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# Monitoring drought dynamics in the Aravalli region (India) using different indices based on ground and remote sensing data

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**Abstract**

The hard-rock hilly Aravalli terrain of Rajasthan province of India suffers with frequent drought due to poor and delayed monsoon, abnormally high summer-temperature and insufficient water resources. In the present study, detailed analysis of meteorological and hydrological data of the Aravalli region has been carried out for the years 1984–2003. Standardised Precipitation Index (SPI) has been used to quantify the precipitation deficit. Standardised Water-Level Index (SWI) has been developed to assess ground-water recharge-deficit. Vegetative drought indices like Vegetation Condition Index (VCI) and Temperature Condition Index (TCI) and Vegetation Health Index (VHI) have been computed using NDVI values obtained from Global Vegetation Index (GVI) and thermal channel data of NOAA AVHRR satellite. Detailed analyses of spatial and temporal drought dynamics during monsoon and non-monsoon seasons have been carried out through drought index maps generated in Geographic Information Systems (GIS) environment. Analysis and interpretation of these maps reveal that negative SPI anomalies not always correspond to drought. In the Aravalli region, aquifer-stress shifts its position time to time, and in certain pockets it is more frequent. In comparison to hydrological stress, vegetative stress in the Aravalli region is found to be slower to begin but quicker to withdraw.


*Keywords:* Drought; Monsoon; GIS; SPI; SWI; AVHRR; GVI; NDVI; VCI; TCI; VHI

## 1. Introduction

Drought has significant adverse effect on the socio-economic, agricultural, and environmental conditions. During drought, severe water-scarcity results in a region due to insufficient precipitation, high evapotranspiration, and over-exploitation of water resources and/or combination of these parameters. Various methods and indices have been developed by many scientists (Palmer, 1965, 1968; Gibbs and Maher, 1967; Shafer and Dezman, 1982; Kogan, 1990, 2002; McKee et al., 1993; Keyantash and Dracup, 2004) for drought analysis using different drought-causative and drought-responsive parameters such as rainfall, soil moisture, potential evapotranspiration, vegetation condition, ground-water and surface-water levels. The drought measuring parameters are not linearly related to one another, these drought indices often have little correlation among themselves. Therefore, it is quite

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common that when one drought index identifies drought at a particular place, another drought index indicates a normal condition at the same place and time (Bhuiyan, 2004). The drought perception varies significantly among regions of different climates (Dracup et al., 1980), while rainfall is the chief causative parameter, soil moisture, streamflow, reservoir storage and ground-water level are the main parameters reflecting drought impacts. While soil moisture responds to precipitation anomalies on a relatively short time scale, ground-water, streamflow, and reservoir storage reflect longer-term precipitation anomalies (Komuscu, 1999). Agricultural and vegetative drought is a manifestation of meteorological and hydrological droughts.

The Asian south-west monsoon is a complex phenomena and the monsoon-rainfall is the only possible means for ground-water recharge particularly in the hard-rock hilly Aravalli region of semi-arid western India. Scarcity of surface-water bodies in this region has made people dependent entirely on ground-water resources for every purpose. A continuous spell of poor rainfall in combination with high temperature in successive years hinders ground-water recharge and imparts stress on ground-water resources leading to severe drought in many parts during both the monsoon and the non-monsoon seasons. The meteorological and hydrological droughts in turn affect the growth of the natural vegetation and crop production.

Water budget is in deficit in most of the basins of Indian Peninsula, where ground-water resources sustain agricultural practices (Brown, 2001). Major parts of the study area experience year-round water deficit. Drought is frequent in the Aravalli region due to poor, limited and untimely rainfall. The summer Indian monsoon is a complex phenomenon and complexity is increasing due to change in numerous atmospheric and land-cover parameters, in recent years, the forecast of onset of monsoon has become more difficult. Again, rainfall occurs in this western region in the final lap of the sinuous path of the monsoon from the Arabian Sea through southern India, the Bay of Bengal, eastern and northern India, therefore, drought in this region is unpredictable. Even commencement of rainfall at the right time cannot guaranty a drought-free season since frequency, intensity, amount and duration of rainfall too play crucial roles in the occurrence of drought.

In the present study, detailed analysis of seasonal drought dynamics has been carried out to identify spatio-temporal drought patterns in meteorological, hydrological, and vegetative spheres. Time-series drought maps of the Aravalli region have been generated in a Geographic Information Systems (GIS) environment using various drought indices. Since aquifer-recharge, agricultural activities, and ecological changes are controlled by rainfall, the present analysis has been focussed on drought during the monsoon and the non-monsoon periods. Standardised Precipitation Index (SPI) has been used to monitor meteorological drought. Standardised Water-Level Index (SWI) has been developed to analyse hydrological drought. Normalised Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), Temperature Condition Index (TCI) and Vegetation Health Index (VHI) have been employed to assess vegetative drought. VHI has been developed through VCI and TCI and is found to be more effective compared to other indices in monitoring vegetative drought (Kogan, 1990, 2001; Singh et al., 2003). Finally, relative drought dynamics in meteorological, hydrological, and vegetative spheres of the Aravalli region has been compared.

## 2. Study area

Rajasthan, the largest state of India is situated in the northwest of the country and exhibits diverse climates in different parts (Fig. 1a). The Aravalli range, one of the oldest mountain ranges of the world runs along the NE–SW direction for more than 700 km covering nearly 40,000 km$^2$ area. The study area (latitude N23°30′–N26°18′ and longitude E72°24′–E74°36′) covers an area of about 25,000 km$^2$ of the main block of the Aravalli range (Fig. 1b). The region is dry for most of the year except the rainy season, and exhibits a semi-arid climate. Rainfall in this region occurs mainly during June–September through the monsoon wind; non-monsoon rainfall is limited and irregular. Water resources, vegetation, and agriculture are under control of the monsoon. The aquifer condition and water resources in this region vary from place to place due to variations in soil, lithology, land-use, geomorphology, topography, and climatic conditions.

The normal water-table depth also varies in different lithologic domains. Gneiss and schist covers most parts in the north, central and southeast where water table lies in the depth range of 10–20 m below ground surface. In phyllites and phyllitic-schists of the south, south-central and eastern Aravalli, the depth of water normally lies within 5–15 m range. Western part of the region is composed mainly of granite and quartzite along with calcite-schist as the subordinate rock type (DST, 1994). In granitic aquifers, the average depth of water varies in the range of 7–15 m while under calc-schist the water level varies between 5 and 10 m below ground surface (GWD, 2000). In the Aravalli region, agricultural

