss; Gr = granite; and Q = quartzite.

Fig. 4. Schematic of water balance components for the command and non-command areas of the study area

Fig. 5(a-e). Mean seasonal groundwater budget components. (a) $GWD_{domestic}$ = groundwater abstractions for domestic purpose; (b) $GWD_{irrigation}$ = groundwater abstractions for irrigation purpose; (c) R_{swi} = recharge due to return flows from surface water irrigation (d) R_{gwi} = recharge due to return flows from groundwater irrigation; and (e) R_{swb} = recharge from surface water bodies

Fig. 6. Spatial distribution of specific yield in the study area

Figs. 7(a,b). Annual variation of monsoon rainfall recharge in the 25 zones

Fig. 8. Mean annual rainfall recharge in the 25 zones

Fig. 9. Box-whisker plots of the annual rainfall for ten rainfall stations

Fig. 10. Distributed mean monsoon rainfall recharge over the study area

Fig. 11. Relative spatial variation of specific yield and water budget components during wet season. WL_r = groundwater level rise; $GWD_{domestic}$ and $GWD_{irrigation}$ = groundwater abstractions for domestic and irrigation purposes, respectively; R_{swi} and R_{gwi} = recharge due to return flows from surface water irrigation and groundwater irrigation, respectively; R_{swb} = recharge from surface water bodies; S_y = specific yield; and R_r = recharge due to monsoon rainfall.

Figs. 12(a-f). Regression between rainfall and recharge for the two zones having highly significant relationship: (a) phyllite-schist non-command of Jhadol, (b) schist non-command of Kotra; two zones having moderate relationship: (c) phyllite-schist non-command of Badgaon, (d) gneiss non-command of Bhinder; and two zones having insignificant relationship: (e) phyllite-schist non-command of Girwa, (f) gneiss command of Dhariawad. RR = rainfall recharge; and MR = monsoon rainfall.

