Various Drought Indices For Monitoring Drought Condition In Aravalli Terrain Of India

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ABSTRACT:

Drought is a natural hazard that has significant impact on economic, agricultural, environmental, and social aspects. The western regions of India (Rajasthan and Gujarat provinces) have suffered with severe droughts at many times in the past. The frequent occurrence of drought in these regions is due to poor and untimely monsoon, abnormally high temperature especially in the summer and various other unfavourable meteorological conditions. Further, due to growing use of water with growing population, the ground water level is found to be continuously declining. The Aravalli region of southern Rajasthan is covered by hard rock and irregular topography with average elevation of 550 m. In the present work, multi-sensors data have been used to deduce surface and meteorological parameters (vegetation index, temperature, evapotranspiration) of Aravalli region for the years 1984 - 2000 together with actual ground data (rainfall, temperature, ground water level) for detailed drought analysis. Using various surface and meteorological parameters, numerous drought indices have been computed and maps of various drought indices have been generated through GIS based interpolation. The Standardised Precipitation Index (SPI) has been used to quantify the precipitation deficit. A Standardised Water-level Index (SWI) has been developed to assess ground water recharge deficit. Vegetative drought index has been calculated using NDVI values obtained from Global Vegetation Index (GVI) of NOAA AVHRR data. Spatial and temporal variations in meteorological, hydrological, and vegetative droughts in the Aravalli terrain have been analysed and correlated for monsoon and non-monsoon seasons during the years 1984 -2000. The results show that none of the drought indices follows any particular spatial and temporal patterns in this hilly terrain of western Indian region. The detailed analysis reveals that meteorological, hydrological and vegetative droughts are not linearly inter related. These indices have been further compared with the vegetation and temperature condition indices approach followed by NOAA. The study shows that combination of various indices offer better understanding and better monitoring of drought conditions for hilly, semi-arid terrain like Aravalli of western India.

1. INTRODUCTION

Drought is a disastrous natural phenomenon that has significant impact on socio-economic, agricultural, and environmental spheres. It differs from other natural hazards by its slow accumulating process and its indefinite commencement and termination. Being a slow process although drought often fails to draw the attention of the world community, its impact persists even after ending of the event. A single definition of drought applicable to all spheres is difficult to formulate since concept, observational parameters and measurement procedures are different for experts of different fields. Beside, the concept of drought varies among regions of differing climates (Dracup *et al.*, 1980). In general, drought gives an impression of water scarcity resulted due to insufficient precipitation, high evapotranspiration, and over-exploitation of water resources or combination of these parameters. There are various methods and indices for drought analysis and they measure different drought-causative and drought-responsive parameters, and identify and classify drought accordingly. However, since these parameters are not linearly correlated with each other, correlation among various kinds of drought is also difficult.

Rainfall has a direct impact on water resources, particularly in hard-rock hilly terrains like the Aravalli of semi-arid western India where monsoon-rainfall is the only possible mean for ground water recharge. A continuous spell of poor rainfall in successive years in combination with high temperature affects ground water recharge and imparts stress on ground water resources leading to severe drought in many parts of this terrain.

The present study aims to analyse the effects of precipitation on aquifer recharge and vegetation of the Aravalli terrain. In the present study, regional aspect of drought has been addressed. Spatiotemporal variation of seasonal drought patterns and drought severity in the Aravalli Terrain has been analysed using Geographic Information Systems (GIS) through various popular and widely used drought indices. Since aquifer-recharge, agricultural activities, and ecological changes in the Aravalli terrain are controlled by the monsoon rain, the present study of drought analysis has been carried out season wise – the monsoon and the non-monsoon or pre-monsoon. Standardised Precipitation Index (SPI) has been used to monitor meteorological drought. SPI offers a quick, handy, simple approach with minimal data requirements (Komuscu, 1999). Standardised Water-level Index (SWI) has been developed for efficient analysis of 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 in the terrain.

