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Erratic Monsoon, Growing Water Demand, and Declining Water Table

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Abstract

In India, water resources are governed by the southwest monsoon. The water demand is increasing day by day due to population growth, rapid urbanisation, and multiple cropping practices. Due to changing climatic conditions monsoon, the chief controller of rainfall is found to be very irregular. Erratic monsoon with insufficient rainfall in combination with high heat-flow and over-exploitation of ground water imparts stress on the water resources, particularly in arid and semi-arid regions. Time-series analysis of water-table fluctuations provides idea about temporal variation of aquifer-recharge and availability of ground-water resources. In the present study, an attempt has been made to assess relative influence of different controlling factors on ground-water recharge. Spatio-temporal variations of rainfall, potential evapotranspiration, ground-water draft and consequent water-table fluctuations in the Aravalli terrain have been analysed using GIS. Visual comparison points out significant decrease in aquifer-recharge and variation in its spatial patterns in yearly and decadal scales owing to large variations in the seasonal rainfall distribution and over-exploitation of the limited water resources. Wells and zones could be demarcated where water table is depleting since a decade, irrespective of change in the rainfall scenario.

***Keywords**:* Monsoon, Aravalli, time series, water table, GIS

1. Introduction

The link between climate variability and the ground-water response is more complex than that with the surface-water regime (Panda et al. 2007). Ground water occurs in a stable system, and responds slowly with a time lag to climate variability. Moreover, the diverse aquifer characteristics respond differently to the surface stresses (Chen et al., 2004; Environment Canada, 2004). Fluctuation of water table is controlled by recharge and discharge. In a semi-arid hard-rock terrain, where streams and channels are mostly dry, seasonal rainfall is the only source of ground-water recharge, whereas discharge takes place through evaporation and withdrawal. With the growing population and industrialization, the demand for water has increased many folds, as a result the water resources are depleting in many parts of the world. The balance between water supply and demand in a sustainable manner, under natural climate variability as well as long-term climate change, is crucial to local viability and vitality (Morehouse, 2000). Rainfall in northern India is governed by the southwest monsoon, which downpours from the middle of June till the end of September. Temporal delay, variability and change in spatial rainfall pattern is of great concern in tropical arid and semi-arid zones, since in those regions natural vegetation and agricultural ecosystems are highly sensitive to small variations of rainfall (Singh *et al.,* 1992). Weak monsoon in successive years affects agricultural activities and aquifer-recharge. The western part of India often suffers from drought due to poor rainfall and high heat flow; and over-exploitation of the limited ground-water resources makes the situation graver. The present study examines the spatio-temporal variations in aquifer-recharge in response to erratic monsoon-rainfall, high

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heat-flow and increasing water demand. A GIS-based time-series analysis has been carried out to compare year wise and intermediate changes in seasonal water-level fluctuation in response to monsoon-rainfall, evapotranspiration and ground-water draft. Furthermore, zones with declining trend of water table have been demarcated.

2. Study area and the geological setup

The Aravalli Range, one of the oldest mountain ranges of the world stretches itself from northern Gujarat up to the central Rajasthan states located in the north-western part of India. The study area (latitude N23º30´- N26º18´ and longitude E72º24´-E74º36´) covers about 25,000 km^2 of the Aravalli Range (Fig. 1) separating 'Thar', the Great Indian Desert from the eastern plains (DST, 2000). The region falls in the semi-arid climatic zone and contains very few surface water bodies. The streams are ephemeral in nature and remain dry for most of the time. The terrain receives more than 90% rainfall during June-September through the southwest monsoon, which enters the terrain from the east. The elevated range of the Aravalli acts as a barrier for the monsoon wind, which can cross the Aravalli only after downpouring in the terrain. Rainfall varies widely within the terrain due to variations in geographic position, physiography, elevation, slope, wind direction, wind speed etc. Most parts in the north, central and southeast of the region are composed of gneiss and schist with mineralogical variations, whereas phyllites and phyllitic-schist is dominant in the some south, south-central and eastern parts (Fig. 2a). Granite and quartzite are the main rocks in the western part of the terrain along with calcite-schist as the subordinate rock type (DST, 1994).

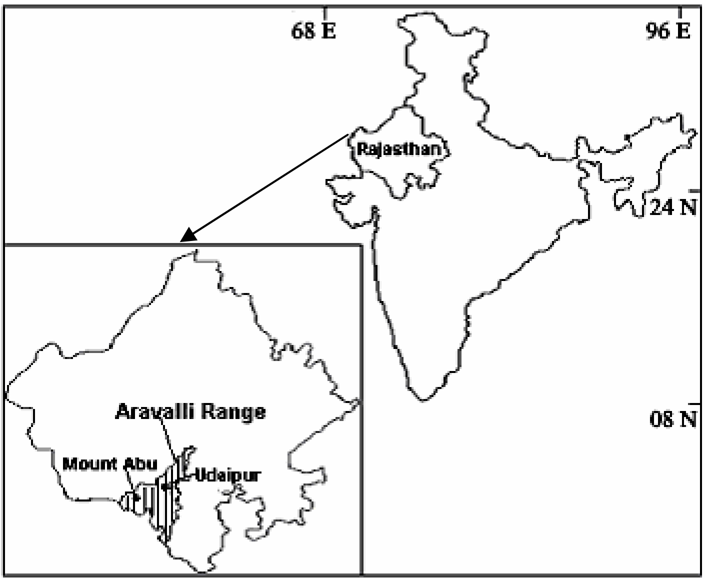

Fig. 1: Location map of the study area

Lithological logs of 188 locations indicate that in three-fourth of the Aravalli region the top soil layer is very thin (0–1 m) and in another 10% area, soil thickness varies within 1-3 m range. In the western, central parts and in some eastern and northern parts, soil thickness varies within 3–10 m (Fig. 2b). Thin soils are characteristic not only of the elevated central and northern parts but also of major eastern and south-western parts with low-relief. Although the eastern part of the region is dominated by pediments and buried pediments and the western part is associated with denudational hills, soil layers are comparatively thicker in the western part, and the thickness varies between 10–35 m of depth. Weathering varies from place to place within the same region depending upon soil and rock types, weathering agents, slope, land use/cover etc. Weathered-zone is as thin as < 10 m in some small areas, whereas two-third parts of the region are associated with medium thickness (10–20 m). Weathered-zone thickness in the range 20–40 m are present in the central and western parts, covering ~ 25% area of the Aravalli, while greater thickness (> 40 m) are found in many western, central, eastern and northern locations (Fig. 2c). Analysis of lithological log data has revealed that subsurface fractures are both continuous and discontinuous i.e. at some places fractures end at shallow depths and at other locations they continue at deeper levels. Greater thickness of both shallow and deep fracture-zones is found in the central, northern and southern parts indicating continuation of fractures above and below the saturated zones. Many places in the western part are devoid of subsurface fractures. In the eastern and central parts, fractures are present only below the saturated zone. Small locations are present having fractures only above the saturated zone. Saturated thickness in major portion of the Aravalli region varies in the range of 5–7 m. However in most parts of north, central and western Aravalli, higher saturated thickness (7–11 m) occurs. In some western and northern locations, saturated thickness is even greater than 11 m. Very thin saturated thickness (0–3 m) is found in some discrete pockets, mainly in the southern parts of the terrain.

