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Monsoon variation and vegetative drought patterns in the Luni Basin in the rain-shadow zone

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Drought has a significant impact on agricultural, ecological and socio-economic spheres. Poor and delayed monsoon, high temperature and insufficient water resources lead to recurrent drought in the Luni River basin located in the rain-shadow zone of western India. In the present study, monsoon variation was studied in relation to spatio-temporal patterns of vegetative drought in the Luni Basin. The Vegetation Condition Index, the Temperature Condition Index and the Vegetation Health Index derived through multi-channel data of NOAA AVHRR satellite were used for drought monitoring, and seasonal variation in rainfall and vegetation response were analysed, compared and correlated. The study finds inconsistent and erratic rainfall patterns in the Luni Basin. The monsoon variation was found to control vegetation health during the monsoon season but sometimes in the non-monsoon period too, and vegetative drought intensity and duration vary widely depending upon moisture and thermal stresses. Inertia in vegetation health is reflected in the inter-seasonal persistence of vegetative drought conditions. The study finds that a good monsoon helps in maintaining vegetation health during following seasons. On the contrary, vegetation health is found to be more sensitive to moisture and thermal stresses in the immediate season after a drought.

1. Introduction

Drought is frequent in north-western India, particularly in Rajasthan state. The region is characterized by hot, dry summers followed by a humid rainy season and dry winter. The monsoon season is three and a half months from mid-June to the end of September, when the south-westerly monsoon wind carries 90% of annual rainfall. Both natural vegetation and agricultural crops are dependent on the availability of water. While the monsoon (Kharif) crop is directly dependent on monsoon-rainfall, the winter (Rabi) crop is dependent mainly on irrigation water. The drought patterns in the regions during the monsoon (June–September) and the non-monsoon seasons (October–May) differ owing to the spatio-temporal variation of rainfall and temperature. The Luni Basin is the major fluvial basin of the Thar Desert, situated in the west and adjacent to the Aravalli terrain. The Aravalli range not only separates the desert from the eastern plains but also influences the amount and distribution of rainfall in the region. The eastern parts of the Aravalli receive higher rainfall in comparison to the rain-shadow zone to the west, including the Luni Basin. Therefore, the overall

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vegetation dynamics and drought patterns in the region are controlled by monsoon dynamics and their interaction with the Aravalli.

In the present study, monsoon variations, rainfall patterns during the monsoon and non-monsoon seasons and the consequent and subsequent response of vegetation were monitored, analysed and interpreted. For visual interpretation, recoded data of rainfall were interpolated to generate distributed rainfall maps. Vegetation responses to rainfall and vegetative drought were studied through various indices developed using remote sensing data. The results reveal some interesting relationships.

2. Study area

The Aravalli range is one of the oldest mountain ranges in the world and stretches from the northern Gujarat to central Rajasthan states of India. It acts as a barrier between the eastern plains of Malwa Plateau and western Thar Desert. The south-westerly monsoon wind collides repeatedly with the Aravalli range leading to down-pours on the eastern side of the Aravalli. The western side becomes a rain-shadow zone and receives very little rainfall and the latter only when the monsoon wind becomes weaker and lighter and able to cross the Aravalli range. The Luni Basin, which lies in the rain-shadow zone to the west of the Aravalli (figure 1), is located between latitudes 23° 41′ and 27° 05′ and longitudes 71° 04′ and 74° 42′ covering an area of 37 363 km^2. The basin is characterized by hard-rock hills of the Aravalli in the east and a gently sloping narrow alluvial plain in the west. The Luni River originates from the western slopes of the Aravalli ranges at an elevation of 772 m above mean sea level near Ajmer. It flows in a south-westerly direction, traversing 511 km in Rajasthan and finally merges into the Rann of Kachchh. The mean annual rainfall over the Luni Basin is 320 mm, ca 91% of which falls during the monsoon season. The region is also characterized by high heat-flow during the summer. The average daily surface temperature during the summer is 40° C, during the rainy season 35° C and, during winter, 10° C. The annual cycle of vegetation in Rajasthan state is bimodal in contrast with the unimodal rainfall regime (Doi 2001). Vegetation in the Luni Basin is either natural or agricultural. Natural vegetation is comprised of forests and shrubs, while agricultural crops are seasonal. Kharif crops and Rabi crops are cultivated in the monsoon and winter seasons, respectively. The region shows wide variability in the commencement of sowing as rainfall intensity and rainfall distribution varies within the crop-growing season (Mann and Singh 1977). In addition, sowing and harvesting of different crops sometimes overlap due to a shift in the arrival and retreat of the monsoon. Due to high heat-flow, scarce rainfall and inadequate water resources, the region suffers from frequent drought both during the monsoon and the non-monsoon seasons.

3. Data and methodology

3.1 *Database and sources*

Monthly rainfall data during 1983–2003 and long-term (1971–2000) mean seasonal rainfall data of 90 rain-gauge stations located within and around the Luni Basin were collected from Rajasthan Groundwater Department, Jodhpur. For analysis of vegetation health and stress, remote sensing data of channels 1, 2 and 4 of Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Administration (NOAA), with a spatial resolution of 16 km, were used to develop

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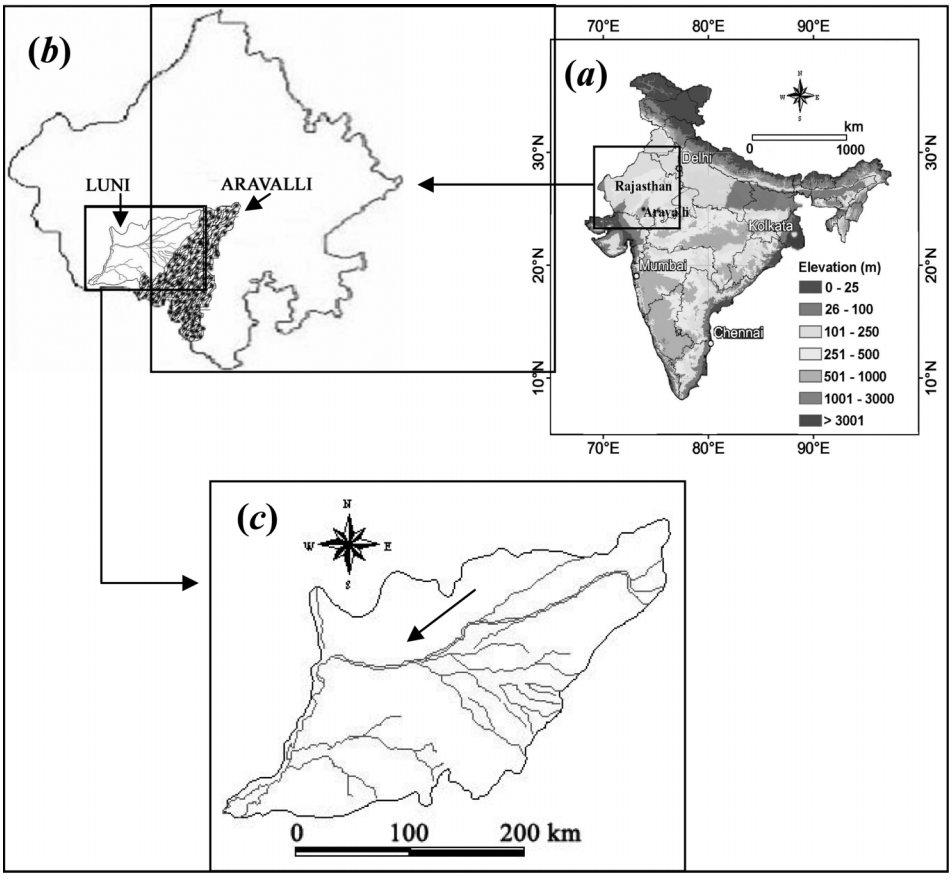