The pictorial results generated through various drought indices have been studied, analysed, compared, and correlated. Beside drought intensity, drought duration in different parts of the terrain has been monitored and interpreted through visual observation of the resultant maps. Drought frequency and speed of drought development in hydrosphere and biosphere has also been monitored and analysed. An attempt has been made in this paper to provide a comprehensive idea of drought through interpretation and correlation of various drought parameters.

2. THE STUDY AREA

The Aravalli Range, one of the oldest mountain ranges of the world stretches itself from northern Gujarat to central Rajasthan states of India, running through more than 700 km. distance and covering nearly 40,000 sq. km. area to separate 'Thar', the Great Indian Desert from the eastern plain land. The study area (latitude N23º30′- N26º18′ and longitude E72º24′-E74º36′) comprises of about 25,000 km^2 of the main block of the Aravalli Range (Figure 1). The terrain exhibits a semi-arid climate with high heat flow during summer.

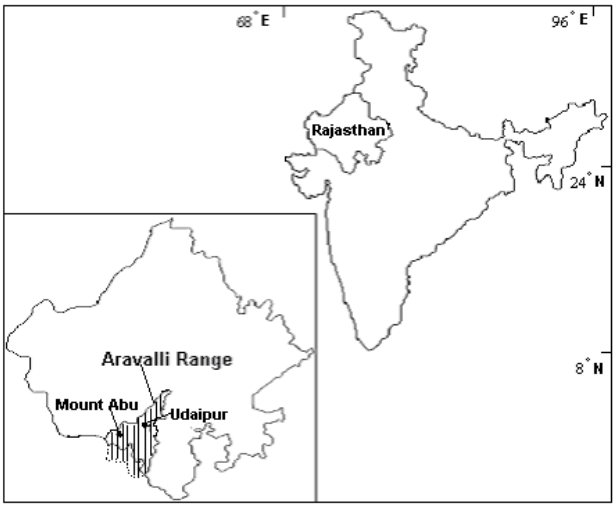

Figure 1

Rainfall occurs mainly during June – September through the monsoon wind; non-monsoon rainfall is limited and irregular. Therefore, water resources, vegetation and agriculture are under control of the monsoon. The ground water condition in this terrain varies from place to place due to variations in soil, lithology, land-use, geomorphology, topography and climatic conditions. Gneiss and schist covers most parts in the north, central and southeast of the terrain, whereas phyllites and phyllitic-schist is dominant in the south, southcentral and some pockets of the eastern Aravalli. Western part of the terrain is composed mainly of granite and quartzite along with calcite-schist as the subordinate rock type (DST, 1994). The normal water table depth also varies in different lithologic domains. In general, ground water fluctuates seasonally within the range of 5m to 20 m (GWD, 2000). In the Aravalli region, agricultural activities are influenced and controlled by rainfall and availability of water resources. Monsoon crops or Kharif crops are cultivated during June to September whereas winter crops or Rabi crops are sewed in the middle of October and harvested in March. In many parts of the region, summer crops and vegetables are cultivated during March – May depending upon availability of water. Double cropping is practiced in some parts whereas many pockets have uncultivated fallow land.

3. DROUGHT INDICES

In the present paper, spatiotemporal patterns of seasonal drought indicated through meteorological, hydrological, and vegetative parameters have been discussed. Analysis has been carried out by dividing the year into two main seasons – the monsoon and the non-monsoon or pre-monsoon since drought in the study area is a function of the monsoon rainfall. The monsoon period consists of four months from June to September while non-monsoon or pre-monsoon period is constituted of the months, intermediate of two successive monsoon periods. Thus, the non-monsoon 1984 - 85 or the pre-monsoon 1985 consists of the months October – December of 1984 and January – May of 1985 and so on. The term 'non-monsoon' has been used for meteorological and vegetative drought analysis since they incorporate all the non-monsoon months. On the other hand, the term 'pre-monsoon' has been used for hydrological drought analysis since ground water level is measured twice a year, once before the commencement of the monsoon and again after the termination of the monsoon.