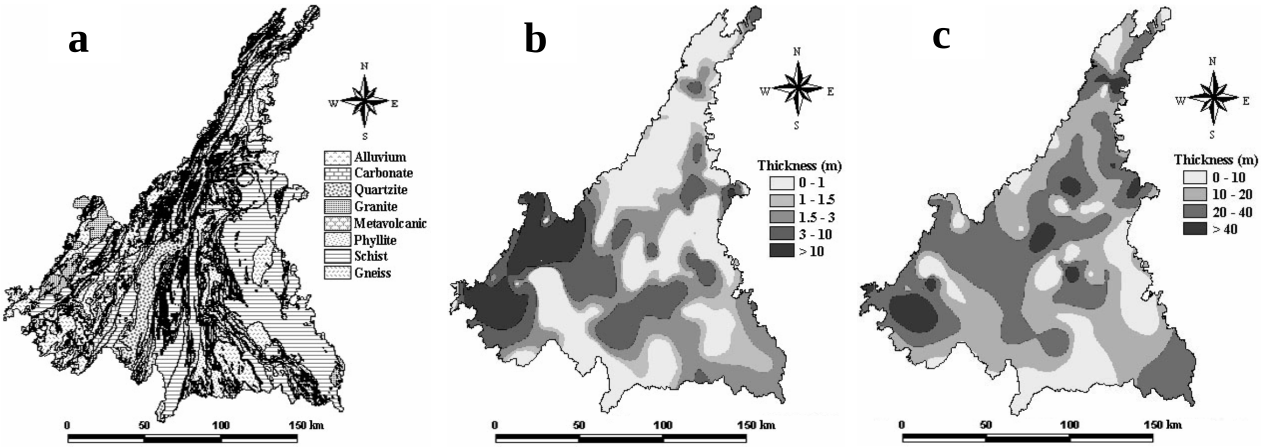

Fig. 2: Spatial distribution and variation of (a) Lithology, (b) Soil thickness, (c) Weathered-zone thickness in the Aravalli terrain

Aquifers in the Aravalli region are unconfined in nature. The average depth to water varies between 5 and 15 m respectively in phyllites and schists, 7 to 15 m in granites, and 10 to 20 m in gneiss below ground surface (GWD Rajasthan 2000). Ground-water level in wells attains the highest (shallowest) level after the monsoon. Afterwards, ground-water level starts falling and reaches the yearly deepest level during summer. The monsoon season commences in late June and recharges the aquifers through infiltration and gravity flow, and the water table rises again. Therefore, seasonal fluctuation of ground-water level in the semi-arid Aravalli region is a direct manifestation of aquifer recharge. Aquifer-recharge is also governed by specific yield of the lithology of the aquifer materials. In the Aravalli region, specific yield (SY) mostly varies between 0.03 and 0.16 (3% to 16%) with small isolated pockets with very high (> 0.4) SY. In phyllite, quartzite, and weathered granite, gneiss and schist with significant clay content, SY is only 0.015, and in sandy alluvium it is as high as 0.16. Intermediate SY is found in weathered granite, gneiss and schist without clay.

3. Data and methodology

Although monsoon varies inter-annually in terms of precipitation intensity, wind speed, and timing of arrival and retreat (Singh, 1994), in the present study, normal monsoon period (June to September) has been considered for analysis. The present study deals with 38 years of rainfall data since 1966 up to 2003. Data of seasonal ground-water levels are available since 1984 and therefore, analysis of water-level fluctuations is restricted to 20 years (1984–2003). For comparison with water-level fluctuations, rainfall patterns and their variations are studied for two decades during 1984–2003. Attribute data of seasonal rainfall (monsoon and non-monsoon) of 35 rain-gauge stations, and pre-monsoon and post-monsoon ground-water levels of 475 wells, measured respectively in May and November (about one month before the arrival and one month after the retreat of the monsoon) have been collected from the Ground Water Department, Jodhpur, Rajasthan and incorporated into separate database. In the Aravalli like many other arid and semi-arid regions where the components like base-flow into streams and net ground-water inflow across the boundary are negligible, ground-water recharge during the monsoon season is the combination of ground water storage change and gross seasonal draft.

Therefore, rainfall induced aquifer-recharge is manifested in the positive fluctuation or rise of ground-water levels. Anomaly in seasonal water-level fluctuation with respect to its long-term seasonal mean is represented by the Water-level Fluctuation Index (WFI), which was developed (Bhuiyan 2006) to quantify recharge deficit. The WFI is computed by dividing the difference between inter-seasonal water-level fluctuation and its long-term mean, by the standard deviation. It can be expressed as:

$$WFI = (F_{ij} - F_{im}) / \sigma \qquad (1)$$

where, F_{ij} is the seasonal water-level fluctuation for the ith water body/ well and jth observation, F_{im} is seasonal mean, and σ is standard deviation.

Water level fluctuates differently in the pre- and post-monsoon periods indicating different controlling factors for the two seasons (monsoon and non-monsoon). It is more so for ground-water levels. For the non-monsoon, the fluctuation of water table mostly reflects the stress side (abstraction and air temperature), whereas that during the monsoon is predominantly controlled by recharge. Despite human intervention and thermal stress, the pre-monsoon water table may better reflect the impact of rainfalls in the preceding monsoon season through lagged recharge. However, it is difficult to separate the anthropogenic effect and temperature impact from the time-lagged recharge effect in the pre-monsoon water table (Panda et al. 2007). Drought affects both surface and sub-surface water levels as it reduces water availability for recharge. Since fluctuation of water levels directly reflects water balance (recharge minus loss), the WFI quantifies recharge-deficit. The WFI values are classified to determine intensity of water-stress (Table 1).

Table 1: WFI classification for assessment of the intensity of water-stress

Water-stress Intensity	WFI Range	Colour
Extreme stress	< -1.64	■
Severe stress	< -1.28	▓
Moderate stress	< -0.84	▒
Mild stress	< -0.25	░
No stress	≥ -0.25	□

For the monsoon season, pre- to post-monsoon fluctuation of ground-water levels are mostly positive (recharge exceeds withdrawal), while for the non-monsoon period, post- to pre-monsoon fluctuations are negative (withdrawal exceeds recharge). Water-stress dose not initiate immediately with negative water balance, but only after crossing the threshold. Again, natural environment is more sensitive to water-stress during the non-monsoon period, particularly in summer. Therefore, the threshold to initiate drought have been set to < -0.25 for the monsoon season and < -0.125 for the non-monsoon season. Stress generates only when the WFI is less than these thresholds.