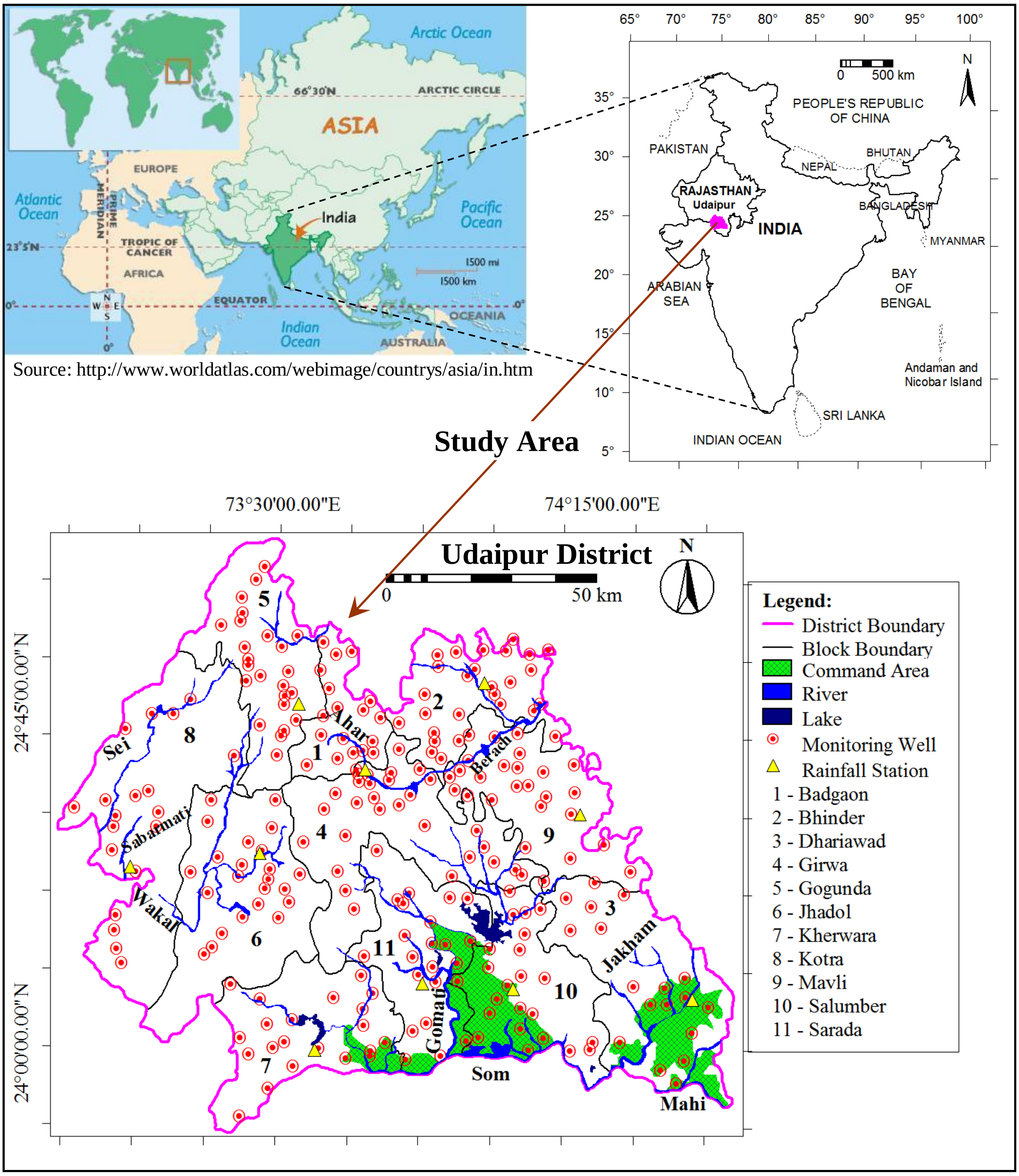

Source: http://www.worldatlas.com/webimage/countrys/asia/in.htm

Fig. 1

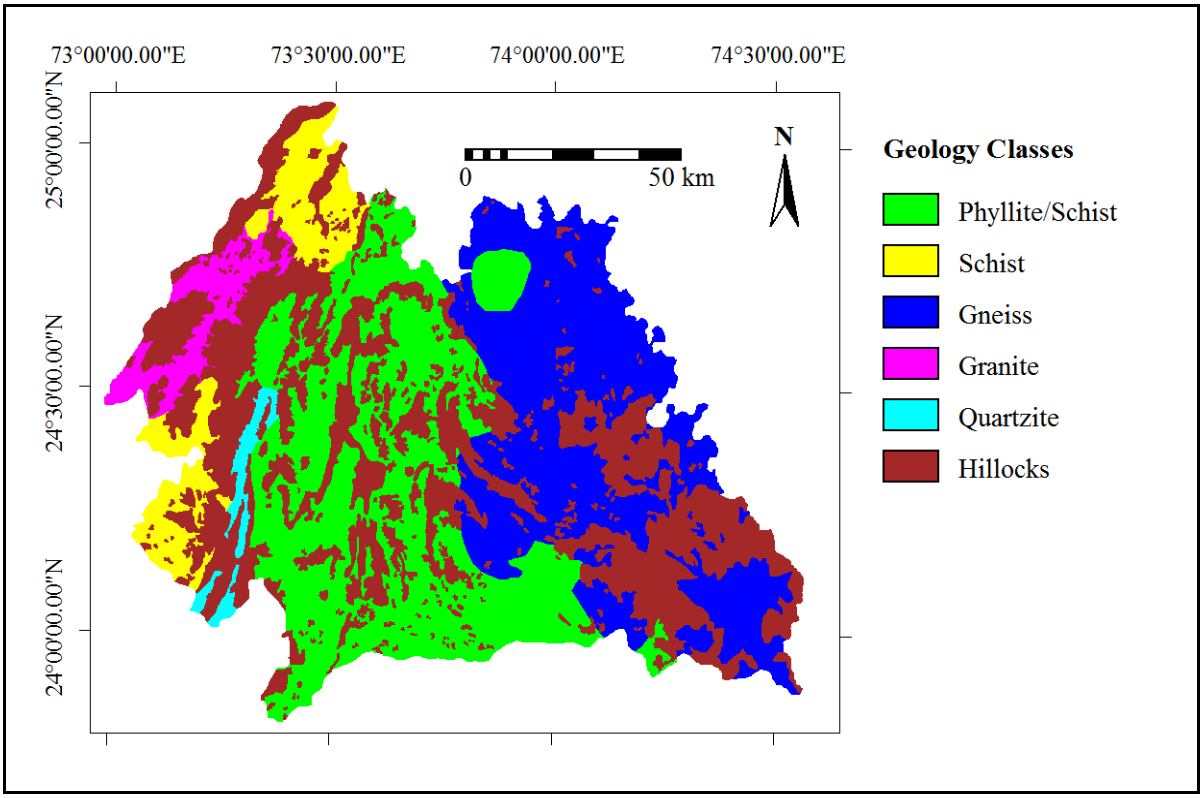

73°00'00.00"E
73°30'00.00"E
74°00'00.00"E
74°30'00.00"E
25°00'00.00"N
24°30'00.00"N
24°00'00.00"N
0
50 km
N
Geology Classes
Phyllite/Schist
Schist
Gneiss
Granite
Quartzite
Hillocks