2.1 Standardised Precipitation Index (SPI)

In order to analyse the impact of rainfall deficiency on drought development in this terrain, SPI has been used to quantify the precipitation deficit in the monsoon and the non-monsoon periods since 1984 up to 2000. The SPI is calculated using the following equation, written as

$$SPI = (X_{ij} - X_{im}) / \sigma \tag{1}$$

where, X_{ij} is the seasonal precipitation at the ith rain-gauge station and jth observation, X_{im} is its long-term seasonal mean and σ is its standard deviation.

Although McKee *et al.*, (1995) in the original classification scheme proposed 'mild drought' for SPI values less than 0.00, in the modified SPI classification scheme of Agnew (1999), there is a straight jump from 'no drought' to 'moderate drought'. In the present study, SPI maps have been classified using the modified scheme of Agnew (1999) to represent various hydro-meteorological drought intensities, however, 'mild drought' has been recognised corresponding to the SPI values less than -0.50, which has a probability of occurrence 0.309 (Agnew, 1999). Seasonal normals of 35 years (1966 – 2000) have been used for calculation of SPI. Instead of averaging anomalies for the entire terrain, SPI has been computed separately for each of the 35 rain-gauge stations falling within and around the study area. Since drought is a regional phenomenon, SPI values of the rain-gauge stations have been interpolated using *Spline* interpolation technique in Arc view 3.2a GIS to demarcate its spatial extent.

2.2 Standardised Water level Index (SWI)

For hydrological drought analysis, examination of stream-flow statistics and run series analysis is the widely used technique. However, since the streams and channels of the Aravalli terrain are dry for most of the time and since domestic and agricultural activities are solely dependent on ground water resources, monitoring and analysis of water table fluctuation has been considered for hydrological drought analysis. In order to monitor hydrological drought in the Aravalli terrain, the pre-monsoon and post-monsoon ground water levels of 541 wells of the region have been analysed. SWI has been developed to scale the ground water recharge deficit. The SWI expression stands as

$$SWI = (W_{ij} - W_{im}) / \sigma \tag{2}$$

where W_{ij} is the seasonal water level for the ith well and jth observation, W_{im} its seasonal mean, and σ is its standard deviation.

SWI value has been classified and used as a measure of hydrological drought intensity. Since ground water level is measured down from the surface, positive anomalies correspond to drought and negative anomalies correspond to 'no-drought' or normal condition. Point values of SWI corresponding to the wells have been interpolated to generate SWI maps of the region using the same technique as for SPI.

2.3 Vegetation Indices

Vegetative and agricultural droughts reflect vegetation stress. 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. It is expressed as

$$NDVI = (Ch2 - Ch1) / (Ch2 + Ch1) \quad (3)$$

VCI, TCI, and VHI have been developed further using the following equations as

$$VCI = 100*(NDVI - NDVI_{min}) / (NDVI_{max} - NDVI_{min}) \quad (4)$$
$$TCI = 100*(BT_{max} - BT) / (BT_{max} - BT_{min}) \quad (5)$$
$$VHI = 0.5(VCI) + 0.5(TCI) \quad (6)$$

where NDVI, $NDVI_{min}$, and $NDVI_{max}$ are the seasonal average of smoothed weekly NDVI, its multiyear absolute minimum and its maximum respectively; BT, BT_{min}, and BT_{max} are similar values for brightness temperature (Kogan, 2001).