Figure 1. Study area: (*a*) India, (*b*) Rajasthan state and (*c*) the Luni River basin.

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indices such as Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), Thermal Condition Index (TCI) and Vegetation Health Index (VHI). Season-wise average values of these indices were used for mapping and monitoring of vegetation health and vegetative drought.

3.2 *Vegetative drought indices*

Vegetation experiences stress due to adverse hydroclimatic and hydrological factors. Vegetative drought appears due to gradual accumulation of vegetative stress. The NDVI reflects the vegetation condition through the ratio of responses in near-infrared (B_2) and visible (B_1) bands of NOAA-AVHRR. It is computed as:

$$\mathrm{NDVI} = (B_2 - B_1)/(B_2 + B_1) \tag{1}$$

The VCI separates the short-term weather-related NDVI fluctuations from long-term ecosystem changes (Kogan 1990, 1995). The VCI rescales vegetation dynamics between 0 and 100 to reflect relative changes in the vegetation condition from extremely bad to optimal (Kogan 1995, Kogan *et al.* 2003). Thus,

$$\mathrm{VCI} = 100((\mathrm{NDVI}) - (\mathrm{NDVI}_{\min}))/((\mathrm{NDVI}_{\max}) - (\mathrm{NDVI}_{\min})) \tag{2}$$

where NDVI, $NDVI_{min}$ and $NDVI_{max}$ are the seasonal average of smoothed weekly NDVI, its multi-year absolute minimum and its maximum, respectively.

Similarly, the TCI represents the relative change in thermal condition in terms of brightness temperature whose values are obtained from the thermal band of NOAA-AVHRR. Subtle changes in vegetation health due to thermal stress, in particular, could be monitored through analysis of the TCI data (Kogan 1995, 2001, 2002). It is expressed as:

$$\mathrm{TCI} = 100(T_{\mathrm{B_max}} - T_{\mathrm{B}})/(T_{\mathrm{B_max}} - T_{\mathrm{B_min}}) \tag{3}$$

where T_{B}, $T_{\mathrm{B_min}}$ and $T_{\mathrm{B_max}}$ are the seasonal average of weekly brightness temperature, its multi-year absolute minimum and maximum, respectively.

While the VCI and TCI characterize moisture and thermal conditions of vegetation, the VHI represents overall vegetation health (Kogan 2001) and is computed as:

$$\mathrm{VHI} = 0.5(\mathrm{VCI}) + 0.5(\mathrm{TCI}) \tag{4}$$

3.3 *Rainfall mapping*

Time-series of rainfall were generated by interpolating seasonal average of 75 (out of 90) rain-gauge stations falling in and around the Luni Basin. Data from the remainder of the rain-gauge stations were used to fill in for missing observations. Interpolation was carried out in ArcView 3.2a using a *spline* technique that works with cubic polynomial function. Since rainfall in arid and semi-arid regions is highly skewed, four neighbouring points were included for spatial interpolation. A tension parameter of 0.1 was chosen, which tries to move the polynomial function close to the data points. The distributed rainfall maps were classified into different ranges (table 1) to analyse the seasonal rainfall patterns.

3.4 *Drought mapping*

Seasonal values of VCI, TCI and VHI were obtained by averaging weekly values of pixels of 4 km spatial resolution sampled to 16 km. Maps were generated by plotting pixel values of the vegetation indices and classified following the established scheme (table 2) to represent drought intensities. Spatio-temporal drought analysis in the Luni Basin was carried out for the monsoon and non-monsoon periods during the years 1983–2003.

Table 1. Different ranges of monsoon- and non-monsoon rainfall in the Luni River basin.

Monsoon rainfall (mm)	Non-monsoon rainfall (mm)	Colour code
0–200	0–10	
201–300	11–25	
301–400	26–50	
401–600	51–75	
>600	>75	

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Table 2. VCI, TCI and VHI classifications for vegetative drought.

Drought class	Values	VCI colour	TCI colour	VHI colour
Extreme drought	≤10			
Severe drought	≤20			
Moderate drought	≤30			
Mild drought	≤40			
No drought	>40			

3.5 *Statistics and correlation analyses*

Statistics of the VCI, the TCI, the VHI and number of pixels with value less than or equal to 40 in the Luni Basin during the monsoon and non-monsoon seasons were computed to ascertain the spatial extent of the drought. Difference and percentage of departure of seasonal rainfall, as well as the VCI, TCI and VHI in the Luni Basin during droughts with respect to their corresponding mean values of non-drought seasons, were also computed, which provide a perception of drought intensity. In order to determine the degree of seasonal rainfall variation or consistency in different years, correlation analysis was carried out using the rainfall data. Similarly, the degree of inertia in vegetation health in successive seasons was evaluated using Spearman's Rank Correlation. This also offers an idea about the resistance of vegetation to drought and its duration.