Maps of rain-gauge stations and well locations have been prepared using the geographic co-ordinates in a GIS environment. Spline interpolation technique with 0.1 ‘tension’ has been found suitable and is used to generate rainfall maps. Since rainfall is controlled by local meteorological parameters, for interpolation, four nearest points have been considered which are on an average separated by 30 km from one another. Point data of the WFI are also interpolated using the same technique. Since water table shows a high degree of spatial continuity (Meijerink et al., 1994), for interpolation of WFI, 10 nearest points (wells) have been chosen. Similarly, maps of rainfall and WFI have been generated for intermediate periods: 1984–1993 and 1994–2003. The patterns of monsoon-rainfall as well as WFI are monitored through graphical analysis as well as visual comparison.

Year wise average seasonal water levels of all hydrological units (rock units of the administrative blocks with or without canal irrigation) are computed. The trend of seasonal ground-water level in every hydrological unit is computed through a linear relation between seasonal ground-water levels and number of years of observation. Thus,

$$D = aW + b \tag{2}$$

where, D = depletion, W = seasonal water level, a and b = constants.

The constants a and b are obtained through a linear regression analysis and are computed as:

$$a = (NS_4 - S_1S_2) / (NS_3 - S_1^2) \tag{3}$$

$$b = (S_2 - aS_1) / N \tag{4}$$

where, $S_1 = \sum_{i=1}^{N} Y_i$, $S_2 = \sum_{i=1}^{N} W_i$, $S_3 = \sum_{i=1}^{N} Y_i^{\ 2}$, $S_4 = \sum_{i=1}^{N} W_i Y_i$,

Y = serial number of the year, W = water level, and N = total number of years.

Positive values of the coefficient ‘a’ indicate declining trend and the magnitude indicates the rate of decline of the water table in the concerned hydrological unit. The entire study area is classified on the basis of season-wise (pre- and post-monsoonal) trend of water level, and zones showing depleting trend of ground-water recharge are demarcated.

Over-extraction of ground water during recurrent droughts is found to reduce springflow and lowered water tables (Zektser et al, 2005). Therefore, water demand and extraction in the region is studied through recorded data of net ground-water drafts. Higher evaporation has been found to reduce ground-water recharge (Chen et al., 2004). An earlier study based on tritium injection (Rangarajan and Athavale, 2000) has inferred negligible water-loss due to evapotranspiration in semi-arid hard-rock areas like the Aravalli. However, detail analysis of temperature and mean potential evapotranspiration (PET) from June to October during 1984–2003 has been carried out, and the mean temperature and PET during the monsoon are calculated (Table 2) using the recorded ground data of Agricultural University, Udaipur and remote sensing data of NCEP, which provide some idea of hydrometeorology of the region.

Table 2: Recorded data of the mean diurnal surface temperature and mean seasonal potential evapotranspiration at (a) Udaipur City, and (b)–(d) at places around the Aravalli terrain, during the Monsoon.

Year	a. 24°58′N, 73°70′E		b. 23°81′N, 73°13′E		c. 23°81′ N, 75° E		d. 25°71′ N, 75° E	
	Mean T °C	Mean PET (cm)	Mean T °C	Mean PET (cm)	Mean T °C	Mean PET (cm)	Mean T °C	Mean PET (cm)
1984	24.65	7.69	25.43	7.81	26.56	7.38	27.60	7.58
1985	25.45	8.11	26.45	9.31	27.33	8.70	28.46	8.91
1986	25.80	8.36	26.65	8.65	27.77	8.04	29.23	8.31
1987	27.10	9.52	27.82	10.37	27.97	9.50	29.81	9.93
1988	26.35	8.48	26.87	8.17	28.01	7.75	28.97	7.89
1989	25.45	6.71	26.96	8.28	27.16	7.67	28.57	7.92
1990	24.85	6.65	26.06	7.39	27.01	7.02	28.41	7.22

1991	24.65	8.42	27.74	8.56	28.38	7.75	30.20	8.02
1992	26.70	8.66	27.09	8.53	27.85	7.77	28.29	7.83
1993	27.00	8.54	27.87	9.48	27.44	8.20	29.04	8.50
1994	24.05	6.59	26.33	6.78	26.28	6.23	27.14	6.34
1995	27.85	8.91	27.72	9.08	27.89	8.17	28.54	8.26
1996	25.55	7.69	27.52	8.13	27.88	7.32	29.06	7.48
1997	24.90	6.65	27.19	8.08	26.40	7.11	27.98	7.48
1998	27.10	7.20	27.24	8.27	26.26	7.78	29.15	7.92
1999	25.25	6.53	26.72	7.92	27.46	7.42	29.44	7.73
2000	25.25	7.87	28.16	8.76	27.86	7.83	29.33	8.06
2001	22.35	5.86	24.37	6.48	25.90	6.31	27.16	6.48
2002	28.60	9.88	31.62	11.10	29.64	10.65	32.40	9.99
2003	25.80	9.03	27.58	10.04	28.10	8.83	30.22	8.80

4. Results and discussion

4.1 Decadal variations of Rainfall dynamics and aquifer response

The Aravalli region like most other places of northern India receives more than 90% of annual rainfall during the monsoon season. The distribution of long-term normal monsoon-rainfall (Fig. 3a) shows 550–700 mm rainfall in major parts of the Aravalli region. Higher rainfall (> 700 mm) is observed along south-eastern and western flanks of the Aravalli. Very high rainfall (> 850 mm) occurs in the western-most part around Mount Abu, which itself receives on an average 1800 mm of rainfall during the monsoon. No significant difference in rainfall distribution is found in the Aravalli region during 1984–1993 and 1994–2003 (Fig. 3b,c). However, in the central and eastern parts, the average monsoon-rainfall during 1994–2003 is found slightly decreased compared to the previous decade. A small increase in rainfall is noticed in the western flank during the later decade. However, overall rainfall scenario remains unaltered in this region in last four decades.

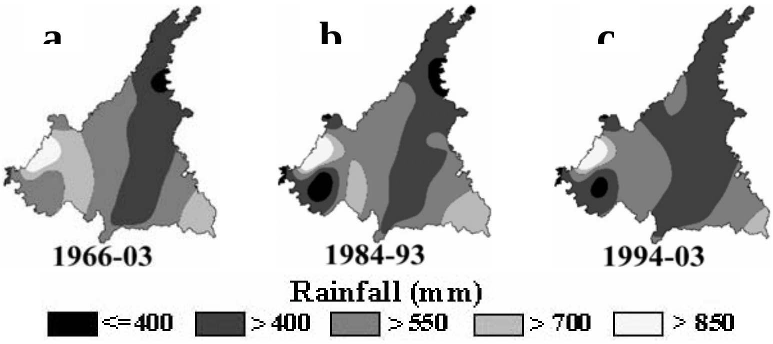

Fig. 3: Monsoon-rainfall in Aravalli terrain: (a) Long-term mean (1966 – 2003),
(b) During 1984 – 1993, (c) During 1994 – 2003

The asymmetric response of water table to monsoon-rainfall is also seen in the decadal observations. Comparison has revealed that fluctuations of water levels during 1984–1993 and 1994–2003 are more or less similar for most parts of the Aravalli terrain but are remarkably different in some pockets (Fig. 4). In the northern parts of the Aravalli, fluctuations

in most wells are found to be doubled in the later decade implying a significant improvement, whereas in many parts in the south the situation was reverse.