Fig. 2

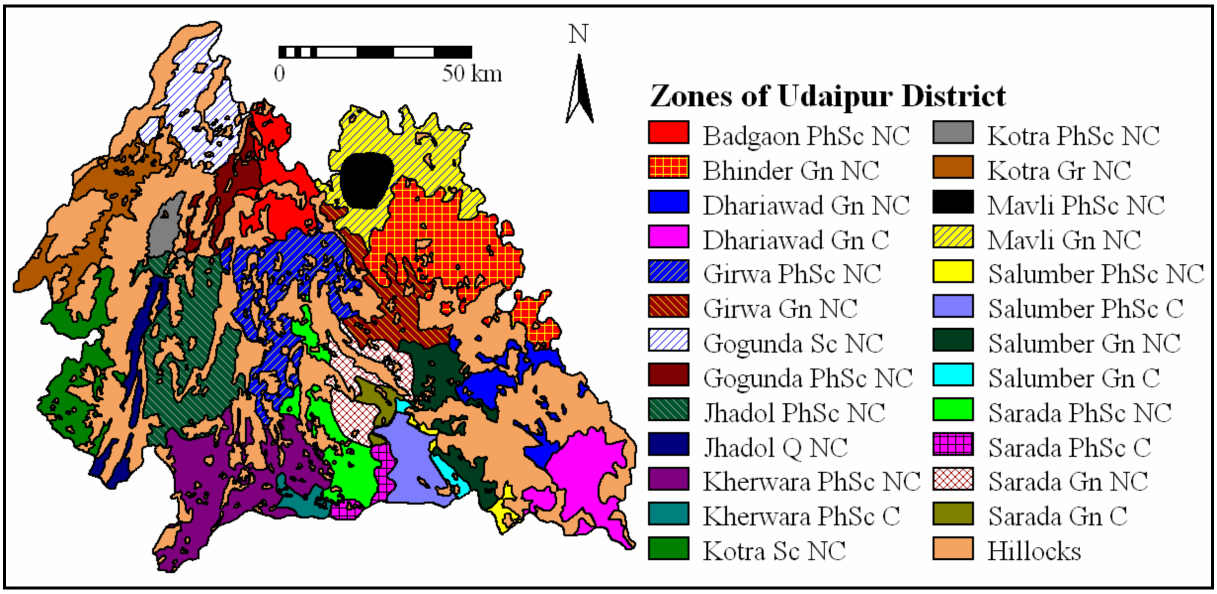

0
50 km
N
Zones of Udaipur District
Badgaon PhSc NC
Bhinder Gn NC
Dhariawad Gn NC
Dhariawad Gn C
Girwa PhSc NC
Girwa Gn NC
Gogunda Sc NC
Gogunda PhSc NC
Jhadol PhSc NC
Jhadol Q NC
Kherwara PhSc NC
Kherwara PhSc C
Kotra Sc NC
Kotra PhSc NC
Kotra Gr NC
Mavli PhSc NC
Mavli Gn NC
Salumber PhSc NC
Salumber PhSc C
Salumber Gn NC
Salumber Gn C
Sarada PhSc NC
Sarada PhSc C
Sarada Gn NC
Sarada Gn C
Hillocks