4. Drought in the Luni Basin

4.1 *Monsoon variations and rainfall patterns*

The south-westerly monsoon wind carries the seeds of rain from the Bay of Bengal. The Aravalli Range is higher than the surrounding land and so the moisture-enriched air mass goes up the slope, showering mostly in the eastern part. When the cloud reaches the leeward side of the Aravalli, it has less moisture and, therefore, the land west of the Aravalli Range receives less rain. More than 90% of the annual rainfall occurs during the monsoon season (June–September) alone and, in certain years, monsoon-rainfall accounts for the total annual rainfall. The withdrawal of the monsoon is a more gradual process than its onset (Das 1996). The arrival and/or retreat of the monsoon also gets delayed in some years, whereas in other years one or both of the events occur early. As a result, the monsoon dynamics vary inter-annually in terms of precipitation intensity, amount, distribution, pattern, wind speed and onset and withdrawal of the monsoon (Singh 1994). Similarly, the number of rainy days varies from year to year and place to place in the region. On average, there are 21 rainy days in the region; the bulk of the rainfall occurs in the month of July but in certain years it shifts even to September.

The time-series analysis reveals a lack of consistency among seasonal rainfall due to large monsoonal variation. Visual analysis and comparison with the long-term (1971–2000) mean rainfall (figures 2(*a*) and (*b*)) also shows the same. The monsoon-rainfall in the Luni Basin follows some patterns with variations in spatial distribution. Notable variation could be observed in rainfall amount and distribution from year to year (table 3). During the years of low rainfall and drought, the amount of rainfall is

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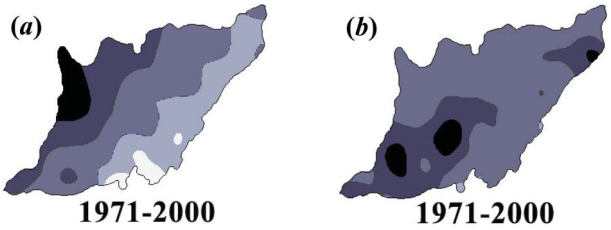

Figure 2. Long-term (1971–2000) mean rainfall in the Luni Basin during the (*a*) monsoon and (*b*) non-monsoon seasons. See table 1 for explanation of shading.

found to decrease gradually from east to west or from north-east to south-west. In the years of countrywide drought (1985, 1986, 1987, 1999, 2000 and 2002), the Luni Basin received very low rainfall (0–200 mm), particularly in 1987 and 2002, when the entire basin was in the grip of extreme drought (figure 3). Most parts of the basin received very low rainfall (0–300 mm) in 1991 also. Rainfall in 1998 was less even than that of the drought year of 2000. Figure 4 shows yearly monsoon-rainfall and the percent of departure with respect to the mean monsoon-rainfall in the non-drought years. In 1985 and 1986, rainfall was 50% below normal, respectively, in 18 and 16 of 32 rain-gauges located within the Luni Basin, whereas, in 1987 and 2002, 28 and 26 rain-gauges, respectively, received less than 60% of normal seasonal rainfall.

Variation in rainfall pattern is observed also during the years of high rainfall. In the years 1990, 1992 and 2003, rainfall was higher (600–850 mm) in the southern parts in comparison to northern or north-eastern parts (300–600 mm). This pattern was reversed in 1994, 1996 and 1997 (figure 5). The amount of rainfall increased significantly in most of the rain-gauge stations in these years. The mean increase in rainfall at different rain-gauges in the years of high rainfall varies from 14% to 88%. The increase was as high as 101% in 1990, considering all the rain-gauges together (figure 4). In the years of moderate monsoon, the pattern remains more or less intact, i.e. rainfall gradually diminishes from the east towards the west.

Contrary to the monsoon-rainfall, rainfall distribution in the Luni Basin during the non-monsoon period was found to be mostly uniform (26–50 mm), except for the north-eastern and south-western parts, which experienced less (0–25 mm) rainfall (figure 2(*b*)). Erratic rainfall patterns could be observed during the non-monsoon period owing to a large spatio-temporal variation in rainfall occurrence and distribution through the north-easterly monsoon wind. In certain years, monsoon and non-monsoon rainfall follows the same pattern, i.e. rainfall gradually decreases from east towards west. A reversal of the normal rainfall pattern is observed during 1986–87, 1992–93, 1994–95, 1995–96, 1996–97 and 1997–98, when rainfall gradually increased from east to west or from south-east to north-west (figures 6 and 7). In other years (1984–85, 1985–86 and 1990–91) non-monsoon rainfall gradually decreased from north-east towards the south-west.

From 1983 to 1995, non-monsoonal rainfall was very low in major parts of the Luni Basin. Almost the entire basin received only 10 mm or less rainfall during the non-monsoon months of 1983–84. Most of the region in the south and south-west received 10 mm or less rainfall in other years too. During 1991–92 and 1993–94 the central and the southern parts received a little higher (25–50 mm) rainfall. Visually, good resemblance could be found in the non-monsoonal rainfall patterns of 1983–84, 1987–88 and 1989–90. Similarly, rainfall during 1985–86, 1988–89 and 1990–91 followed the pattern of 1984–85, whereas rainfall in 1992–93 closely resembled that during 1986–87

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Table 3. Correlation matrix for yearly monsoon-rainfall in the Luni Basin during 1984–2003.

	M-84	M-85	M-86	M-87	M-88	M-89	M-90	M-91	M-92	M-93	M-94	M-95	M-96	M-97	M-98	M-99	M-00	M-01	M-02	M-03
M-84	1.00																			
M-85	0.33	1.00																		
M-86	0.37	0.50	1.00																	
M-87	0.06	0.03	0.52	1.00																
M-88	0.52	0.14	0.52	0.30	1.00															
M-89	0.45	0.09	0.63	0.48	0.67	1.00														
M-90	–0.08	0.38	0.50	0.09	0.17	0.27	1.00													
M-91	0.31	–0.04	0.49	0.44	0.65	0.58	–0.08	1.00												
M-92	0.24	0.35	0.56	0.28	0.11	0.26	0.55	0.04	1.00											
M-93	0.34	0.58	0.63	0.07	0.24	0.33	0.71	0.17	0.57	1.00										
M-94	0.37	0.20	0.50	0.19	0.56	0.62	0.30	0.45	0.44	0.39	1.00									
M-95	0.42	0.13	0.37	0.38	0.50	0.45	–0.25	0.54	–0.07	0.00	0.43	1.00								
M-96	0.51	–0.02	0.27	0.18	0.41	0.36	–0.26	0.44	–0.01	0.02	0.19	0.55	1.00							
M-97	0.34	0.04	0.45	0.34	0.51	0.58	0.16	0.37	0.38	0.19	0.66	0.44	0.57	1.00						
M-98	0.38	0.12	0.31	0.46	0.35	0.44	–0.29	0.43	–0.23	0.00	0.09	0.42	0.51	0.25	1.00					
M-99	0.33	0.16	0.41	0.38	0.43	0.39	–0.13	0.64	0.13	0.13	0.49	0.58	0.60	0.59	0.56	1.00				
M-00	0.16	0.05	0.42	0.56	0.46	0.49	0.15	0.48	0.08	0.22	0.17	0.28	0.12	0.12	0.42	0.16	1.00			
M-01	0.33	0.03	0.47	0.69	0.44	0.53	0.18	0.49	0.36	0.34	0.38	0.40	0.50	0.50	0.46	0.58	0.49	1.00		
M-02	0.36	0.55	0.51	0.32	0.29	0.26	0.31	0.15	0.58	0.68	0.38	0.29	0.15	0.26	0.15	0.30	0.29	0.45	1.00	
M-03	–0.10	0.38	0.37	0.02	0.01	0.01	0.62	–0.10	0.47	0.53	–0.01	–0.19	–0.31	–0.05	–0.25	–0.18	0.14	–0.07	0.37	1.00

M-84, monsoon-rainfall in the year 1984; M-85, monsoon-rainfall in the year 1985; and so on.