Brightness temperature values are obtained from the thermal band (Ch4) of NOAA-AVHRR. NDVI generally provides a broad overview of the vegetation condition and spatial vegetation distribution in a region. Vegetative drought is closely related with weather impacts. However, in NDVI, the weather component gets subdued by strong ecological component. 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 rescales vegetation dynamics in between 0 and 100 to reflect relative changes in the vegetation condition from extremely bad to optimal (Kogan, 1995, 2003). VCI and TCI characterises respectively the moisture condition and thermal condition of vegetation while VHI represents overall vegetation health (Kogan, 2001). Since favourable weather provides optimal moisture condition, high values of VCI correspond to healthy and unstressed vegetation. On the other hand, low TCI values correspond to vegetation stress due to dryness by high temperature. TCI provides opportunity to identify subtle changes in vegetation health due to thermal effect as drought proliferates if moisture shortage is accompanied by high temperature (Kogan, 2002). During calculation of VHI, an equal weight has been assumed and assigned to both VCI and TCI since moisture and temperature contribution during a vegetation cycle is currently not known (Kogan, 2001). Regional VHI maps have been generated through interpolation of the point values and classified using the scheme developed by Kogan (2002) and further modified*. VCI and TCI have been classified following the same scheme as VHI. Kogan (1995, 2001, 2003) formulated, calculated, and applied VCI, TCI, and VHI based on smoothed weekly NDVI and BT values. However, in the present study all these parameters have been calculated and analysed season wise by averaging weekly values. For comparison and correlation among different kinds of drought, SPI, SWI, and VHI maps of the same years have been displayed one beneath the other (Figure 5).

3. DROUGHT IN THE ARAVALLI TERRAIN

3.1 Meteorological Drought

Visual observation of the time series SPI maps of the monsoon and non-monsoon periods indicate that drought is frequent and even persistent in many parts of the Aravalli terrain. They further show that meteorological drought scenario in the terrain changed continuously with season. Beside years with exceptional good non-monsoon rainfall, Aravalli terrain regularly experienced mild drought for most of its parts in the non-monsoon period. The condition returns to normalcy if the monsoon wind appears timely and showers heavily. Spatio-temporal drought scenario in the Aravalli terrain in both the monsoon and the non-monsoon periods fallows an erratic pattern due to inconsistent and unstable rainfall pattern (Bhuiyan *et al.*, 2004).
During the years 1984 - 1985, insufficient rainfall resulted seasonal drought in some pockets of northern and southwestern Aravalli. In the year 1986 drought resulted in those province during both the monsoon and non-monsoon seasons. Poor monsoon visited the Aravalli terrain in succession in the year 1987 resulting severe drought in major sectors in the north and south. Some small pockets in the north, south, and central parts suffered even extreme drought. The drought condition improved and worsened alternatively in the monsoon and non-monsoon periods respectively during the years 1988 - 90. Although good monsoon rainfall helped most parts of the terrain to avoid drought in the year 1992, some pockets in the north, south, east, and west of the terrain experienced drought during 1992 – 1993 non-monsoon and 1993 monsoon seasons. In the year 1995, moderate drought affected some pockets in the eastern and southern sectors, while during the non-monsoon period drought appeared in the northern and eastern Aravalli. However, it was the western Aravalli experiencing drought during 1996 monsoon! The drought reappeared in the terrain during the monsoon of 1999 too but the situation became worst during the monsoon season of 2000, when northern, eastern, southern, and southwestern sectors of the province formed a continuous drought-belt (Figure 5).

3.2 Hydrological Drought

Time series analysis of SWI maps reveals that hydrological drought in the Aravalli terrain during both the pre-monsoon and post-monsoon periods follow an alternate pattern with minor local variations. During the pre-monsoon period, many discrete pockets all over the terrain experienced moderate to extreme hydrological droughts in last two decades. Although during the years 1984 – 1985, major parts of the terrain were free from drought, the drought situation degraded gradually in the following years.