Fig. 3

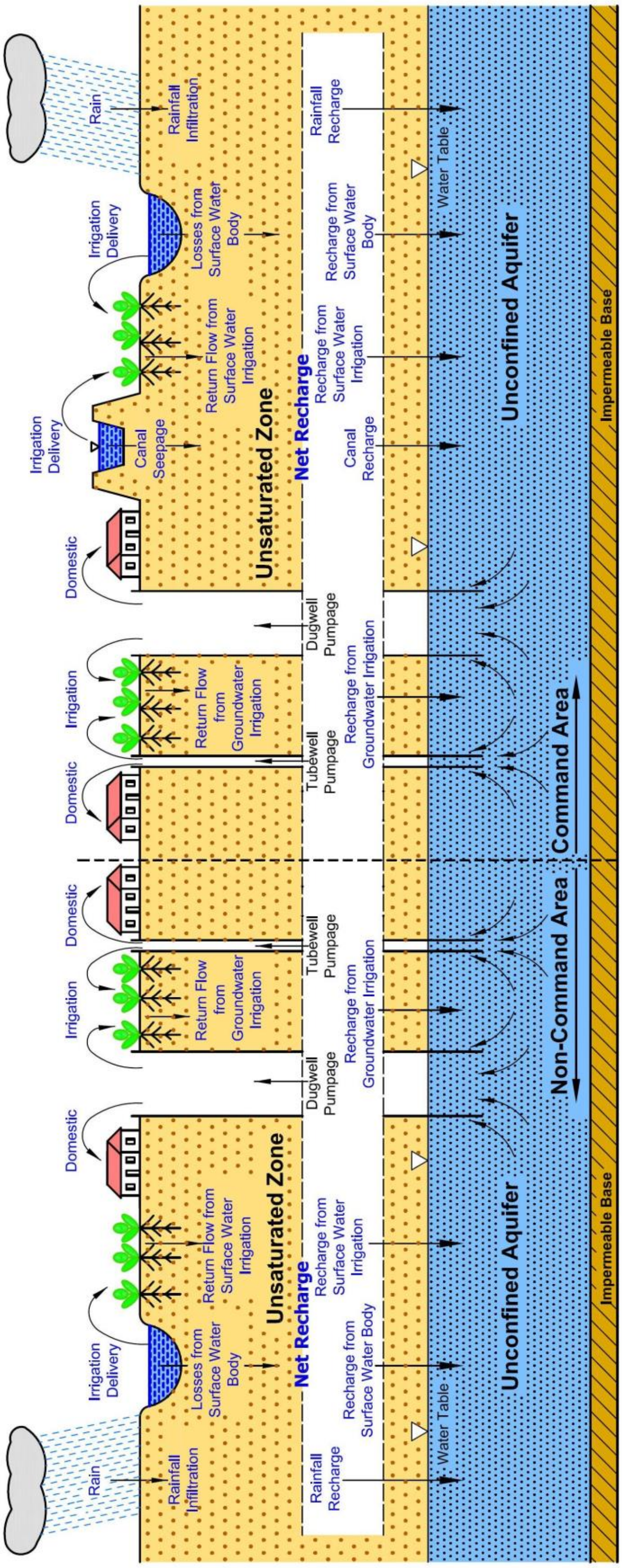
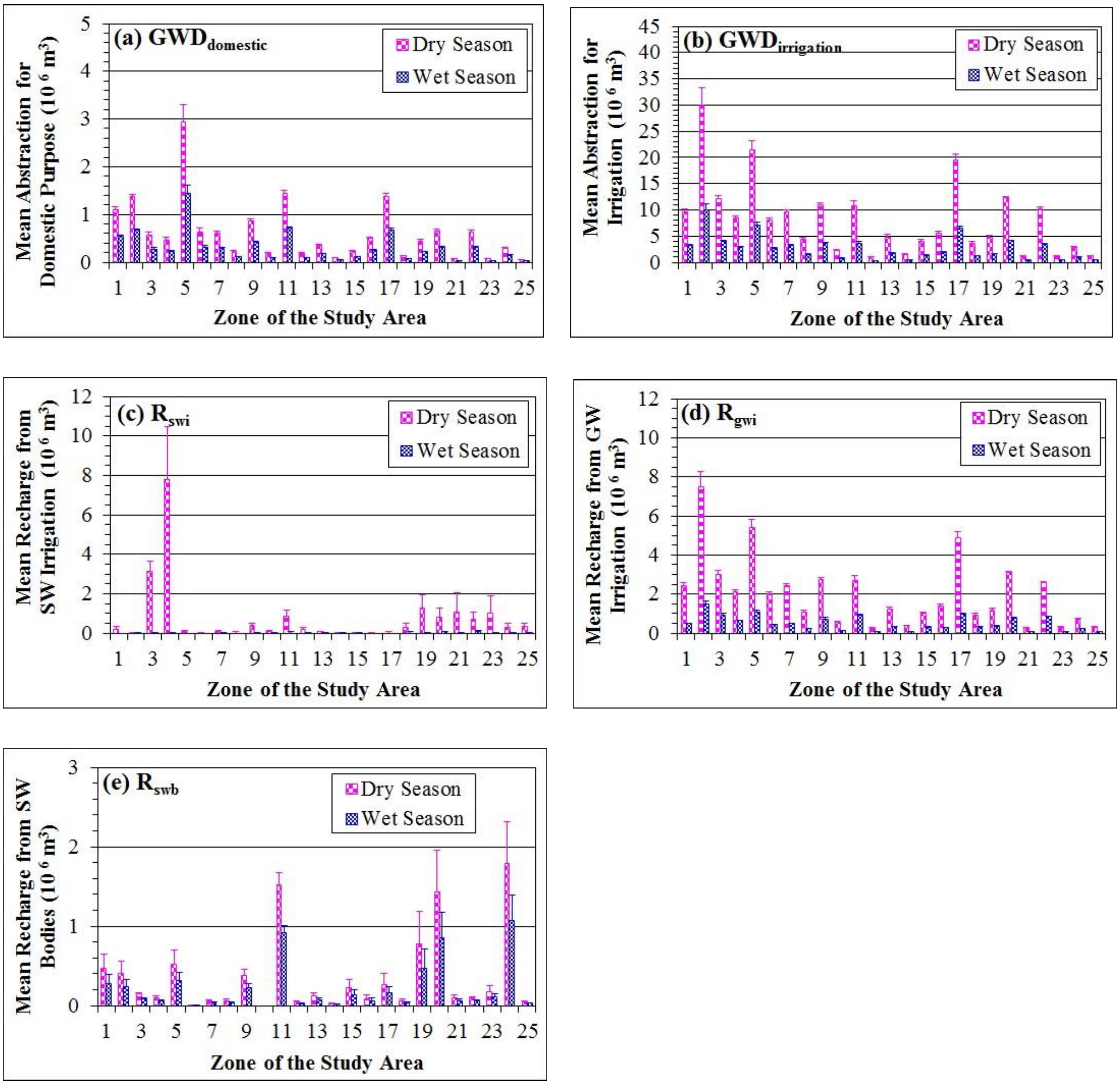
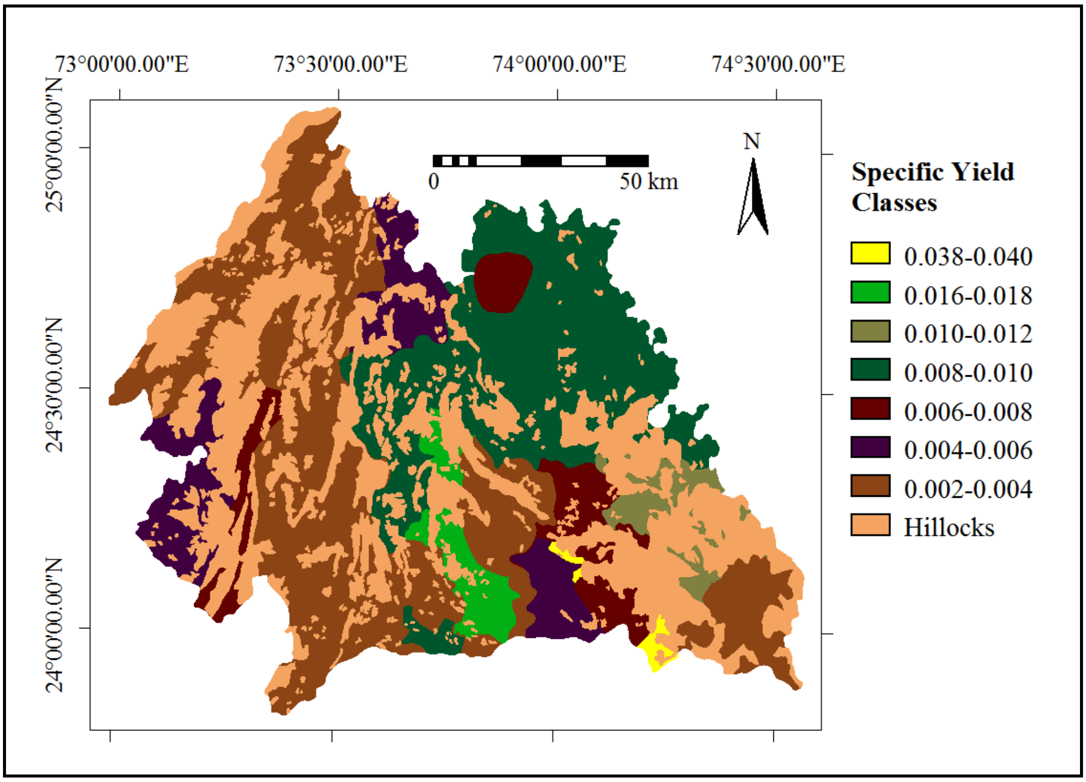