Fig.4: Seasonal (pre- to post-monsoon) fluctuation of the water table in the Aravalli terrain. (a): mean fluctuation during 1984–2003, (b): mean decadal fluctuation during 1984–1993, (c): mean decadal fluctuation during 1994–2003.

4.2 Inter-annual variability

Hills and mountains generally have strong influence over rainfall distribution (Singh and Kumar, 1997). However, the Aravalli region lying between the arid Thar Desert in the west and sub-humid plains in the east shows irregular patterns and significant inter-annual variability. Variation in topography, elevation, land-use, and local meteorological factors are likely causes for this variation. Monsoon varies inter-annually in terms of precipitation intensity, wind speed, and timing of arrival and retreat (Singh, 1994). On the basis of rainfall amount, the years can be categorised into years of good, intermediate, and poor monsoons. The time series analysis shows that in the Aravalli region, spatio-temporal rainfall distribution varies randomly and in some particular years the distribution was almost reverse. In 1985, rainfall was low (50–400 mm) particularly in north and some parts in the east, west, and south. The year 1987 was drought-year when almost entire region including the Mount Abu received less than 400 mm rain. In other dry years (1995, 1999, 2000 and 2002) rainfall patterns are found to be different (Fig. 5). In 1987, 1999 and 2002, rainfall was less than 550 mm even at Mount Abu that alone generally receives about 1800 mm of rainfall during monsoon (DST, 1994). The Indian summer of 2002 was the sixth driest in 130 years (Webster and Hoyos, 2004). Rainfall was 19% below normal in most parts of India, and in Rajasthan it was 64% below normal during the monsoon of 2002 (Waple and Lawrimore, 2003). In Aravalli, the deviation from the normal rainfall was as high as -49% in Rajsamand, -67% in Sirohi and -33% in Udaipur districts occupying respectively, the north, west and south-central-east of the region (UNDP, 2002). Combined effect of El Nińo and Equatorial Indian Ocean Oscillation (EQUINOO) is considered responsible for the monsoonal droughts of 1987 and 2002 (Gadgil et al., 2003). On the other hand, the region remains wetter in the years 1988, 1990, 1992 and 1994 with wide variation in rainfall distribution patterns (Fig. 6). In 1990, entire western part received more than 850 mm rainfall and Mount Abu alone, received rainfall over 2900 mm. In 1992 and 1994, higher rainfall was observed in the entire Aravalli region including Mount Abu (~2800 mm). Excessive rainfall in 1994 is likely to be associated with the La Nina event. In Mount Abu region, excessive rainfall occurred also in years 1988 (>1800 mm) and 1997 (>2000 mm). In other years (1989, 1996, 1997, 2001, and 2003) monsoon was normal, when the entire Aravalli region received moderate rainfall. However, the spatio-temporal rainfall distributions followed no definite trend or pattern.

Aquifers in the Aravalli region are under the control of the monsoon as recharge takes place with the whims of monsoon-rainfall. In general, places with higher infiltration capacity experience higher positive fluctuation (rise) of water table even with below normal rainfall, whereas major parts of the region with low infiltration capacity provide reasonably high positive fluctuations only when rainfall is above normal. Aquifers in the northern, eastern, central, and western parts show 3.5–7 m fluctuations; certain locations receive comparatively higher fluctuations (12–15 m) owing to higher (> 0.21) infiltration coefficient (i.e. 21% rainfall). Some locations in the north, central, and west show moderate (8–10 m) to high (> 10 m) positive fluctuations owing to higher (> 0.15) infiltration coefficient. Southern and south-eastern Aravalli shows very low (< 1.5 m) fluctuation due to low (0.05–0.1) infiltration capacity.

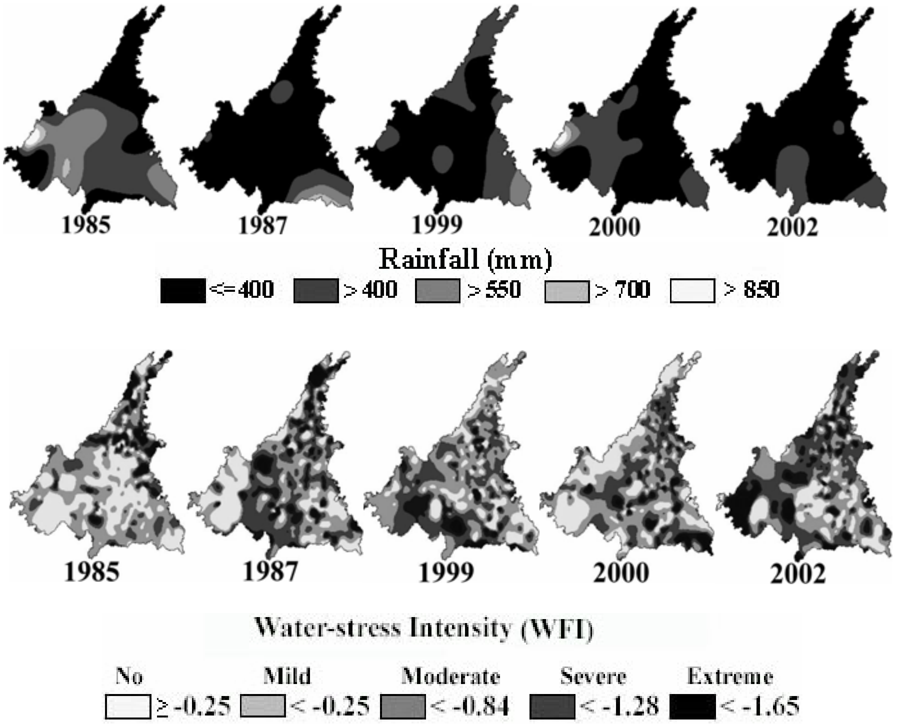

Fig. 5: Rainfall patterns in the years of intense meteorological drought and accumulated water-stress in response to monsoon-rainfall as revealed by the WFI

Water-stress developed in major parts of the Aravalli region during the monsoon of 1984, 1986, 1989, and 1995 causing sharp decline of the water table and depletion of water resources due to enormous recharge deficit. Intense monsoon-drought affected the entire terrain in 1999, 2000, and 2002, and prevailed in major parts of the terrain in 1985 and 1987. Fluctuation is found to be poor particularly in 1987 and 2002, the years of intense drought compared to other drought years (Fig. 5). During 2002 monsoon, the drought was catastrophic, when most of the wells and reservoirs dried up and ground-water level declined by more than 2 standard deviation. In Rajsamand, Sirohi and Udaipur districts covering the study area, 21 out of 33 reservoirs/ tanks became dry during the monsoon of 2002 causing large scale ecological damage, mass-migration and death (UNDP 2002).