* *Through personal communication*

In the year 1986, post-monsoon water level was normal or near normal in major parts of the terrain except some discrete pockets in the west, and south. Before commencement of the 1987 monsoon, many regions all over the terrain were hit by mild drought and one major pocket in the south-west suffered from extreme hydrological drought. The drought situation further aggravated during the monsoon period of 1987, when except the western sector rest of the terrain was affected by moderate to severe hydrological drought. Except the western sector, the terrain underwent a temporary recovery from the water stress during the monsoon of 1989. The year 1989 is also marked by a shift in drought from the east towards the west. This shift in drought pattern caused some western pockets to suffer from moderate to extreme droughts consistently since 1989 until 1996. Since the year 1997, the drought shifted again from the west towards the eastern parts of the terrain (Figure 2).

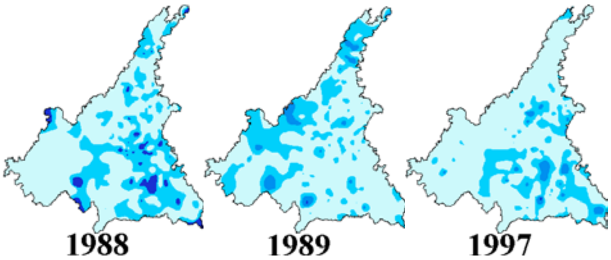

Figure 2

The drought condition worsened gradually from the pre-monsoon of 1998 onwards, and in the post-monsoon period of 2000, almost the entire terrain was in the grief of acute drought. The SWI maps show that some pockets particularly in the western sector of the terrain frequently suffered from water stress either in the monsoon or non-monsoon period (Figure 3 & 5) or in both seasons (Figure 5).

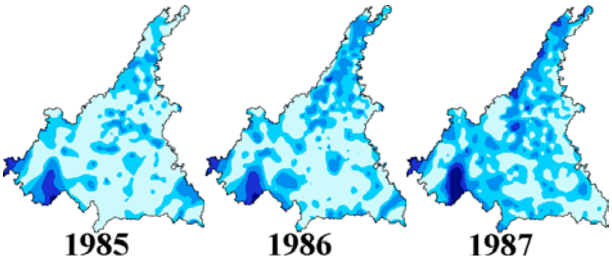

Figure 3

3.3 Vegetative Drought

Vegetative drought as observed and understood through NDVI, VCI, TCI, and VHI implies that like meteorological drought, it also appears in the Aravalli province in irregular pattern. Major parts of the Aravalli terrain show favourable vegetation condition for most of the years under consideration. There is no direct relationship among VCI, TCI, and precipitation (Singh *et al.*, 2003). Extremely unhealthy vegetation (very low VHI) is generally associated with severe moisture (low VCI) and thermal stress (low TCI) and vice versa. However, vegetation health could be represented by many other combinations of VCI and TCI. For example, in the year 1993 inspite of thermal stress (magenta, light, and dark orange) the entire Aravalli terrain could maintain healthy vegetation due to extremely favourable moisture condition. On the contrary, good vegetation health was maintained in the next year too inspite of extreme moisture stress (yellow, orange and red), this time due to optimal thermal condition (Figure 4).