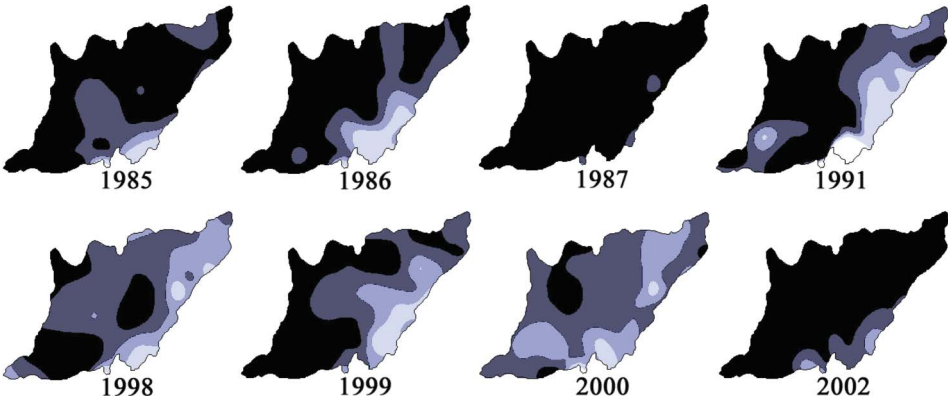

Figure 3. Years of low rainfall with varied rainfall patterns. See table 1 for explanation of shading.

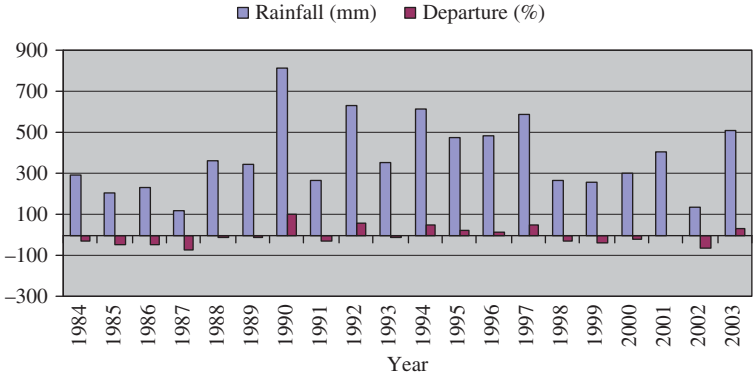

Figure 4. Time-series of monsoon-rainfall and yearly percent of departure from the mean.

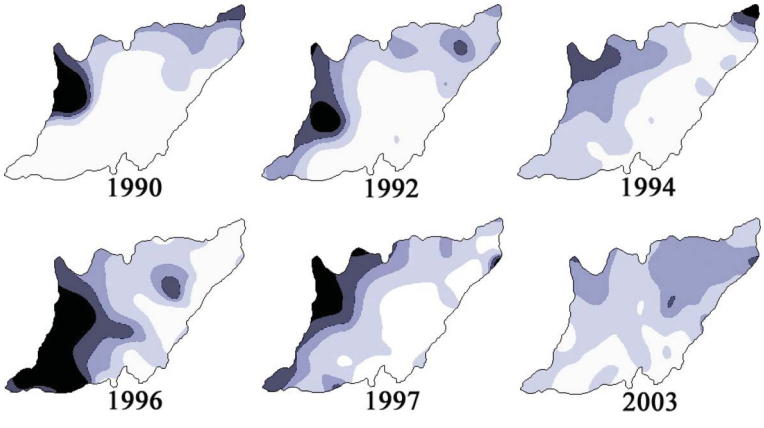

Figure 5. Years of excessive rainfall. See table 1 for explanation of shading.

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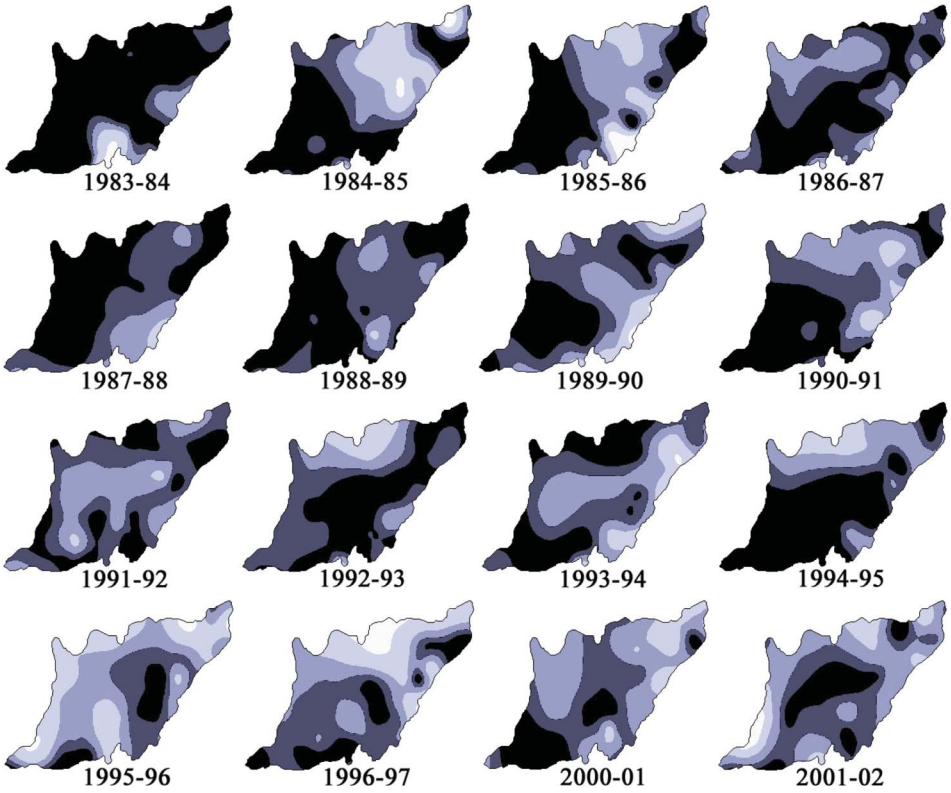

Figure 6. Non-monsoonal rainfall patterns and spatial distributions in the non-wet years. See table 1 for explanation of shading.