Rain
Rainfall Infiltration
Irrigation Delivery
Losses from Surface Water Body
Return Flow from Surface Water Irrigation
Domestic
Unsaturated Zone
Net Recharge
Rainfall Recharge
Recharge from Surface Water Body
Recharge from Surface Water Irrigation
Water Table
Unconfined Aquifer
Impermeable Base
Dugwell Pumpage
Recharge from Groundwater Irrigation
Irrigation
Return Flow from Groundwater Irrigation
Tubewell Pumpage
Non-Command Area
Command Area
Canal Seepage
Canal Recharge

Fig. 4


(a) GWD$_{domestic}$
Dry Season
Wet Season
Mean Abstraction for Domestic Purpose (10^6 m^3)
0
1
2
3
4
5
1 3 5 7 9 11 13 15 17 19 21 23 25
Zone of the Study Area
(b) GWD$_{irrigation}$
Dry Season
Wet Season
Mean Abstraction for Irrigation (10^6 m^3)
0
5
10
15
20
25
30
35
40
45
1 3 5 7 9 11 13 15 17 19 21 23 25
Zone of the Study Area
(c) R$_{swi}$
Dry Season
Wet Season
Mean Recharge from SW Irrigation (10^6 m^3)
0
2
4
6
8
10
12
1 3 5 7 9 11 13 15 17 19 21 23 25
Zone of the Study Area
(d) R$_{gwi}$
Dry Season
Wet Season
Mean Recharge from GW Irrigation (10^6 m^3)
0
2
4
6
8
10
12
1 3 5 7 9 11 13 15 17 19 21 23 25
Zone of the Study Area
(e) R$_{swb}$
Dry Season
Wet Season
Mean Recharge from SW Bodies (10^6 m^3)
0
1
2
3
1 3 5 7 9 11 13 15 17 19 21 23 25
Zone of the Study Area

Figs. 5(a-e)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73°30'00.00"E
74°00'00.00"E
74°30'00.00"E
25°00'00.00"N
24°30'00.00"N
24°00'00.00"N
0
50 km
N
Specific Yield Classes
0.038-0.040
0.016-0.018
0.010-0.012
0.008-0.010
0.006-0.008
0.004-0.006
0.002-0.004
Hillocks