In the years of good monsoon (1988, 1989, 1990, 1992, 1994, 1996, 2001, and 2003), the Aravalli terrain was mostly free from water-stress. Higher (2.5–5 m) positive fluctuation has been observed particularly in 1988, 1990, 1992 and 1994 owing to good rainfall (Fig. 6). From the time-series it is evident that water-stress and drought during monsoon season is controlled by recharge except the western part that suffers from frequent drought irrespective rainfall amount.

There are only seven wells at the central and south-eastern parts of the region, which are found to undergo a gradual and continuous rise in ground-water levels. On the contrary, in many parts of eastern, south-eastern and central Aravalli the situation has been degraded; in some wells, both pre-monsoon and post-monsoon water levels have declined up to 30m BGL. Post-monsoon ground-water level is consistently failing to rise with respect to pre-monsoon level in many wells since 1998, irrespective of rainfall amount (Fig. 7). However, the trends and patterns of lowering of water table are found to vary in wells; in some wells the trend is gradual (Fig. 7a, b), in certain wells the decline is sharp and steady (Fig. 7c, d), while in others the fluctuation follows the rainfall pattern (Fig. 7e, f). These wells are randomly distributed all over the terrain but are mostly confined to the eastern, central and southern parts, where water table is shallower. The continuous declining trend in these wells irrespective of rainfall amount indicates inadequate recharge due to insufficient rainfall and over-exploitation of ground-water resources, since other physical parameters are found to be stable.

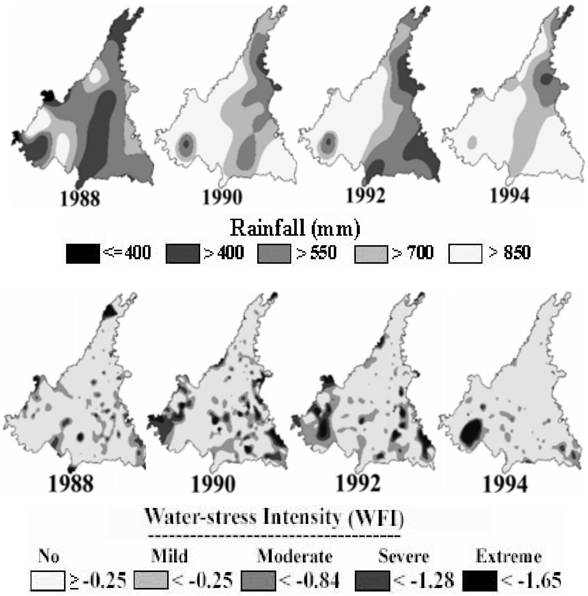

Fig. 6: Years of excessive monsoon-rainfall and its positive impact on ground-water recharge in the Aravalli terrain.

During the non-monsoon period, hydrological drought affected wells all over the terrain, but not the entire region at a time. Previous work (Bhuiyan et al. 2006) has shown that in major parts of the Aravalli region the pre-monsoon water table declined in the alternate years of 1992, 1994, and 1996 (non-monsoon of 1991-92, 1993-94, and 1995-96). During the pre-monsoon of 1997, the declining trend ceased in the western part but started in some eastern locations. Based on the WFI time-series, zones could be demarcated in the western part that suffered consistently from water-stress both during the monsoon season (Fig. 8) and the non-monsoon period (Fig. 9). Cumulative frequency of water-stress of different intensities has been computed for every well location using the WFI values. Majority of the wells are found to be associated with moderate frequency (0.4–0.6) of water-stress both for the monsoon and non-monsoon seasons. However, contrary to the assumption at many locations water-stress is more frequent during the monsoon than in the non-monsoon period (Fig. 10). This is possibly due to early arrival and/or late withdrawal of the monsoon in some of the years causing rainfall and lagged aquifer-recharge during the non-monsoon period. Following equation (2), hydrological units with depleting water table have been demarcated. Figure 11 shows that pre-monsoon water table declines gently, whereas post-monsoon water table decline is steeply, in both the decades (1984-1993 and 1994-2003). It is interesting to observe that the declining water table of pre-monsoon shows rising trend in many parts of the terrain in the later decade, whereas post-monsoon water table has declined more steeply in major parts of eastern and central Aravalli in the later decade.