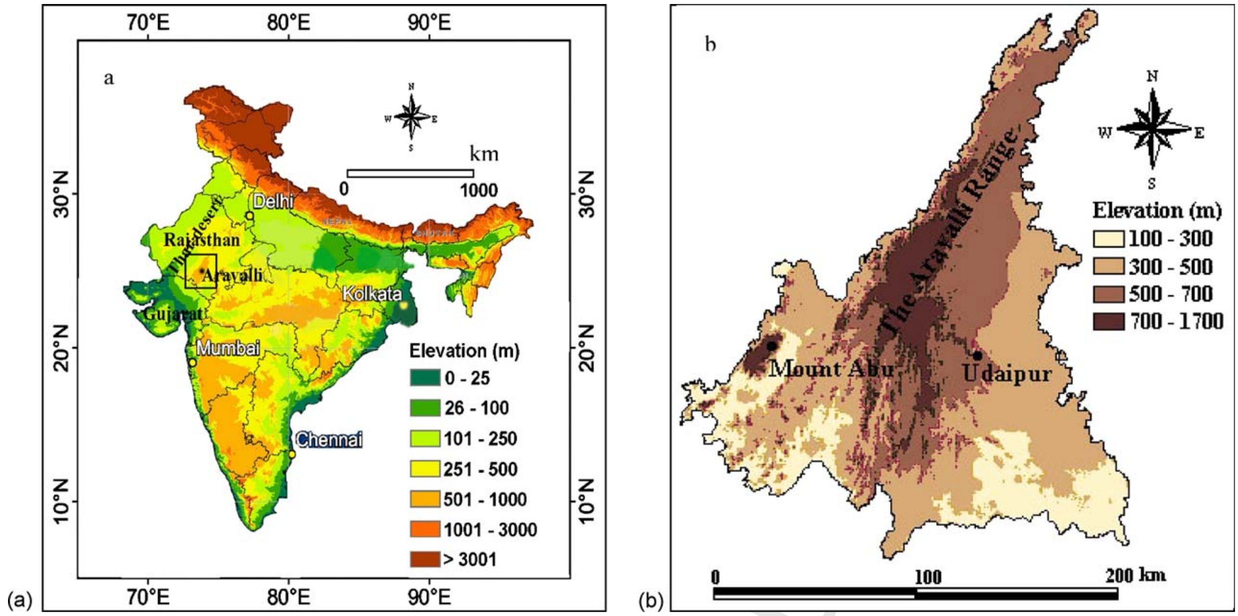


Fig. 1. (a) Location of the Aravalli region and (b) study area.

activities are influenced and controlled directly by rainfall and availability of water resources. Monsoon (Kharif) crop is the main crop and is cultivated during June–September whereas winter (Rabi) crop is sown in mid October and harvested in March. In many parts of the region, summer crop and vegetables are cultivated during March–May depending upon the availability of irrigation-water. In some parts of the Aravalli region, double cropping is practiced whereas many pockets have uncultivated fallow land.

## 3. Drought indices

### 3.1. Standardised Precipitation Index

McKee et al. (1993, 1995) proposed Standardised Precipitation Index to assess anomalous and extreme precipitation. Monthly precipitation data are taken from Ground Water Department, Jodhpur, Rajasthan. Since precipitation data are mostly skewed, in order to compute SPI, precipitation data are normalised

Table 1
SPI, SWI, and VHI classification schemes

| Drought Classes \ Classification Schemes | SPI (McKee et al., 1993) | SWI (Bhuiyan, 2004) | VHI (Kogan, 2002) |
|---|---|---|---|
| **Extreme drought** | < – 2.0 | > 2.0 | < 10 |
| **Severe drought** | < – 1.5 | > 1.5 | < 20 |
| **Moderate drought** | < – 1.0 | > 1.0 | < 30 |
| **Mild drought** | < 0.0 | > 0.0 | < 40 |
| **No drought** | > 0.0 | < 0.0 | > 40 |

using gamma function. SPI is based on the probability of precipitation for any desired time scale. The SPI is based on the probability of precipitation for any desired time scale and spatially invariant indicator of drought (Guttman, 1998, 1999). It involves fitting a gamma probability density function to a given frequency distribution of precipitation totals for a station (Edwards and McKee, 1997). The SPI is computed by dividing the difference between the normalised seasonal precipitation and its long-term seasonal mean by the standard deviation. Thus,

$$\mathrm{SPI} = \frac{X_{ij} - X_{im}}{\sigma} \quad (1)$$

where, $X_{ij}$ is the seasonal precipitation at the $i$th rain-gauge station and $j$th observation, $X_{im}$ the long-term seasonal mean and $\sigma$ is its standard deviation. Five classes of SPI as shown in Table 1 are used in the present study.

### 3.2. Standardised Water-Level Index

Standard Water-Level Index was proposed to monitor anomaly in ground-water level as a correspondent of aquifer-stress (Bhuiyan, 2004). The ground-water level data are taken from the Ground Water Department, Jodhpur, Rajasthan. The SWI is computed by normalising seasonal ground-water level and dividing the difference between the seasonal water level and its long-term seasonal mean, by standard deviation. For normalisation, an incomplete gamma function has been used similar to SPI. Thus,

$$\mathrm{SWI} = \frac{W_{ij} - W_{im}}{\sigma} \quad (2)$$

where, $W_{ij}$ is the seasonal water level for the $i$th well and $j$th observation, $W_{im}$ its seasonal mean, and $\sigma$ is its standard deviation.

SWI is an indicator of water-table decline and an indirect measure of recharge, and thus an indirect reference to drought. Since ground-water level is measured from ground surface down into observation wells, positive anomalies correspond to water-stress and negative anomalies represent 'no drought' condition (Table 1).

### 3.3. Vegetative drought indices

Vegetative and agricultural droughts reflect vegetation-stress caused due to adverse climatic and hydrologic factors. NDVI reflects the vegetation condition through the ratio of responses in near infrared (Ch2) and visible (Ch1) bands of Advanced Very High Resolution Radiometer (AVHRR) of NOAA. Vegetative Condition Index is related to the long-term minimum and maximum NDVI (Kogan, 1990) and is related as:

$$\mathrm{NDVI} = 100 \times \frac{\mathrm{Ch2} - \mathrm{Ch1}}{\mathrm{Ch2} + \mathrm{Ch1}} \quad (3)$$

$$\mathrm{VCI} = 100 \times \frac{\mathrm{NDVI_{max}} - \mathrm{NDVI}}{\mathrm{NDVI_{max}} - \mathrm{NDVI_{min}}} \quad (4)$$

where NDVI, $\mathrm{NDVI_{min}}$, and $\mathrm{NDVI_{max}}$ are the seasonal average of smoothed weekly NDVI, its multi-year absolute minimum and its maximum, respectively. We have taken NOAA AVHRR NDVI product for the period 1984–2003 from Distributed Active Archive Centre (DAAC) at the Goddard Space Flight Centre (GSFC) (http://disc.gsfc.nasa.gov).

Vegetative drought is closely related with weather impacts. In NDVI, strong ecological component subdues the weather component. On the other hand, VCI separates the short-term weather-related NDVI fluctuations from the long-term ecosystem changes (Kogan, 1990, 1995). Therefore, while NDVI shows seasonal vegetation dynamics, VCI varies in the range 0 and 100 to reflect relative changes in the vegetation condition from extremely bad to optimal (Kogan, 1995; Kogan et al., 2003). Similarly, Temperature Condition Index represents the relative change in thermal condition in terms of brightness temperature whose values are obtained from the thermal band (Ch4) of NOAA–AVHRR. The TCI is given as:

$$\mathrm{TCI} = 100 \times \frac{\mathrm{BT_{max}} - \mathrm{BT}}{\mathrm{BT_{max}} - \mathrm{BT_{min}}} \quad (5)$$

where BT, $\mathrm{BT_{min}}$, and $\mathrm{BT_{max}}$ are the seasonal average of weekly brightness temperature, its multi-year absolute minimum, and maximum, respectively.

Higher VCI values correspond to favourable moisture condition and represent unstressed vegetation. Subtle changes in vegetation health due to thermal stress in specific could be monitored through analysis of TCI data (Kogan, 1995, 2001, 2002). While VCI and TCI characterise by varying moisture and thermal conditions of vegetation, Vegetation Health Index represents overall vegetation health which was used by Kogan (2001) who gave five classes (Table 1) of VHI that was used for drought mapping. VHI is computed and expressed as:

$$\mathrm{VHI} = 0.5(\mathrm{VCI}) + 0.5(\mathrm{TCI}) \quad (6)$$

## 4. Drought mapping

The terms 'monsoon' and 'non-monsoon' have been used for meteorological and vegetative drought analysis since it involves summing up or averaging of the monitoring parameters. For hydrological drought analysis, the terms 'pre-monsoon' and 'post-monsoon' have been used since ground-water level is measured twice a year, once before the commencement of the monsoon and again after the end of the monsoon. Thus, the non-monsoon 1984–1985 or the pre-monsoon 1985 consists of the months October–December of 1984 and January–May of 1985.