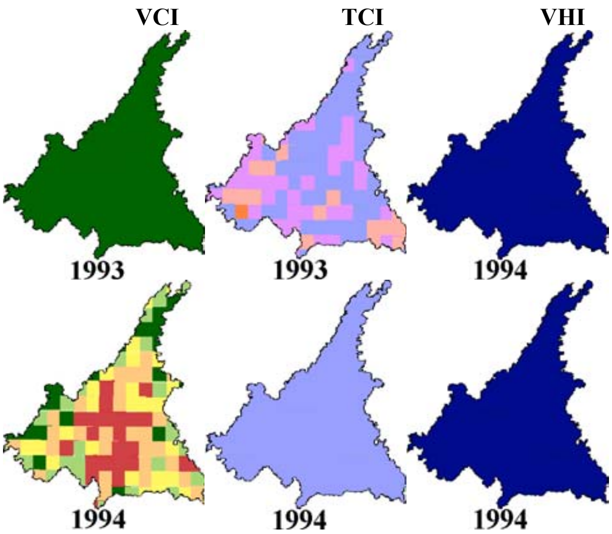

Figure 4

The Aravalli terrain experienced vegetative drought for the three consecutive years of 1985, 1986 and 1987 before regaining back vegetation health during the monsoon of 1988. The vegetation stress reached culmination in the year 1987 when almost the entire terrain suffered from severe to extreme vegetative degradation. Vegetation suffered mild stress in the years 1989, 1991, 1992, and 1995 but only in some pockets. In both the seasons of the intermediate years, vegetation in the Aravalli terrain was free of stress. Vegetation in some discrete pockets all over the terrain was under stress again during the monsoon period of 2000.

3.4 Comparison and Correlation

Precipitation and evapotranspiration are the chief causative parameters while water level is the main responsive parameter of drought. Vegetative drought is a manifestation of meteorological and hydrological droughts. The time-series drought maps generated through various drought indices indicate that meteorological, hydrological and vegetative droughts in the Aravalli terrain are not linearly correlated with one another. Moreover, speed of drought development and drought duration are also different in different spheres. Therefore, it is quite 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.

During the years 1986 - 1987, insufficient rainfall in both the monsoon and non-monsoon periods gradually resulted severe meteorological and hydrological droughts in almost the entire terrain except some pockets. Gradual development of meteorological and hydrological drought in turn imparted extreme stress on vegetation health resulting acute vegetative drought during the monsoon of 1987 (Figure 5). In the year 1992, the entire terrain received good monsoon rainfall. Deficiency in rainfall during non-monsoon period has resulted water stress in the western sectors. Hydrological drought covered more area during the monsoon of 1993 inspite of good rainfall. Vegetation enjoyed an excellent health owing to the support of good monsoon. In the year 1995, monsoon rainfall was better in the western sector than the east.