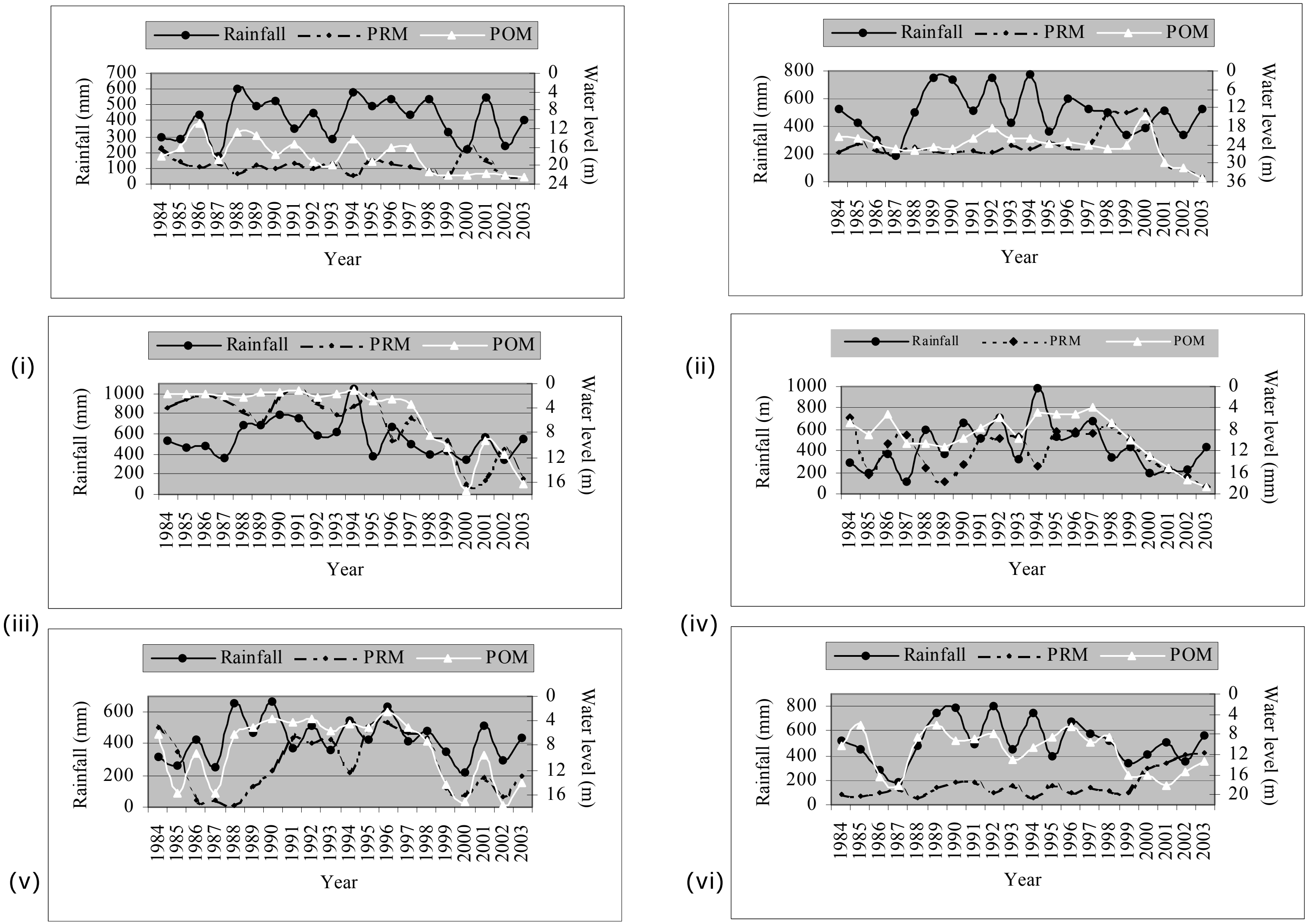

Fig. 7: Trends and patterns of monsoon rainfall, and pre-monsoon (PRM) and post-monsoon (POM) ground water levels in some of the wells undergoing depletion. Inadequate aquifer-recharge is evident during 1998 to 2003.

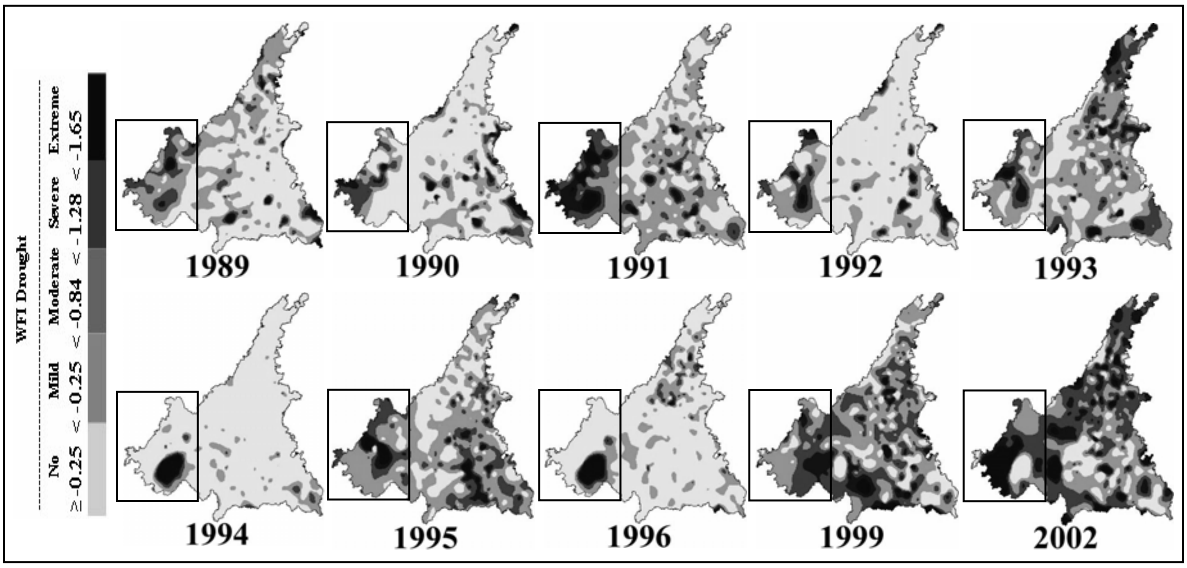

Fig. 8: State of water-stress and drought as revealed by the WFI. Certain zones in the western Aravalli (in box) experience water-stress irrespective of poor and good monsoon-rainfall, indicating excess water extraction than the recharge.

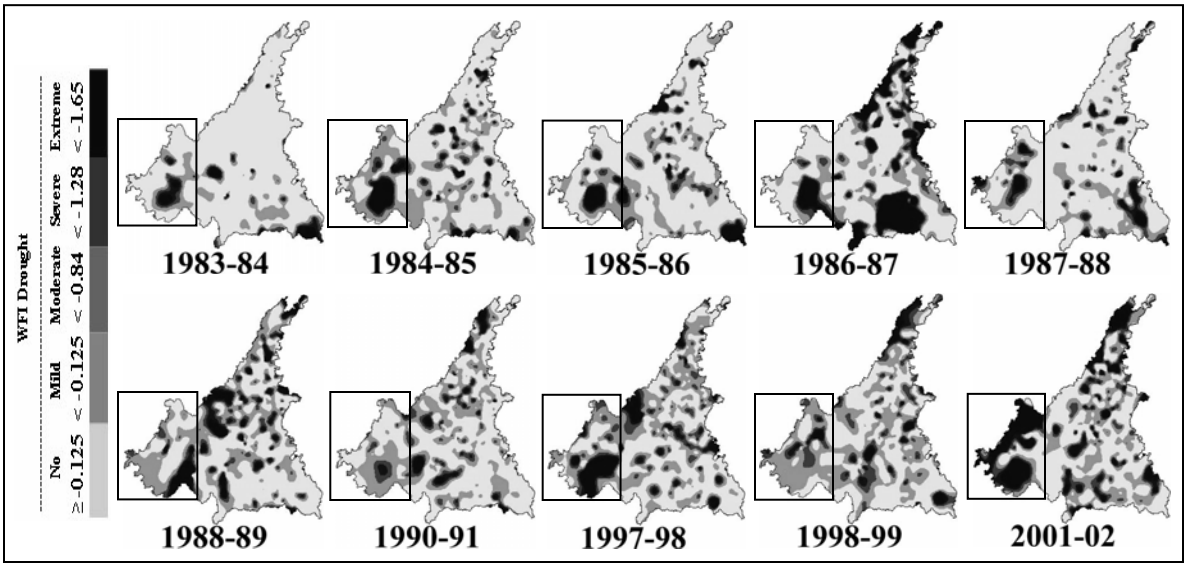

Fig. 9: Several pockets in the same western part of the Aravalli (in box) consistently suffer from water-stress and hydrological drought even during the non-monsoon period.