### 4.1. Mapping meteorological drought with SPI

SPI has been used to quantify the precipitation deficit in the monsoon and the non-monsoon periods from 1984 to 2003. Monthly rainfall data have been collected from Ground Water Department, Jodhpur, Rajasthan. The use of 1961–1990 thirty-year averaging period for the calculation of SPI is questionable particularly for arid regions (Agnew, 2000). Therefore, for the computation of SPI, long-term mean is calculated using seasonal rainfall data of maximum available years, i.e. of 38 years (1966–2003). Since drought is a regional phenomenon, to demarcate its spatial extent, SPI values of the 35 rain-gauge stations in and around the Aravalli region (Fig. 2a) have been interpolated using spline interpolation technique in ArcView 3.2a GIS package. Classification of SPI maps has been carried out using the method proposed by Mc Kee et al. (1995) and explained by Edwards and McKee (1997), to represent various hydro-meteorological drought intensities.

### 4.2. Mapping hydrological drought with SWI

The pre-monsoon and post-monsoon ground-water levels of 541 wells of the region (Fig. 2b) have been collected from the Ground Water Department, Jodhpur, Rajasthan, and have been analysed to study the drought effects on hydrological regime. SWI value has been classified and used as a reference to hydrological drought severity (Table 1). SWI has been computed using the mean seasonal water levels of 20 years (1984–2003). SWI values of the wells have been interpolated in a GIS environment to generate SWI maps of the region using similar technique used in SPI.

### 4.3. Mapping vegetative drought with VHI

VCI, TCI, and VHI values of the study area have been computed for the monsoon and the non-monsoon periods during the years 1984–2002 by averaging weekly values. VHI maps have been generated by plotting pixel values of VHI having 16 km spatial resolution, and have been classified to represent various drought intensities (Table 1).

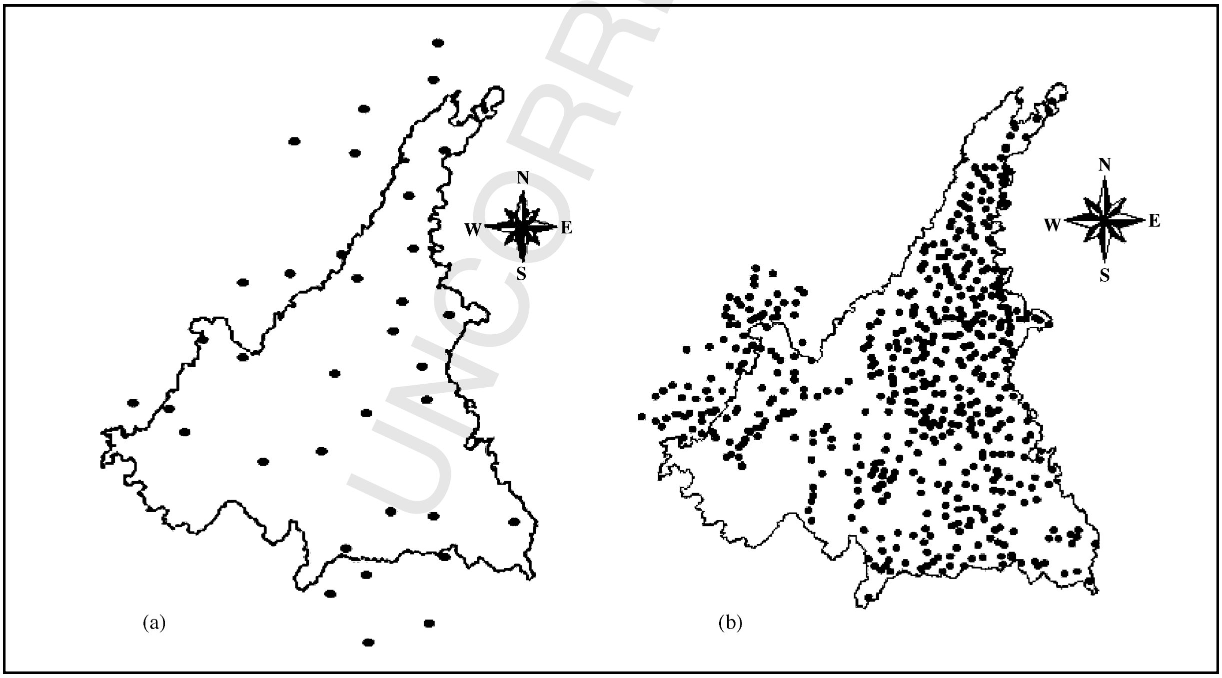


Fig. 2. (a) Rain-gauge stations and (b) observation wells in and around the Aravalli.

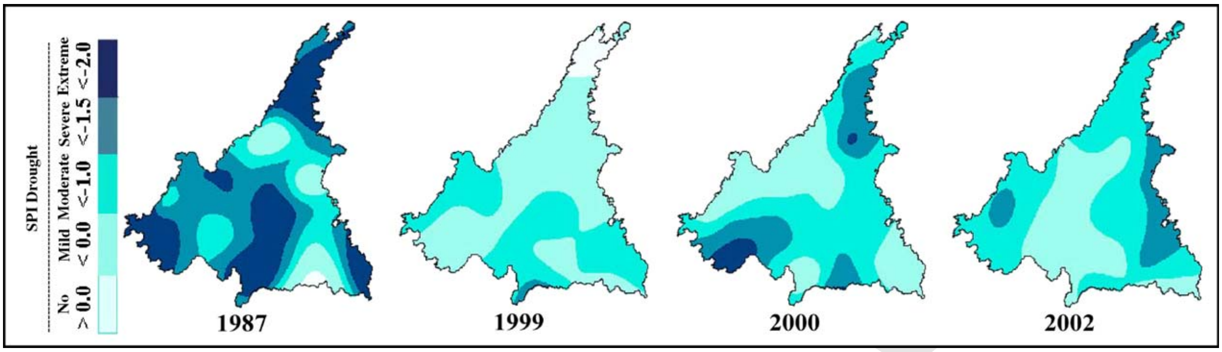


Fig. 3. Years of intense meteorological drought during monsoon.

## 5. Results and discussion

### 5.1. Meteorological drought

Severe to extreme drought occurred during 1984–1987 in discrete pockets in two seasons, during 1987 monsoon, the entire Aravalli region suffered with drought. In other years, monsoon period was mostly drought-free, moderate drought appeared in some parts of the Aravalli region during the monsoon season of 1991, 1993, 1995, and 1999. Severe drought was observed in the year 2000, when the northern, eastern,