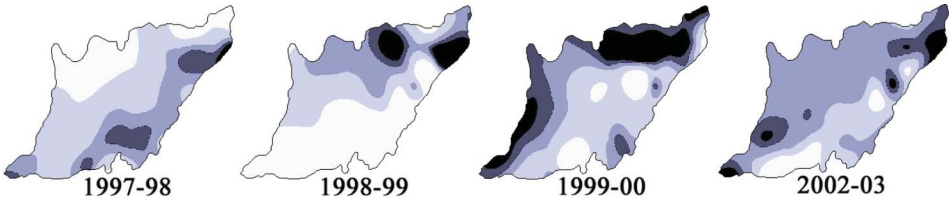

Figure 7. Years of excessive non-monsoonal rainfall. See table 1 for explanation of shading.

(figure 6). However, higher correlation (R) could be found between the rainfalls during 1984–85 and 1996–97, between 1985–86 and 1988–89, between 1986–87 and 1994–95, between 1989–90 and 1997–98, between 1996–97 and 1997–98, and between 1993–94 and 2000–01(table 4).

Significantly large departure (–60% to –100%) in non-monsoonal rainfall was noticed in both the drought and non-drought years (figure 8) in comparison to the mean non-monsoonal rainfall in the non-drought years. It is quite interesting that while most parts of the country including the Luni Basin suffered from severe to extreme monsoon-droughts in 1999, 2000 and 2002 (figure 3), non-monsoon rainfall during 1998–99, 1999–2000 and 2002–03 was significantly high (figure 7). In these years, most

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Table 4. Correlation matrix for yearly non-monsoonal rainfall in the Luni Basin during 1984–2003.

	83–84	84–85	85–86	86–87	87–88	88–89	89–90	90–91	91–92	92–93	93–94	94–95	95–96	96–97	97–98	98–99	99–00	00–01	01–02	02–03
83–84	1.00																			
84–85	–0.09	1.00																		
85–86	0.11	0.21	1.00																	
86–87	0.12	0.34	0.18	1.00																
87–88	0.29	–0.02	0.57	0.04	1.00															
88–89	–0.05	0.19	0.75	0.32	0.41	1.00														
89–90	0.05	0.35	0.32	–0.08	0.41	0.13	1.00													
90–91	–0.14	0.22	0.32	0.26	0.44	0.42	0.26	1.00												
91–92	–0.04	0.40	0.17	–0.06	0.28	0.10	0.40	0.09	1.00											
92–93	–0.03	0.02	0.10	0.49	0.25	0.30	0.03	0.43	0.07	1.00										
93–94	–0.05	0.00	0.20	0.25	0.27	0.46	0.09	0.55	0.06	0.05	1.00									
94–95	–0.07	0.01	0.27	0.61	0.23	0.41	–0.02	0.46	–0.16	0.51	0.48	1.00								
95–96	0.24	–0.16	–0.08	0.33	0.09	–0.14	0.17	0.03	0.16	0.13	0.25	0.36	1.00							
96–97	–0.10	0.69	0.31	0.35	0.09	0.17	0.52	0.15	0.45	0.27	0.01	0.31	0.22	1.00						
97–98	0.08	0.34	0.17	0.24	–0.01	–0.07	0.62	0.05	0.53	0.16	–0.06	0.13	0.51	0.66	1.00					
98–99	0.34	0.16	0.29	0.04	0.52	0.34	0.29	0.00	0.48	–0.02	0.16	–0.15	0.28	0.18	0.12	1.00				
99–00	0.31	0.32	0.24	–0.11	0.31	0.22	0.22	–0.01	0.52	–0.15	0.08	–0.28	–0.15	0.09	0.10	0.51	1.00			
00–01	0.16	0.27	0.31	0.39	0.35	0.28	0.44	0.56	0.08	0.09	0.64	0.55	0.40	0.42	0.35	0.18	–0.04	1.00		
01–02	0.11	0.31	–0.14	0.58	0.02	–0.02	0.13	0.16	–0.03	0.26	0.20	0.22	0.47	0.25	0.19	0.31	0.00	0.29	1.00	
02–03	0.16	0.19	0.24	0.04	0.32	0.22	0.20	–0.12	0.23	–0.07	0.02	–0.06	–0.08	0.15	–0.04	0.58	0.52	–0.04	0.20	1.00

83–84 represents rainfall during the non-monsoon (October to May) of 1983–84; 84–85 represents non-monsoonal rainfall of 1984–85 and so on.

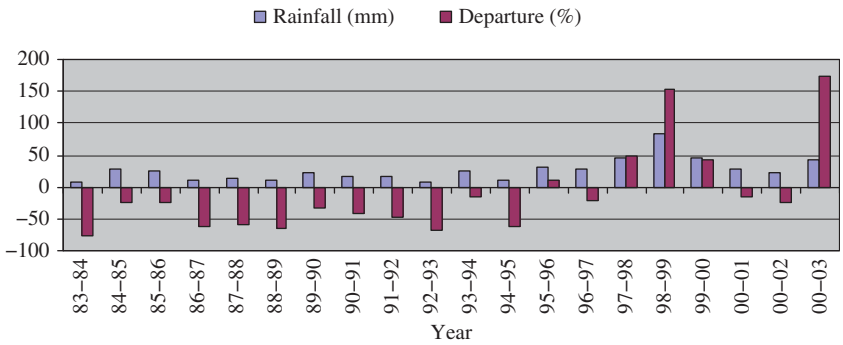

Figure 8. Time-series of non-monsoonal rainfall and percentage of departure from the mean.

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of the rain-gauges received excess rainfall compared to the long-term (1971–2000) mean. High non-monsoonal rainfall during October–November of 1997–98 and 1998–99 took place mostly due to delayed termination of the monsoon. In 1999–2000 the basin received pre-monsoon rainfall during April–May. Rainfall occurred during 2002–03 between December 2002 and February 2003 through the north-east monsoon wind, and also in May 2003 due to a pre-monsoonal depression in the Arabian Sea.