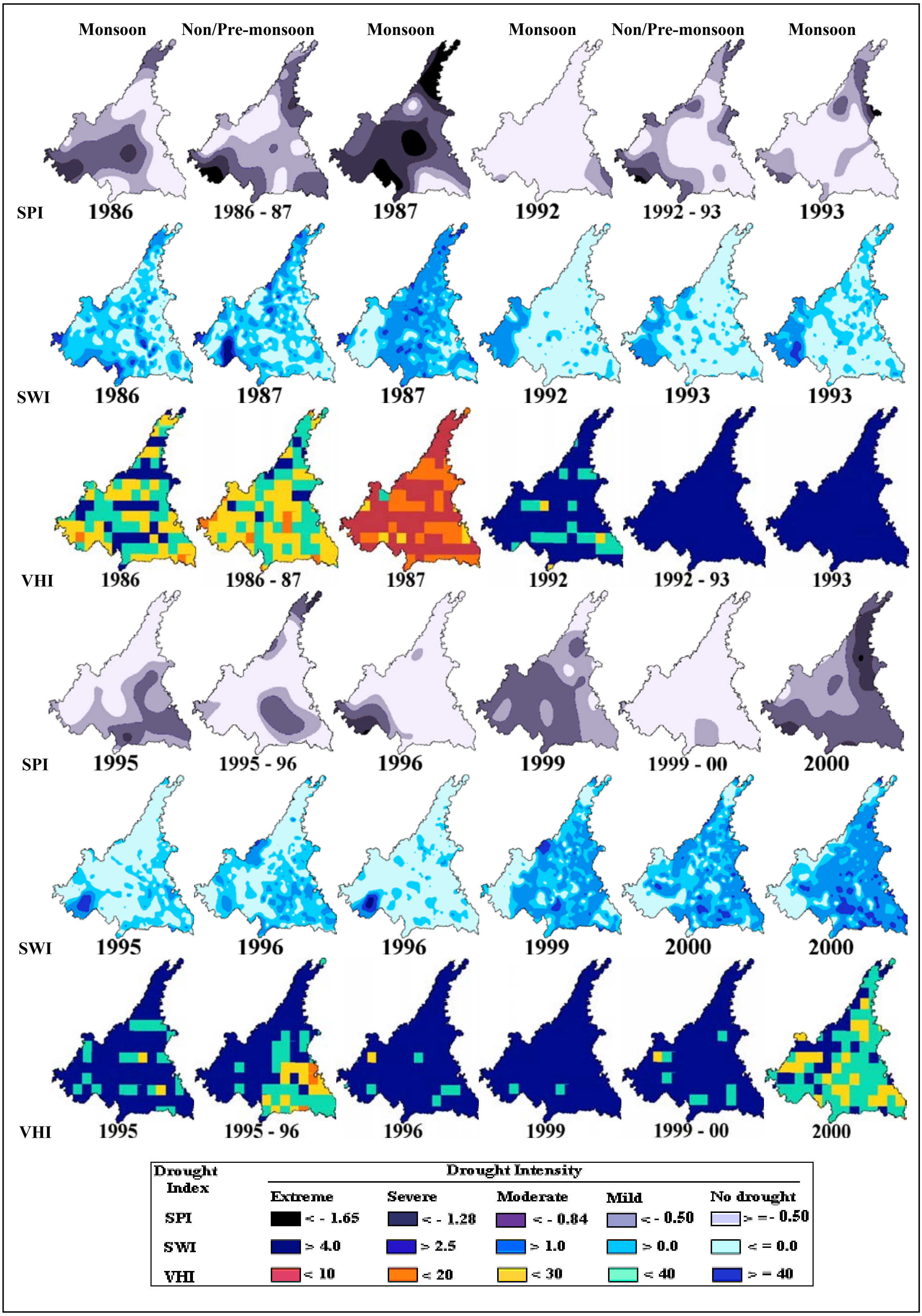
Monsoon
Non/Pre-monsoon
Monsoon
Monsoon
Non/Pre-monsoon
Monsoon
SPI
1986
1986 - 87
1987
1992
1992 - 93
1993
SWI
1986
1987
1987
1992
1993
1993
VHI
1986
1986 - 87
1987
1992
1992 - 93
1993
SPI
1995
1995 - 96
1996
1999
1999 - 00
2000
SWI
1995
1996
1996
1999
2000
2000
VHI
1995
1995 - 96
1996
1999
1999 - 00
2000
Drought Index
Drought Intensity
Extreme
Severe
Moderate
Mild
No drought
SPI
< - 1.65
< - 1.28
< - 0.84
< - 0.50
> = - 0.50
SWI
> 4.0
> 2.5
> 1.0
> 0.0
< = 0.0
VHI
< 10
< 20
< 30
< 40
> = 40

Figure 5

On the contrary, hydrological drought intensity was reverse in the terrain while vegetation health was almost normal. During 1995 – 1996 non-monsoon season, poor rainfall imparted stress on both aquifer recharge and vegetation health, particularly in the eastern sector. Aravalli terrain received good monsoon rainfall in the year 1996 except a western pocket. As a result, the terrain was free of hydrological drought except the western pocket and normal vegetation health was regained. During 1999 – 2000, the terrain encountered two successive poor monsoons and an intermediate normal non-monsoon period. A good non-monsoon rainfall was insufficient for aquifer recharge. Consequently, hydrological stress that initiated during the monsoon of 1999 resulted severe drought all over the terrain during the monsoon of 2000. Mild to moderate vegetative drought resulted all over the terrain during the monsoon of 2000, as vegetation could not withstand the impact of two successive poor monsoons and three consecutive hydrological droughts.

4. CONCLUSIONS

The SPI maps show that meteorological drought appear in the Aravalli terrain frequently but in an irregular manner. They further reveal that meteorological drought being a function of precipitation is not partial to any particular sector of the Aravalli terrain i.e. the terrain cannot be classified into drought zones and no-drought zones based on SPI anomaly. Although 80% of the annual rainfall occurs in the monsoon season, drought visits the terrain in either seasons and in some years in both the seasons.