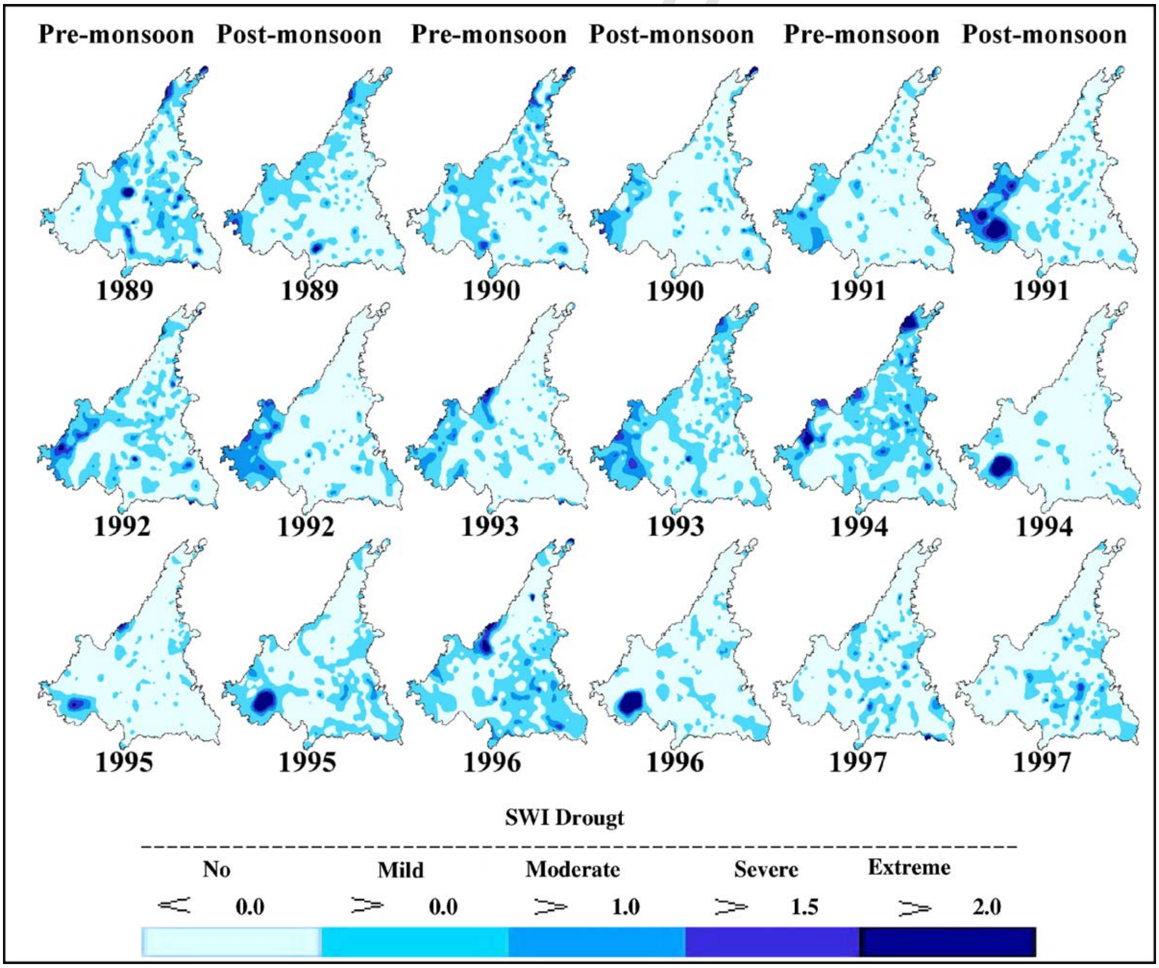


Fig. 4. Water-table depletion-zones.

southern, and southwester sectors of the province were affected by severe to extreme drought. During 2002, the monsoon was poor as a result the whole region suffered with drought. During 1999–2002, just within a span of 4 years, monsoon-drought appeared throughout the Aravalli region three times (Fig. 3). During 2002, most parts of India affected by below-average rainfall, causing the first all-India drought since 1987 ending a 14-year run of average monsoon rains. The monsoon season of 2002 was 19% drier compared to normal (Waple and Lawrimore, 2003), and as much as 60–70% below normal in whole of Rajasthan region. Monsoon-drought of 2002 was unique since rain failed in the very beginning of the season (Samra, 2002). In this year deviation from the normal rainfall was as high as −49% in Rajsamand, −67% in Sirohi, and −33% in Udaipur districts of Rajasthan province that comprise the study area (UNDP, 2002). During the non-monsoon period most parts of the Aravalli region were drought-free except some particular years. During 1984–1991, the region experienced non-monsoon drought in the alternate years, however, the intensity was mild to moderate for most parts. Various parts of the region experienced mild to moderate non-monsoonal drought during 1991–1992 and 1995–1996.

### 5.2. Hydrological drought

Decline of water level takes place in various pockets both during the monsoon and the non-monsoon periods depending upon rainfall, temperature and draft. During years 1984–1986, major parts of the Aravalli region were free from water-stress despite of poor rainfall. Except the western part, the region experienced severe water-stress during 1987 due to monsoon failure. Till the pre-monsoon of 1989, eastern Aravalli pockets experienced water-table decline but the western part was free from water-stress. The monsoon of 1989 is marked by a shift in declining trend from the east towards the west. Rainfall alone could not be responsible for this as no such shift of rainfall pattern was observed. This shift caused some western pockets

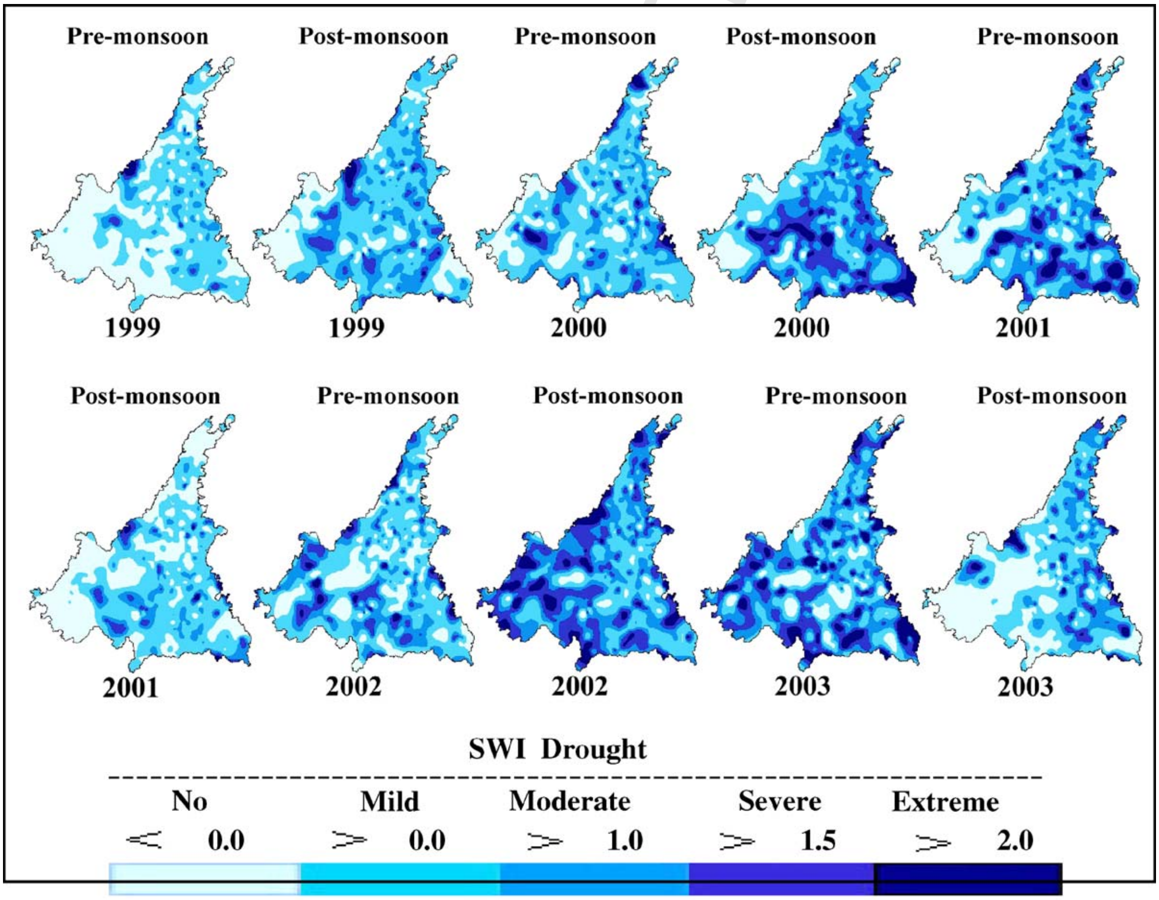


Fig. 5. Years of continuous hydrological drought.