Fig. 6

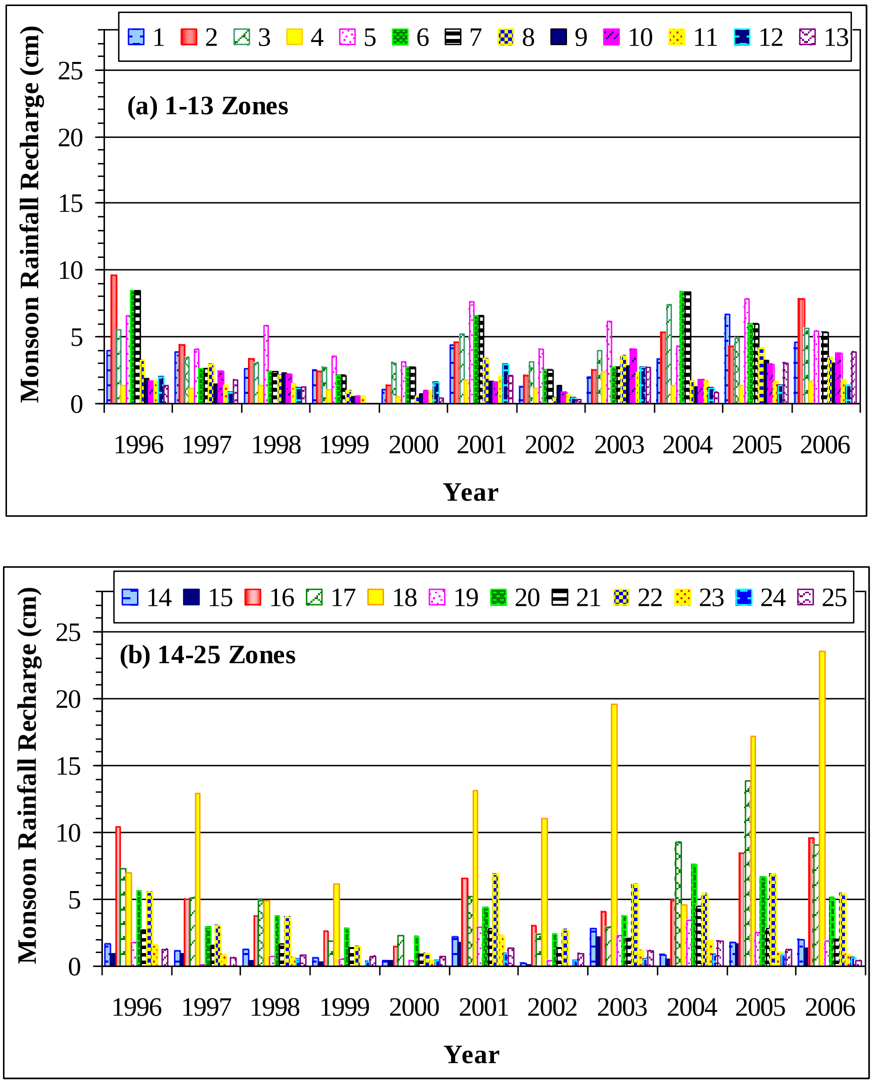

▤ 1 🟥 2 ▨ 3 🟨 4 ▩ 5 🟩 6 ▤ 7 ▩ 8 ■ 9 ▨ 10 ▩ 11 ■ 12 ▨ 13
(a) 1-13 Zones
Monsoon Rainfall Recharge (cm)
0
5
10
15
20
25
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Year
▤ 14 ■ 15 🟥 16 ▨ 17 🟨 18 ▩ 19 🟩 20 ▤ 21 ▩ 22 ▩ 23 ■ 24 ▨ 25
(b) 14-25 Zones
Monsoon Rainfall Recharge (cm)
0
5
10
15
20
25
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Year

Fig. 7(a,b)

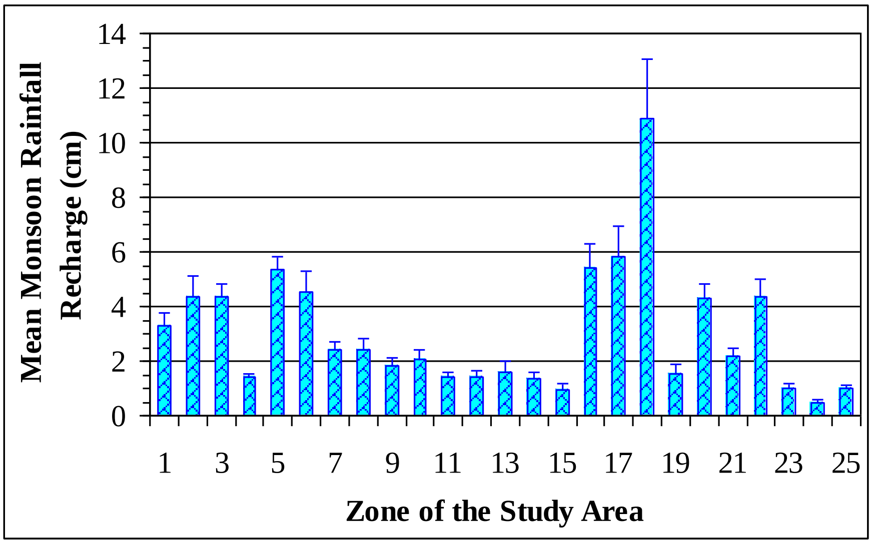

Mean Monsoon Rainfall Recharge (cm)
0
2
4
6
8
10
12
14
1
3
5
7
9
11
13
15
17
19
21
23
25
Zone of the Study Area

Fig. 8

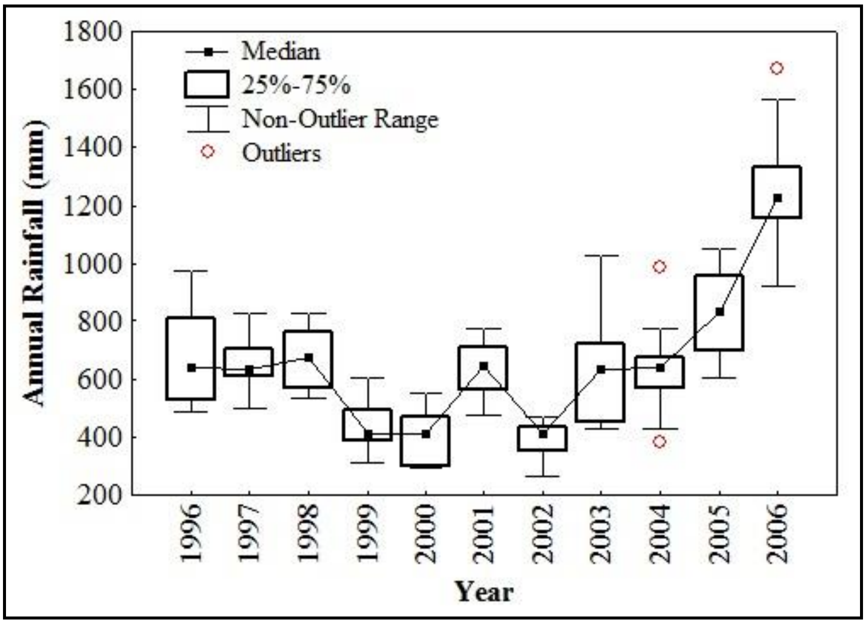

Median
25%-75%
Non-Outlier Range
Outliers
Annual Rainfall (mm)
200
400
600
800
1000
1200
1400
1600
1800
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Year