The SWI algorithm and classification scheme functions successfully in monitoring hydrological drought in the Aravalli terrain. The SWI maps reveal that unlike meteorological drought, hydrological drought follows some patterns in the Aravalli terrain. They further demarcate some drought zones and drought prone areas. The most remarkable discovery of the time-series maps of SWI is the alternate shift of drought and drought pattern with time.

In the Aravalli terrain, vegetative drought sets no seasonal or spatial pattern. The VHI maps indicate that vegetation growth is although dependent on water supply through rainfall and irrigation, it can withstand adverse meteorological and hydrological conditions for several seasons to maintain good vegetation health. In the Aravalli terrain, hydrological drought develops faster and recovers slower. On the contrary, vegetative drought is slow to begin but quicker to withdraw.

Drought being a natural hazard refers to the adverse impacts on natural spheres and not to the causes for the impacts. Since precipitation is the primary cause for drought development, negative SPI anomalies do not always correspond to drought in reality, as it takes no account of impact. Therefore, SWI and VHI together presents better pictures and perceptions of drought, particularly in the semi-arid terrain of Aravalli.

References from Journals:

Agnew, C. T. 2000. Using the SPI to identify drought. Drought *Network News*, 12(1), pp. 6-12.

Bhuiyan, C., Flügel, W. A., and Singh, R. P., 2004. Behavior of Ground Water Table in Response to Monsoon Rainfall in Parts of Aravalli Terrain*, J. Hydrol.* (Communicated).

Dracup, J. A., Lee, K. S., and Paulson Jr, E. G., 1980. On the Definition of Droughts. *Water Resources Research*, 16(2), pp. 297-302.

Kogan, F. N., 1990. Remote sensing of weather impacts on vegetation in non-homogeneous areas. *Int. J. Remote Sensing*, 11(8), pp. 1405-1419.

Kogan, F. N., 1995. Application of vegetation index and brightness temperature for drought detection. *Advance in Space Res*earch, 15(11), pp. 91-100.

Kogan, F. N., 2001. Operational Space Technology for Global Vegetation Assessment. *Bull. Amer. Meteor. Soc.,* 82(9), pp. 1949-1964.

Kogan, F. N., 2002. World Droughts in the New Millennium from AVHRR-based Vegetation Health Indices. *Eos, Transactions,* Amer. Geophy. Union, 83(48), pp. 562-563.

Kogan, F. N., Gitelson, A., Edige, Z., Spivak, l., and Lebed, L., 2003. AVHRR-Based Spectral Vegetation Index for Quantitative Assessment of Vegetation State and Productivity: Calibration and Validation. *Photogrammetric Engineering & Remote Sensing,* 69(8), pp. 899-906.

Komuscu, A. U., 1999. Using the SPI to Analyze Spatial and Temporal Patterns of Drought in Turkey. *Drought Network News*, 11(1), pp. 7-13.

Singh, R. P., Roy, S., and Kogan, F. N., 2003. Vegetation and temperature condition indices from NOAA-AVHRRA data for drought monitoring over India. *Int. J. Remote Sensing*, 24(22), pp. 4393-4402.

References from Books:

Department of Science and Technology (DST), Govt. of Rajasthan, India, 1994. *Resource Atlas of Rajasthan*.

ESRI, 1996*. Using Arc View GIS.*

References from Other Literatures:

Ground Water Department (GWD), Government of Rajasthan, India, 2000. *Annual Report* (Unpublished).

Mc Kee, T. B., Doesken, N. J., and Kleist, J., 1995. Drought monitoring with multiple time scales. In: *Proceedings of the Ninth Conference on Applied Climatology*, pp. 233-236. Amer. Meteor. Soc., Boston.

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