to suffer from moderate (SWI > 1.0) to extreme (SWI > 2.0) during 1989–1996 (Fig. 4). Although discrete pockets all over the region experienced water-stress in these years, decline was not consistent in any part other than the western part. The continuous decline of the water level is supposed to be due to enormous ground-water consumption exceeding its recharge resulting negative water budget. Due to low rate of ground-water recharge and higher rate of consumption, restoration of ground-water level generally takes a long time (Kondoh et al., 2004). Severe hydrological drought appeared in the region during 1999–2003 as rain-clouds failed to precipitate (Fig. 5). As revealed by the post-monsoon ground-water level, the drought condition was worst during the monsoon of 2002, when most of the wells and reservoirs dried up. In Rajsamand, Sirohi and Udaipur districts 21 of 33 reservoirs/tanks became dry in 2002 during the monsoon (UNDP, 2002).

### 5.3. Vegetative drought

The annual cycle of vegetation in Rajasthan state is bimodal in contrast with the unimodal rainfall regime (Doi, 2001). During 1984 and prior to the 1985 monsoon, the Aravalli region shows normal vegetation (VHI > 40). During the monsoon of 1985, the vegetation experienced stress and loss of vegetation health. The region experienced exceptionally a continuous drought spell since the monsoon of 1985 until the commencement of monsoon in 1988 owing to poor rainfall in three consecutive monsoon and one intermediate non-monsoon seasons (Fig. 6). The worst situation was encountered during the 1987 monsoon when the whole region suffered with the severe to extreme vegetative drought (VHI < 20) due to extreme rainfall deficiency. The region was almost drought-free in the following years, and mild to moderate droughts appeared in certain seasons locally. Drought appeared all over the Aravalli region again during the monsoon of 2000, after a gap of 9 years. During 2000–2002 the region was affected by drought (10 < VHI < 40) owing to poor rainfall and water-stress (Fig. 7). During 2002, vegetation in the Aravalli region similar to most north-western parts of India experienced stress (VHI < 20) dew to deficient monsoon (Singh and Kogan, 2002). Agricultural practices, particularly timing of sowing

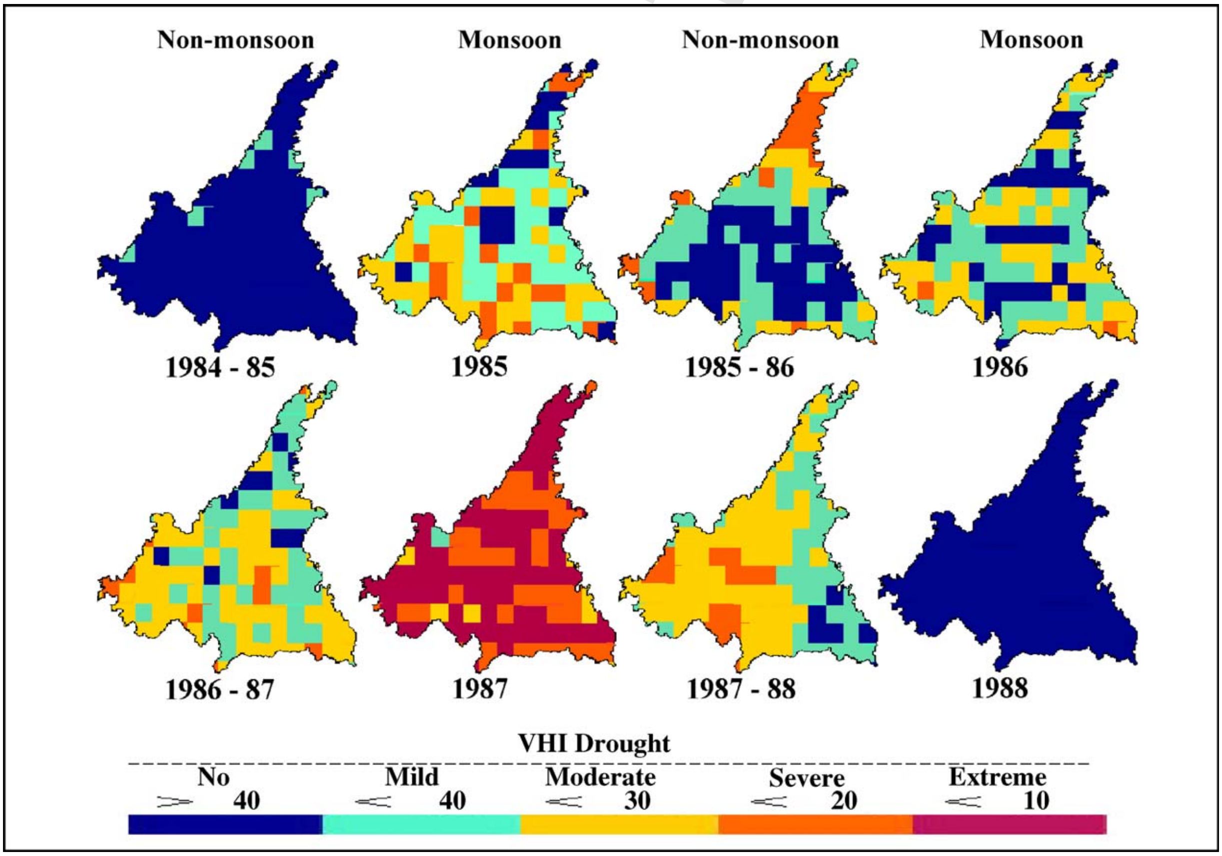


Fig. 6. Vegetative-drought dynamics during 1984–1988.