Fig. 9

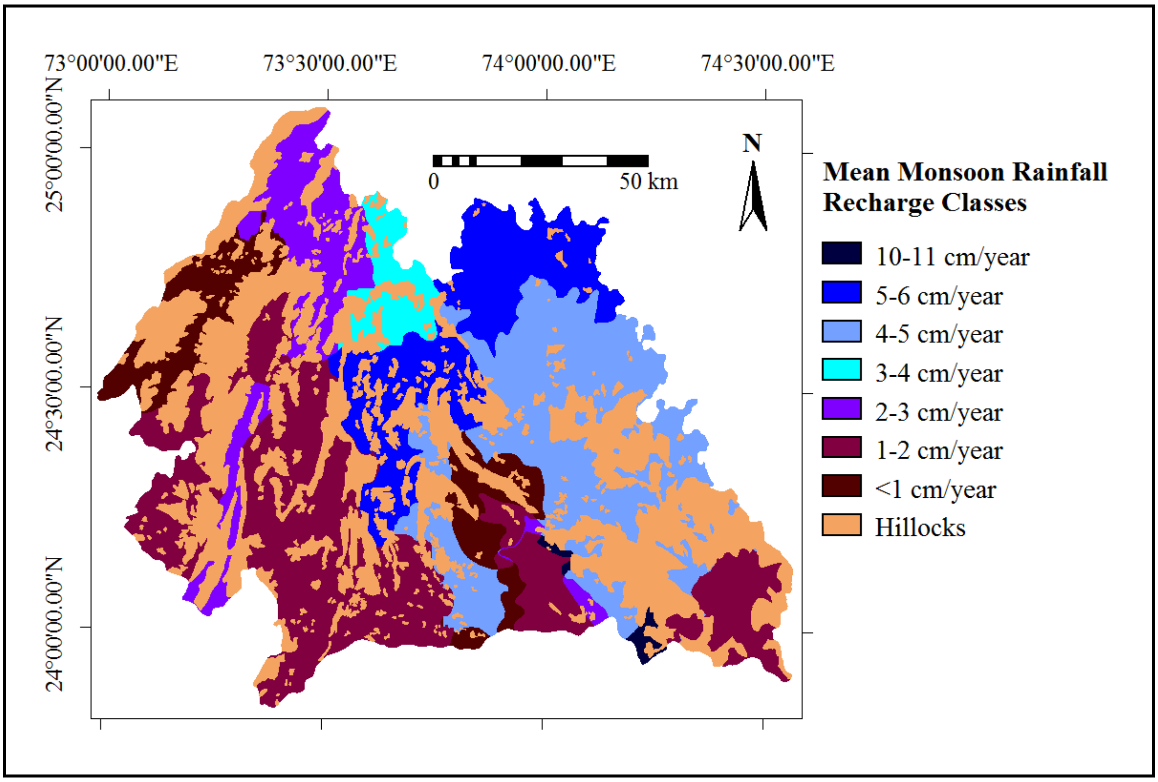

73°00'00.00"E
73°30'00.00"E
74°00'00.00"E
74°30'00.00"E
25°00'00.00"N
24°30'00.00"N
24°00'00.00"N
0
50 km
N
Mean Monsoon Rainfall Recharge Classes
10-11 cm/year
5-6 cm/year
4-5 cm/year
3-4 cm/year
2-3 cm/year
1-2 cm/year
<1 cm/year
Hillocks