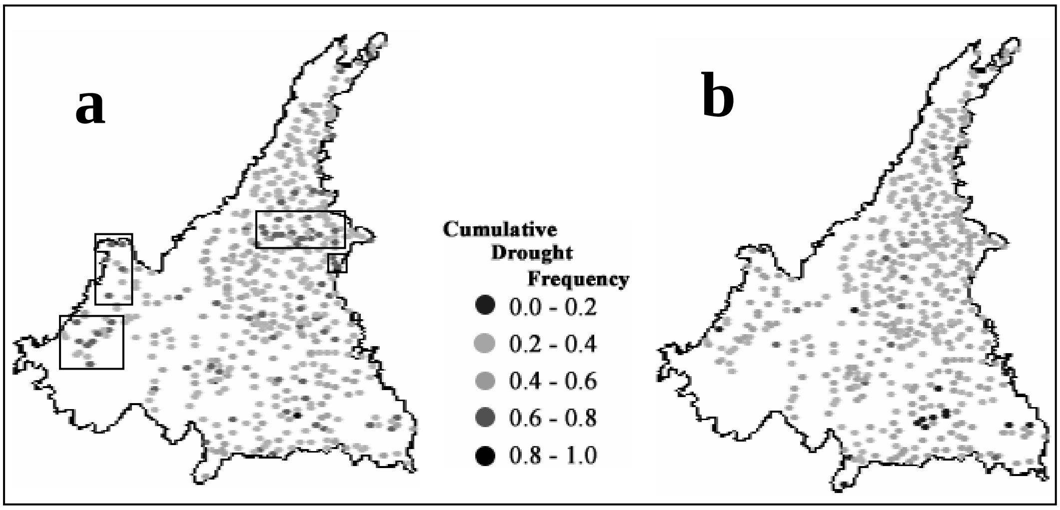

Fig. 10: (a) Zones having wells with high frequency (0.6–0.8) of water-stress during monsoon, (b) Frequency of non-monsoonal water-stress is moderate (0.4–0.6) in most wells in the northern and central Aravalli.

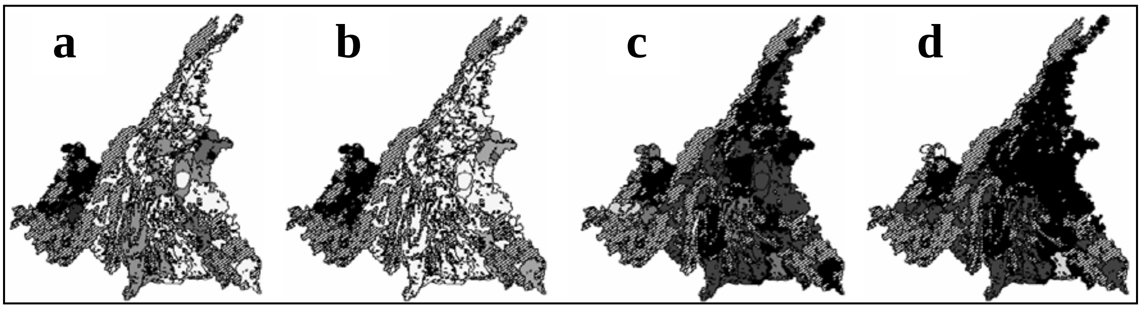

Fig. 11: Ground water depletion-zones and state of (a) pre-monsoon water level during 1984-1993, (b) pre-monsoon water level during 1994-2003, (c) post-monsoon water level during 1984-1993, (d) post-monsoon water level during 1994-2003 (white: no decline, grey: small decline, black: steep decline).

Influence of ground-water extraction or over-exploitation on seasonal water level and recharge has been studied based on available data on net ground-water draft. Year wise net ground-water draft during 1996–2000 has been analysed and compared through visual interpretation, which indicates that net ground-water draft was less in the eastern part of the region but substantially increased in the northern and central Aravalli during 1999–2000 (Fig. 12). Overall, no major change in ground-water extraction is observed during the normal years (1996–1998) and droughts (1999 and 2000).

Influence of temperature and evapotranspiration on the water regime is studied through the recorded ground data as well as those derived using remote sensing data (Table 2). It has been found that the mean temperature in the region during monsoon varies in the range of 22–33 ºC, and the mean daily evaporation varies in the range of 5–10 mm during two decades. Monthly PET computed using the temperature data and the Thornthwaite equation (Thornthwaite, 1948) are found to be slightly higher compared to the ground data of actual evaporation of Udaipur. Owing to their geographical vicinity and climatic homogeneity, these computed data are correlated with the ground data for optimisation and better approximation. Figure13a and b-d shows the temporal variation of mean diurnal surface temperature and mean evaporation respectively at Udaipur and other locations around the study area during the monsoon. It is evident that PET varies proportionately with the variation of surface temperature.

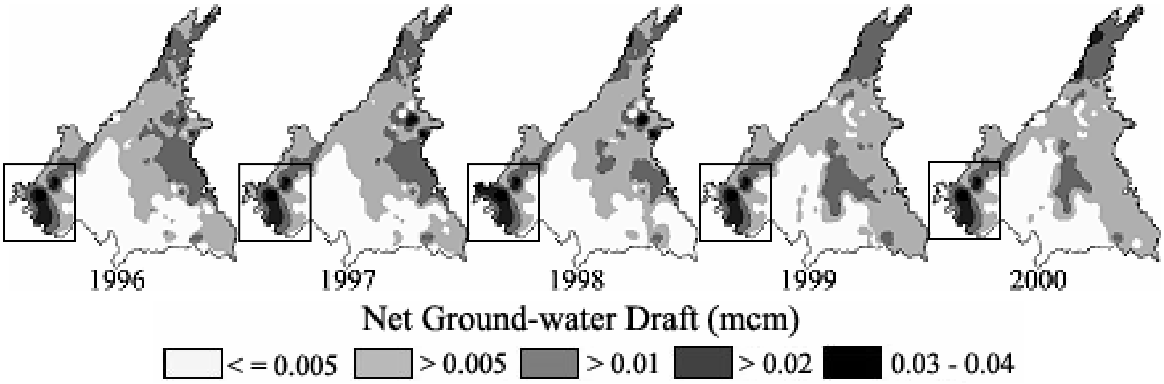

Fig. 12: Year-wise variation of ground-water draft in different parts of the Aravalli region during 1996 – 2000. Not much increase in draft is observed in the drought years of 1999 and 2000.