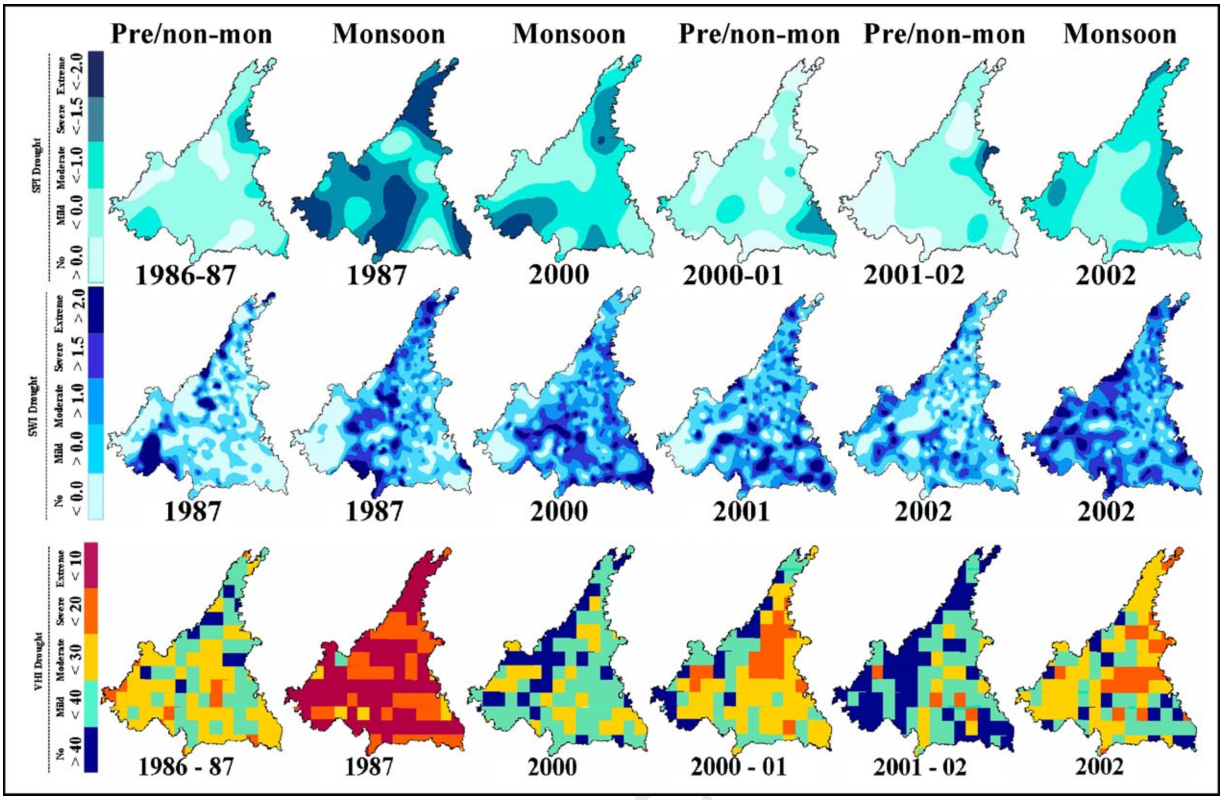


Fig. 7. Years of good correlation among SPI, SWI, and VHI.

and harvesting has a significant bearing in shaping the NDVI patterns (Doi, 2001). The agriculture was severely affected during the year 2002, since crops could not be sown at all due to failure of rainfall-commencement (Samra, 2002). Estimated damage of actual crop-area percentage in the Rajsamand, Sirohi and Udaipur districts comprising the study area during the monsoon of 2002 are 85, 50, and 25%, respectively, owing to drought (UNDP, 2002).

### 5.4. Relative drought dynamics

SPI maps indicate that meteorological drought in the Aravalli region appears randomly in both the monsoon and non-monsoon seasons. Irregular drought pattern in this region is due to inconsistent rainfall distribution (Fig. 8). Meteorological drought scenario in the region changed continuously with season depending upon rainfall amount and spatial distribution. Again, since drought is not persistent to any particular sector for more than two consecutive monsoon or non-monsoon seasons, no ‘drought zone’ can be delineated.

Drought in the ground-water system develops only slowly from meteorological droughts through recharge-deficit, and over-exploitation of ground-water resources further enhances (Peters et al., 2003). During 1984–2003, the depleting trend of water table shifted periodically from the east towards the west and vice versa (Fig. 9). However, certain pockets particularly in the western sector continue to suffer from water-stress for a long duration irrespective of good or poor rainfall.

Vegetative drought neither follows any spatio-temporal pattern nor shows a linear relationship with meteorological and/or hydrological droughts. An earlier study by Singh et al. (2003) failed to find any direct relationship among VCI, TCI, and precipitation. Good correlation however has been observed between SPI and VHI (Fig. 10) during the monsoon season (1985, 1986, 1987, 1990, and 1994) and between SWI and VHI in certain years during the non-monsoon season (1985–1986, 1989–1990, 1994–1995, 1995–1996, and 1996–1997) (Fig. 11). The reason could be that in the Aravalli region rain, 90% of the annual rainfall occurs during the monsoon, directly supporting Kharif cropping that covers 65% of annual cultivation, whereas in the non-monsoon period agriculture is entirely dependent on irrigation from ground-water resources. Therefore, during monsoon vegetation health is dependent on

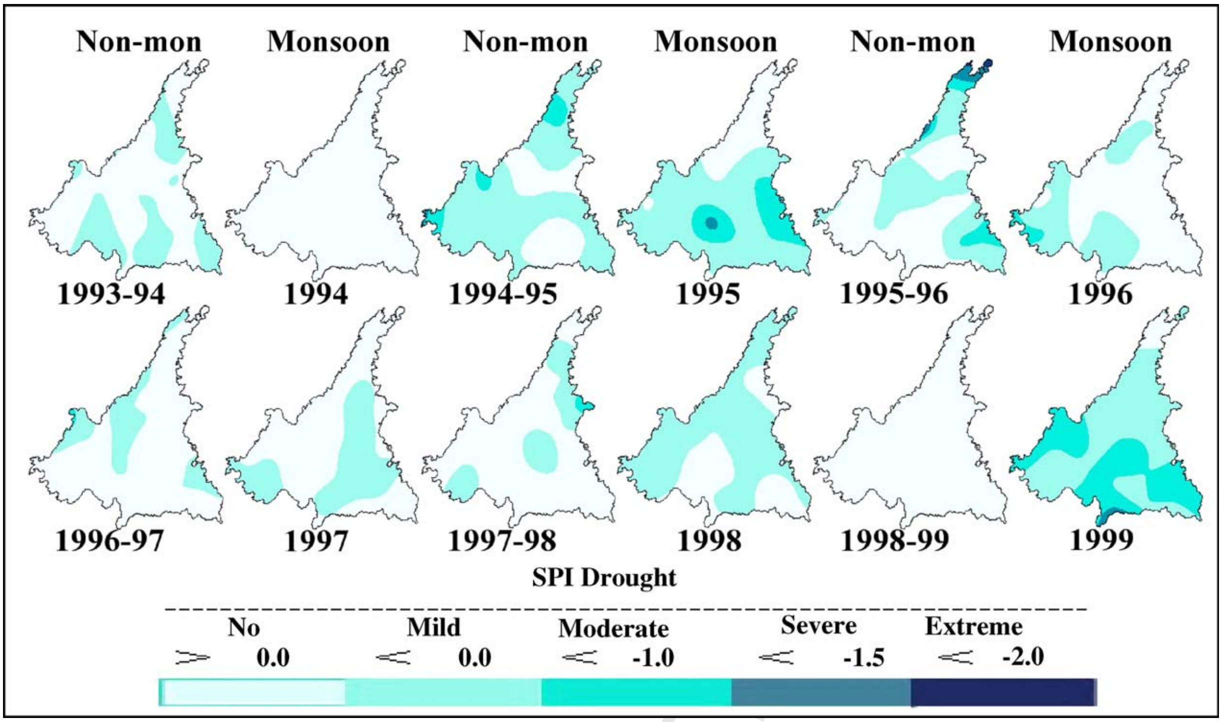


Fig. 8. Irregular meteorological drought.

rainfall but in between termination of one monsoon and commencement of the next, it is controlled by irrigation through ground water. In certain years, reasonably good match is observed among all three drought indices—SPI, SWI, and VHI (Fig. 7).

Drought impacts are usually first apparent in agriculture (Komuscu, 1999). However, the VHI maps reveal that although vegetation growth and health is dependent on water supply either by rainfall or by irrigation, vegetation in the Aravalli region could withstand adverse meteorological and hydrological conditions and maintained normal vegetation health for several seasons in spite of poor rainfall or water-stress (Fig. 12).

Analysis, correlation and comparison amongst SPI, SWI, and VHI maps indicate that a deficient rainfall as per the SPI index does not always correspond to hydrological or vegetative drought. On the contrary, drought may appear in the hydrological and vegetative spheres inspite of normal rainfall according to SPI. The lack of correspondence of hydrological and vegetative drought with SPI is more prominent during the non-monsoon season (Fig. 13).