Fig. 10

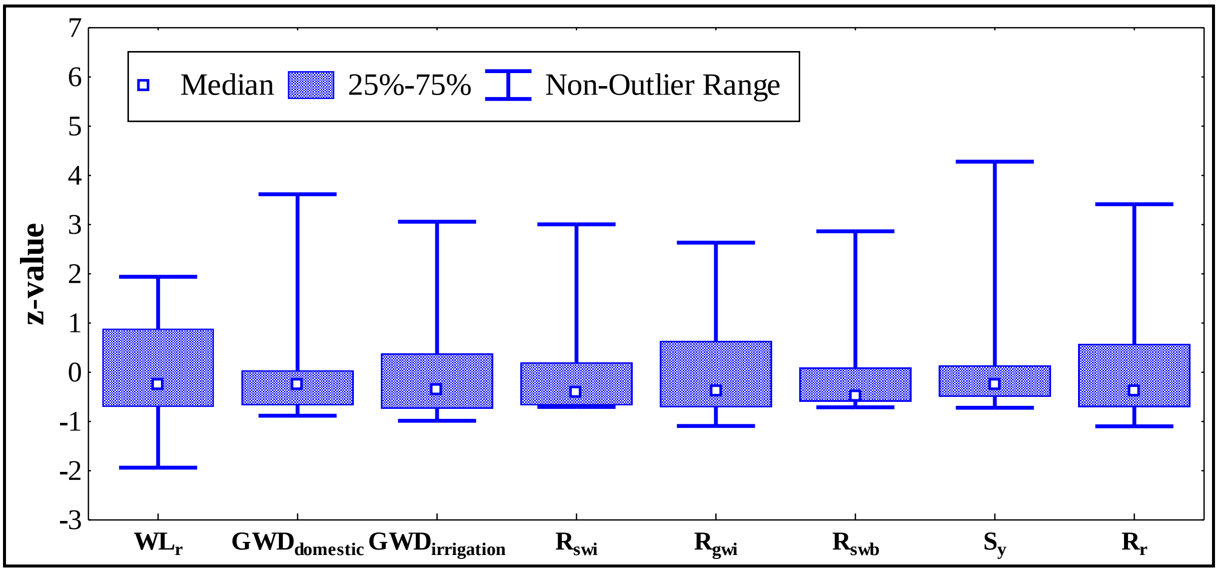
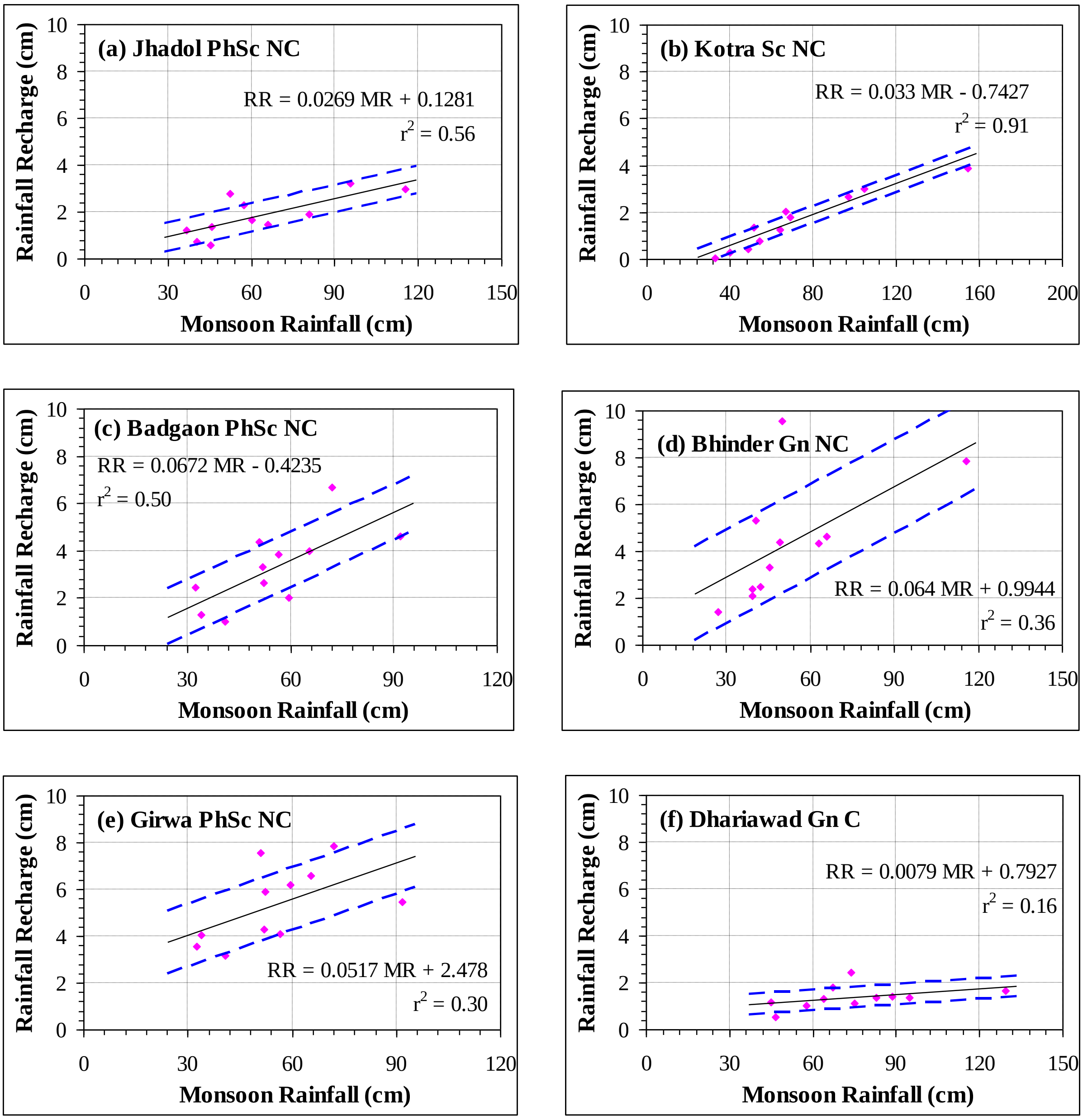

Median
25%-75%
Non-Outlier Range
z-value
7
6
5
4
3
2
1
0
-1
-2
-3
WL_r
$GWD_{domestic}$
$GWD_{irrigation}$
R_{swi}
R_{gwi}
R_{swb}
S_y
R_r

Fig. 11


(a) Jhadol PhSc NC
RR = 0.0269 MR + 0.1281
r^2 = 0.56
Rainfall Recharge (cm)
Monsoon Rainfall (cm)
0
2
4
6
8
10
0
30
60
90
120
150
(b) Kotra Sc NC
RR = 0.033 MR - 0.7427
r^2 = 0.91
Rainfall Recharge (cm)
Monsoon Rainfall (cm)
0
40
80
120
160
200
(c) Badgaon PhSc NC
RR = 0.0672 MR - 0.4235
r^2 = 0.50
Rainfall Recharge (cm)
Monsoon Rainfall (cm)
(d) Bhinder Gn NC
RR = 0.064 MR + 0.9944
r^2 = 0.36
Rainfall Recharge (cm)
Monsoon Rainfall (cm)
(e) Girwa PhSc NC
RR = 0.0517 MR + 2.478
r^2 = 0.30
Rainfall Recharge (cm)
Monsoon Rainfall (cm)
(f) Dhariawad Gn C
RR = 0.0079 MR + 0.7927
r^2 = 0.16
Rainfall Recharge (cm)
Monsoon Rainfall (cm)

Figs. 12(a-f)