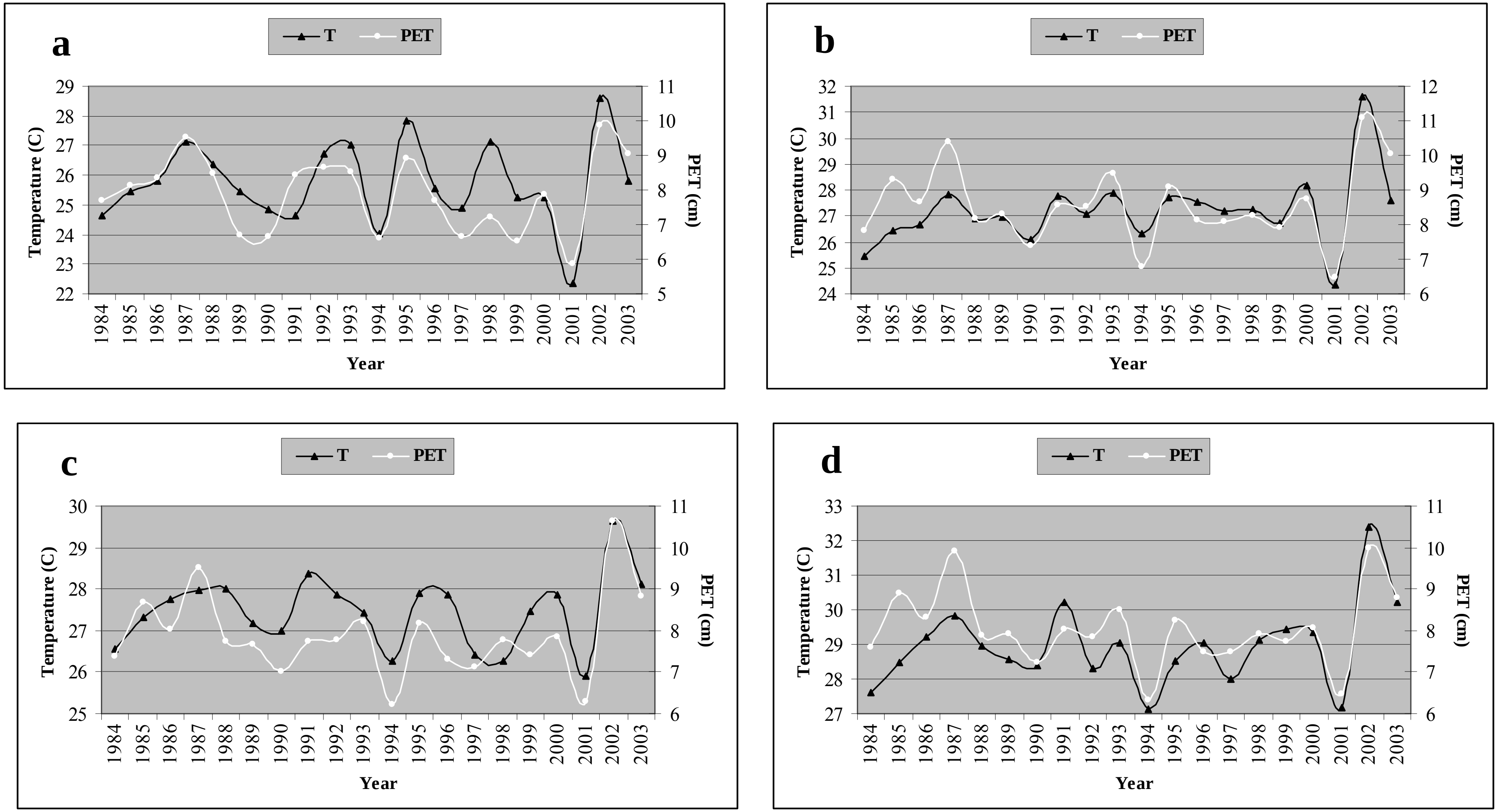

Fig. 13: Temporal variations of mean daily temperature and mean seasonal potential-evapotranspiration during monsoon

5. Discussion

Rajasthan's economic growth is largely dependent on ground water as it supports 71% of the irrigation and 90% of the drinking water. Due to tremendous exploitation of ground water by the State and private users, out of 236 ground-water zones, only 20.8% were categorized as safe in 2001 in terms of water availability and exploitation, while rest reached the stage of semi-critical (8.9%), critical (33.9%) and over-exploited (36.4%). The causes of ground-water depletion include population growth, economic expansion, decline in ground-water recharge and over-abstraction caused by the rapid increase in the number of wells and tubewells and the progress in pumping technology (Rathore 2005).

Like the rest part of the Rajasthan state, the continuous decline of the water table in the Aravalli region is related to poor rainfall and over-extraction, exceeding actual recharge. Due to rapid and tremendous growth of population, agriculture, and industry, water consumption and construction of wells have been increased many folds last five decades (Fig. 14). It is observed that when natural recharge ceases, water levels decline rapidly at first and more gradually as time passes (Mallick and Banerji 1979). Due to low rate of recharge and higher rate of consumption, restoration of ground-water level generally takes a long time (Kondoh et al. 2004). In arid and semi-arid regions like the Aravalli terrain, where components like base-flow into streams and net ground-water inflow across the boundary are negligible, ground-water balance can be computed simply as:

$$\text{Balance} = \text{Input} - \text{Output} = \text{rRch} + \text{oRch} - \text{mDrft} \qquad (5)$$

where, rRch is the recharge from rainfall alone through infiltration, oRch is the recharge from other sources, and mDrft is the total monsoonal ground-water draft.

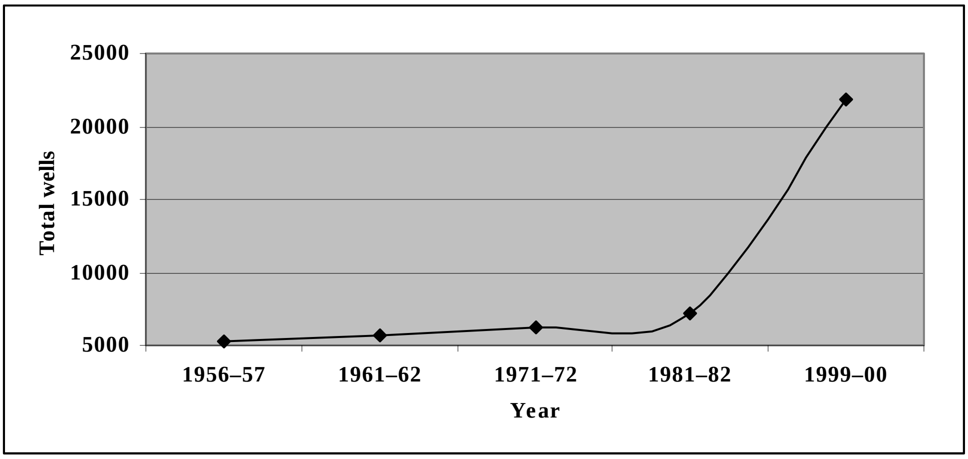

Fig. 14: Density of wells/1,000 km^2 in the study area during 1956-2000

Table 3 shows that during the five year span (1996–2000), rainfall varied randomly in the study area, and was very low in the drought years 1999 and 2000. Therefore, ground-water recharge was small, but draft (extraction) was not reduced to balance low recharge. As a consequence, water table declined sharply particularly during 1999-2000. Although rainfall is comparatively higher (> 700 mm) in major part of the western Aravalli, probability of normal rainfall is low in most parts of the western sector, and has large spatial variation. The western Aravalli is also associated with wide range (0.01 to > 0.40) of infiltration capacity, denoted as rainfall infiltration factor (RIF). The pockets in the western Aravalli that frequently suffer from drought are associated with > 550 mm of monsoon-rainfall, 0.375–0.45 probability (i.e. 37.5% to 45% chance) of normal monsoon-rainfall, and 0.01–0.40 RIF (1% to 40% of rainfall). Again,