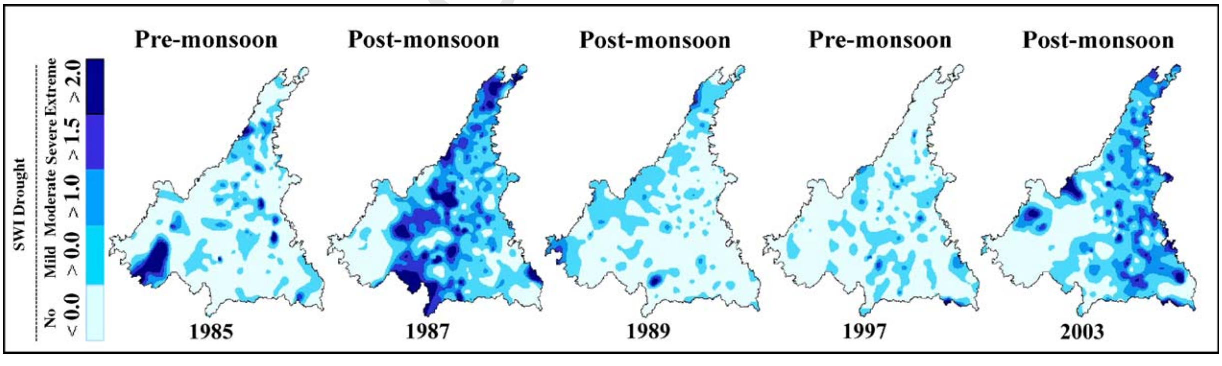


Fig. 9. Spatio-temporal shift of hydrological drought.

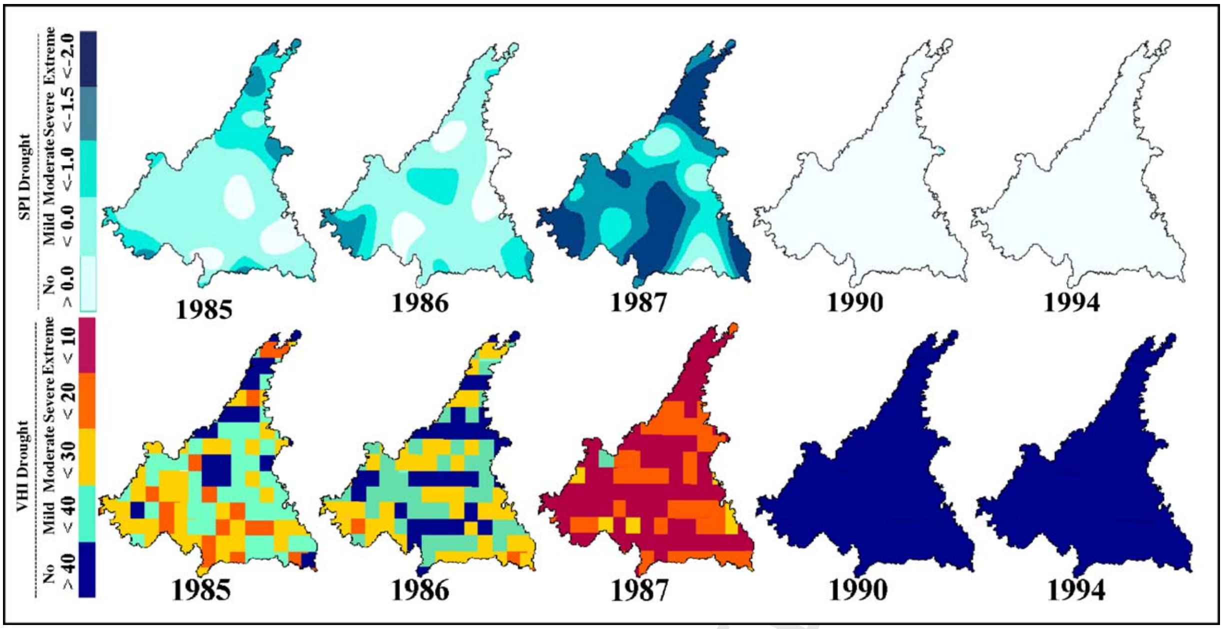


Fig. 10. Correlation between monsoonal SPI and VHI.

## 6. Conclusions

The SPI maps indicate that meteorological drought appears in the Aravalli region in a random fashion, in either seasons and in some years in both the seasons. However, seasonal meteorological drought has a short life span. The SWI maps reveal that in the Aravalli region aquifer-stress shifts its position time to time and the migration is alternate from east to west and vice versa. In comparison to hydrological stress, vegetative stress in the Aravalli region is slower to begin but quicker to withdraw. Vegetation generally maintains

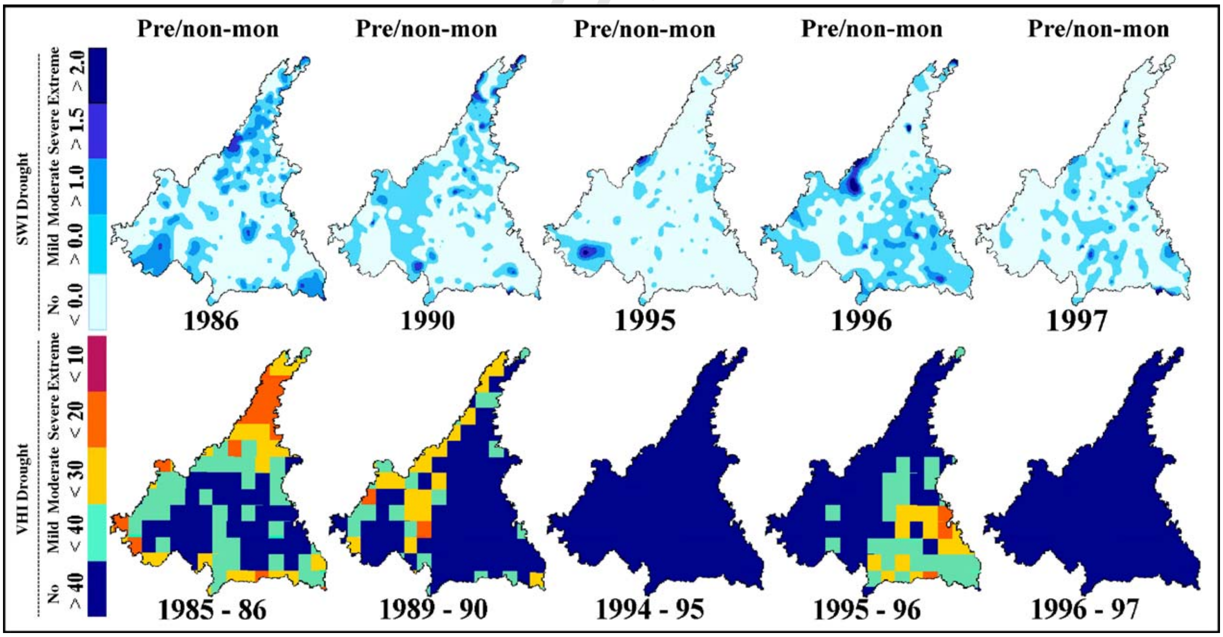


Fig. 11. Correlation between non-monsoonal SWI and VHI.