4.2 *Stress patterns and vegetation health*

A close association between the spatial variability of rainfall and vegetation cover is well established through remote sensing data on vegetation vigour and quantity (Nicholson *et al.* 1990). Significant positive relations between NDVI and precipitation have been noted in various arid and semi-arid parts of Africa, at continental (Lotsch *et al.* 2003, Zhang *et al.* 2005) and regional scales (Hielkema *et al.* 1986, Malo and Nicholson 1990, Nicholson *et al.* 1990, Davenport and Nicholson 1993, Richard and Poccard 1998). In the present study, yearly correlation between rainfall and the VHI is found to be lacking or weak. Figures 9 and 10 show that although the VHI varies with

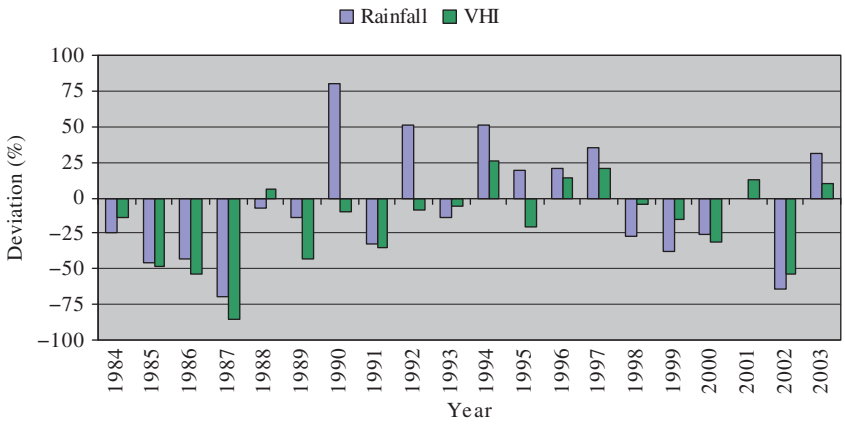

Figure 9. Time-series of percentage of departure of the monsoon-rainfall and the corresponding VHI.

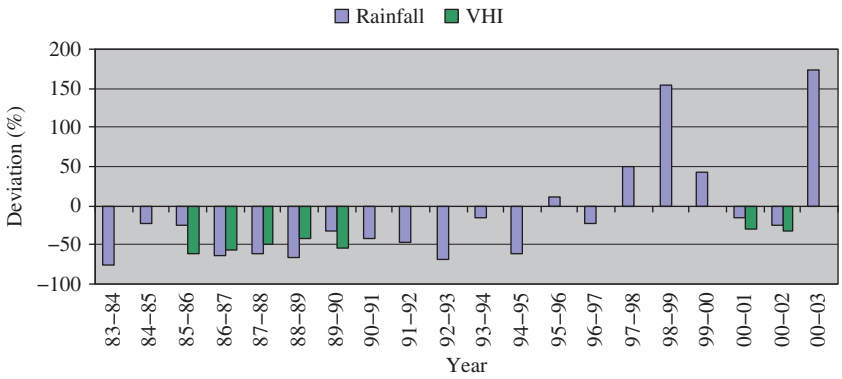

Figure 10. Time-series of percentage of departure of the non-monsoonal rainfall and the corresponding VHI.

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the rainfall departure both during the monsoon and non-monsoon seasons, the amount of their departure is not proportionate. The non-proportionality in variations and weak correlations (low R^2) between rainfall and vegetation health is due to slow vegetation recovery, especially after extreme conditions. For example, in 1990, departure of rainfall was plus 175% but that of the vegetation health was below normal. The reason for this is the long drought during the monsoon of 1985–87 followed by another in 1989, plus the long non-monsoon drought prior to 1990. The situations during the 1992 monsoon and 1997–2000 non-monsoons were similar. While precipitation restores the temporal balance of rainfall immediately, for vegetation it takes some time to recover. Thus, only a moderate correlation ($R^2 = 0.47$) could be found between mean rainfall and the mean VHI in the Luni Basin, considering all monsoon seasons. A slightly higher correlation ($R^2 = 0.56$) is obtained for the years of monsoon-droughts. However, in certain years, the pattern of VHI is found to display a good resemblance to the distribution of monsoon-rainfall, and the correlation between mean rainfall and mean VHI is found to be higher ($R^2 = 0.76$), indicating a stronger influence of rainfall in those years (figure 11).

Vegetation health is governed by moisture and thermal conditions. While precipitation (rainfall) in association with other hydrometeorological parameters (dew, humidity, etc.) supports the moisture requirement, the thermal equilibrium is

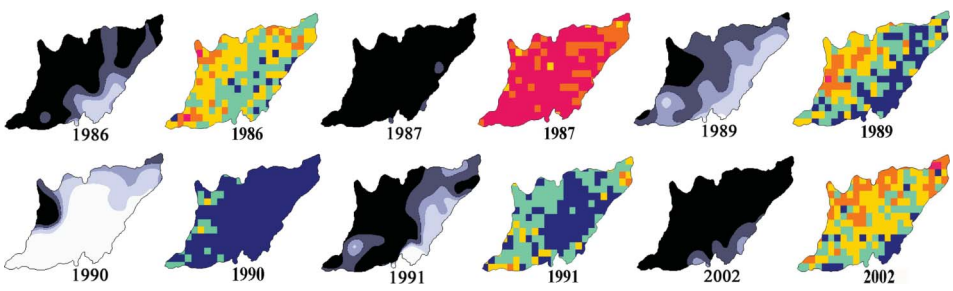

Figure 11. Good resemblance in the spatial distribution of monsoon-rainfall and corresponding VHI patterns. See tables 1 and 2 for explanation of shading and colour.

maintained by ground and air temperature. Lack of precipitation generates moisture stress, whereas abnormally high air and surface temperatures impart thermal stress on vegetation. Vegetative drought results either by sudden development of abnormally high stresses, or by gradual accumulation of mild stresses. In general, moisture stress and thermal stress are developed simultaneously; however, in certain seasons the two kind of stress lack synchronicity. Table 5 shows that during the monsoon season of 1985, 1986, 1987, 1989 and 2002 both moisture-stress (VCI$\leq$40) and thermal-stress (TCI$\leq$40) affected major parts of the basin (more than half of 222 pixels covering the study area), resulting in intense drought. In the years 1984, 1988, 1990 and 2000, many parts of the basin suffered from moisture-stress; however, the thermal condition in vegetation was favourable in most parts. The case was reversed during the monsoon of 1991, 1993, 1995 and 1999.