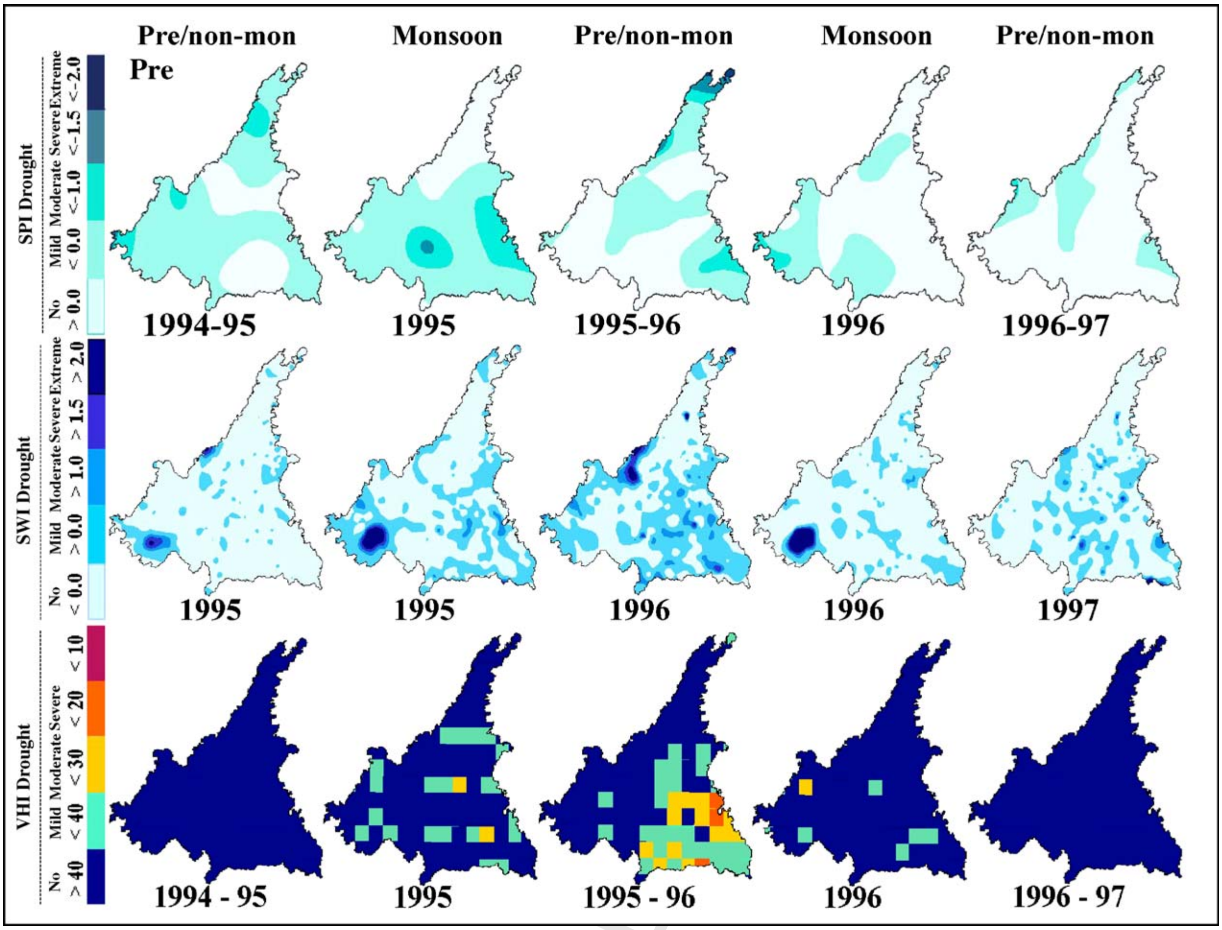


Fig. 12. Resistance of vegetation to adverse hydro-meteorological condition.

normal health for longer duration. There are some hydrological stress-zones and drought prone areas. However, no meteorological or vegetative drought-zones could be demarcated.

The time-series maps of different droughts reveal no linear correlation among meteorological, hydrological, and vegetative droughts in the Aravalli region. Moreover, speed of drought development and drought duration also varies widely. Therefore, identification, classification, and analysis of drought dynamics are highly influenced by the monitoring parameters. Natural hazards refer to the adverse impacts on natural spheres and not to the causes for the impacts. SPI monitors precipitation deficit, the primary cause for drought development but takes no account of the impact. Despite of negative SPI, a region could be free from water-stress and might maintain normal vegetation. Thus, negative SPI anomalies not always correspond to drought. On the contrary, drought may appear in hydrologic and vegetative spheres inspite of positive SPI. Besides, SPI classification schemes rely on the assumption of drought to follow the scale of probability and normal statistics which is debatable. SWI and VHI, however, represent the negative impact of adverse meteorological and hydrological conditions on water and vegetation, therefore SWI and VHI present better picture of drought.

## Uncited references

Kroll and Vogel (2002), Samra (2004), Wu et al. (1997), Yue and Pilon (2005), Yevjevich (1972), Zhou and Wang (2003).

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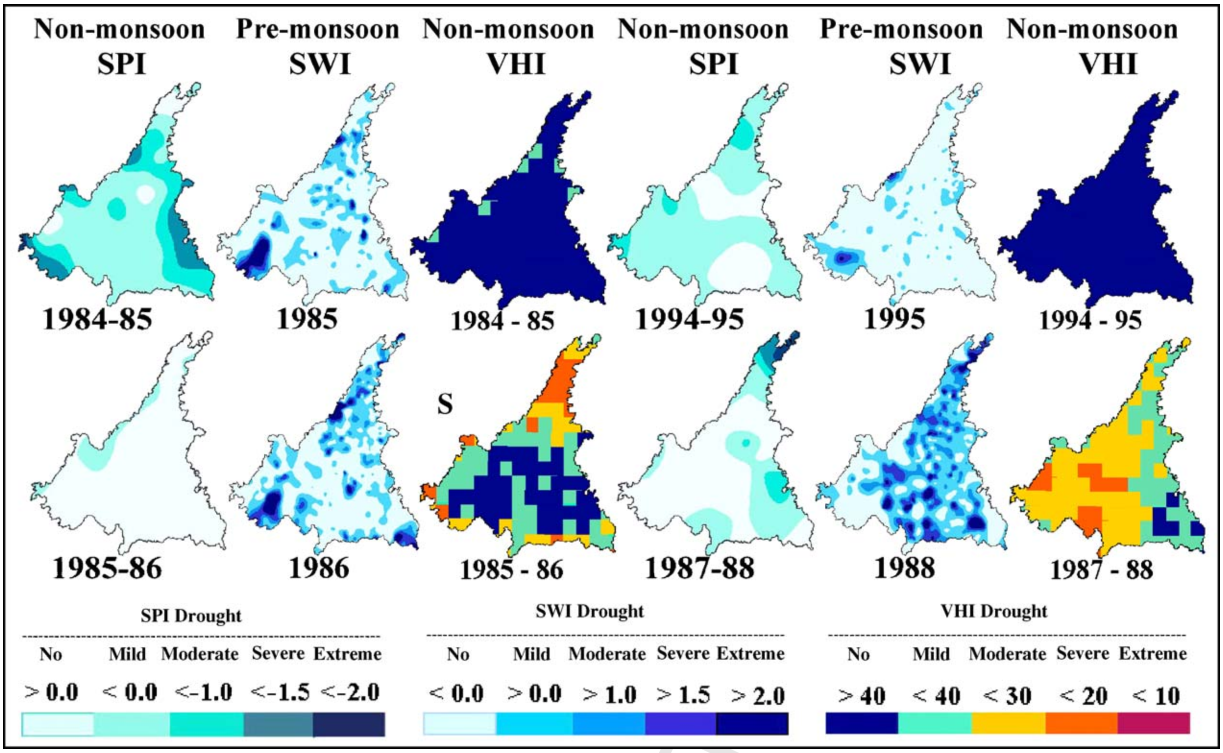


Fig. 13. Failure of SPI to correspond with hydrological and vegetative droughts.

hydrological data used in the present study. We are grateful to the two reviewers for giving their suggestions that have helped us to improve the original version of the paper.

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