A lack of synchronicity between the VCI and the TCI could be found also in the non-monsoon period (table 6). Many parts of the basin suffered both from moisture-stress and thermal-stress during the 1985–86, 1986–87, 1988–89, 1989–90 and 2002–03 non-monsoons. However, major parts of the basin suffered only from moisture-stress during 1984–85, 1987–88, 1999–2000 and 2000–01, but were free from thermal-stress. In contrast, the basin was mostly free from moisture-stress and experienced only thermal-stress during 1990–91, 1995–96, 1996–97 and 2001–02. During the non-monsoon of 1987–88, in spite of normal thermal conditions, mild to moderate drought appeared all over the Luni Basin due to extreme moisture-stress from a delayed and poor monsoon. During the non-monsoon of 1995–96, favourable moisture conditions countered the thermal-stress and the drought failed to appear. The 1988 monsoon enjoyed excellent vegetation health, when the moisture and thermal conditions were opposite to those of the non-monsoon of 1995–96. However, in 2000,

Table 5. Mean values of the VCI, the TCI and the VHI, and number of pixels (out of 222) with value less than or equal to 40 in the Luni Basin during the monsoon.

Year	VCI	$\leq$40	TCI	$\leq$40	VHI	$\leq$40
1984	44	91	62	18	53	21
1985	35	156	29	181	32	184
1986	17	119	40	116	29	209
1987	10	222	7	219	9	222
1988	42	104	87	0	65	0
1989	40	113	29	190	35	159
1990	46	75	64	16	55	24
1991	56	29	23	213	40	126
1992	57	20	53	36	55	5
1993	76	0	38	130	57	4
1994	59	53	94	0	76	0
1995	62	16	36	146	49	33
1996	76	3	63	25	70	3
1997	85	2	62	25	74	3
1998	61	27	55	42	58	29
1999	57	18	46	69	52	29
2000	34	158	50	38	42	90
2001	70	3	67	2	69	0
2002	32	172	24	201	28	202
2003	69	7	62	4	61	6

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Table 6. Mean values of the VCI, the TCI and the VHI, and number of pixels (out of 222) with value less than or equal to 40 in the Luni Basin during the non-monsoon.

Year	VCI	≤40	TCI	≤40	VHI	≤40
83–84	58	17	72	1	65	0
84–85	39	131	57	5	48	36
85–86	21	207	27	209	24	216
86–87	17	218	38	145	27	213
87–88	6	222	59	2	32	205
88–89	48	70	25	213	36	158
89–90	33	176	25	210	29	200
90–91	69	7	46	80	57	17
91–92	49	57	52	32	51	23
92–93	77	1	75	1	76	0
93–94	56	41	87	0	72	0
94–95	63	27	75	0	69	1
95–96	74	0	32	173	53	18
96–97	75	1	45	69	60	9
97–98	83	1	72	3	77	1
98–99	75	4	59	18	67	1
99–00	40	121	79	0	60	3
00–01	39	133	49	33	44	95
01–02	63	12	23	210	43	94
02–03	39	103	41	72	40	79

83–84 represents non-monsoon (October–May) of 1983–84, and so on.

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favourable thermal conditions could not counter excessive moisture-stress to save the Luni Basin from drought (figure 12).

4.3 *Vegetative drought dynamics*

Vegetative drought is a manifestation of meteorological and hydrological droughts. The time-series maps of VHI indicate that vegetative drought is highly influenced by rainfall and temperature. Moreover, patterns, speed of drought development and drought duration are also different in different parts of the Luni Basin. The Luni Basin enjoyed excellent vegetation health during the monsoon of 1984 owing to high rainfall; mild stress developed in certain western and southern pockets. In 1985, the entire basin was under the grip of drought; however, the intensity varied in different parts. From east to west, the drought intensity was found to be gradually higher and, in the central and western parts, the intensity was extreme. During 1986–87, insufficient rainfall in both the monsoon and non-monsoon periods gradually resulted in severe meteorological drought. This, in turn, imparted extreme stress on vegetation health, resulting in moderate to severe vegetative droughts in 1986 and extreme vegetative drought in 1987. The continuous dry spell of the monsoon left no hope for the vegetation to recover from the previous drought conditions. This 'recovery effect' (Malo and Nicholson 1990, Martiny *et al.* 2005) is evident (figure 13) during the non-monsoon of 1987–88. The recovery effect is prevalent particularly when there is poor rainfall and/or high heat-flow in the immediate season following a drought. After excellent vegetation health in 1988, the basin again suffered from mild to severe drought in major parts during the post-monsoon of 1988 and pre-monsoon of 1990, while in 1991 mild drought prevailed in the basin except in the eastern and central

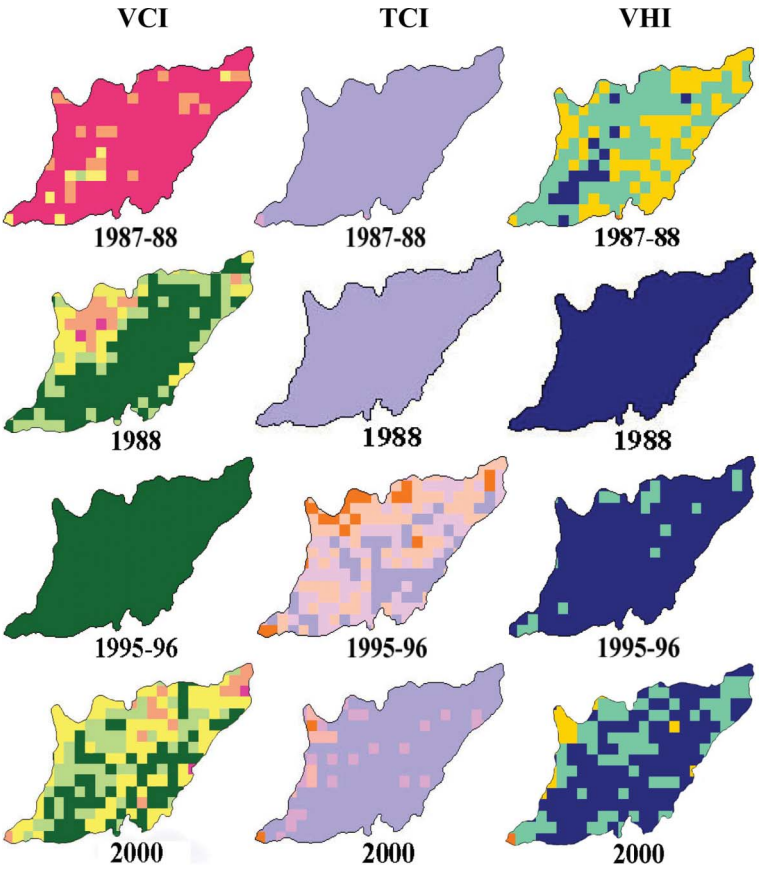

Figure 12. Non-synchronous occurrence of the VCI, TCI and VHI. See table 2 for explanation of colour.

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parts (figures 13 and 14). Vegetation health started degrading again after the non-monsoon of 2001–02 and, during the 2002 monsoon, the entire basin was into the grip of drought (figures 11 and 14). The agricultural sector was affected severely during the 2002 drought since crops could not be sown at all due to the delayed arrival of the monsoon and failure of rainfall (Samra 2002). Analysis of the vegetation indices reveals that intense drought appears only when both moisture-stress and thermal-stress affect the vegetation health. The percentage of departure of the VHI was higher in those drought seasons when departure of both the VCI and the TCI were significantly high from their respective mean values during the non-drought seasons (table 7).

Spearman's Rank Correlation indicates a strong relation between the VHI of the two successive seasons during 1986 to 1991, referred to as the 'recovery effect'. Higher values of Spearman's correlation were obtained (table 8) when VHI values were reclassified (0 for 'no-drought' and 1 for 'drought') and ranked on the basis of drought (VHI ≤ 40) and no-drought (VHI > 40) conditions.

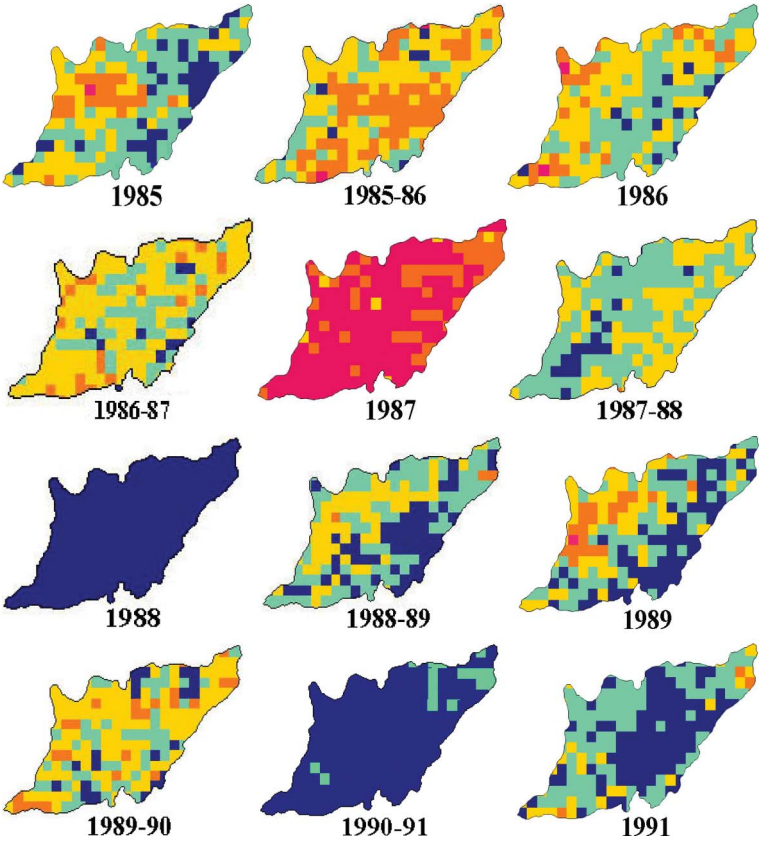

Figure 13. VHI maps showing the 'recovery effect'. See table 2 for explanation of colour.

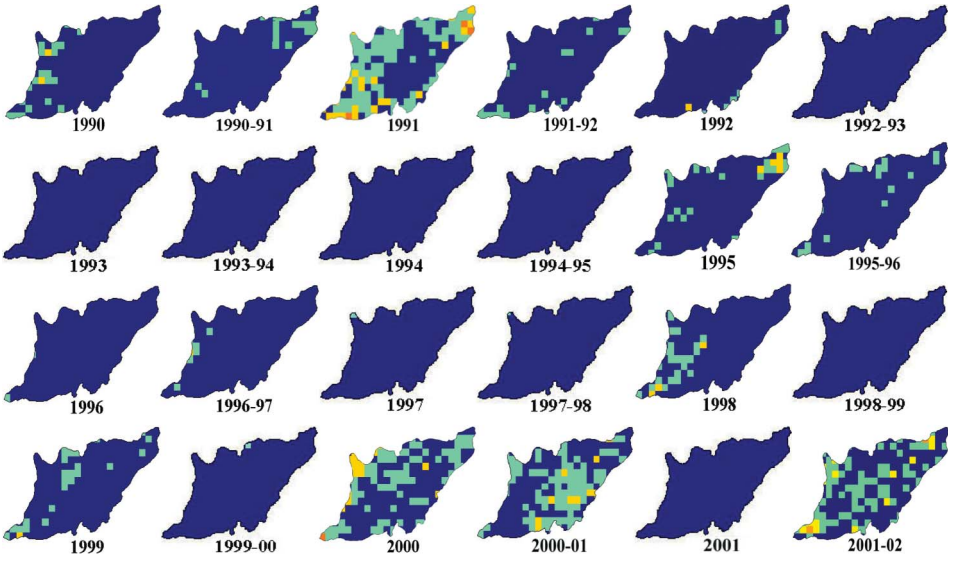

Figure 14. 'Memory effect' in the vegetation of the Luni Basin as revealed by the VHI. See table 2 for explanation of colour.

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Table 7. Difference and percentage of departure (Dep) of the VCI, TCI and VHI in the Luni Basin during droughts with respect to their corresponding mean values of non-drought seasons.

Season	VCI – VCIn	Dep (%)	TCI – TCIn	Dep (%)	VHI – VHIn	Dep (%)
m1985	–29	–45.1	–35	–55.8	–29	–47.9
nm85–86	–44	–67.5	–40	–59.7	–39	–61.4
m1986	–47	–73.0	–24	–37.5	–32	–53.1
nm86–87	–49	–74.7	–29	–43.6	–36	–56.8
m1987	–55	–84.6	–56	–87.7	–52	–85.7
nm87–88	–60	–91.5	–8	–11.3	–30	–48.4
nm88–89	–18	–27.7	–42	–62.2	–27	–42.2
m1989	–24	–36.8	–35	–55.4	–26	–43.6
nm89–90	–33	–50.4	–42	–62.1	–34	–53.9
m1991	–9	–14.3	–41	–64.2	–21	–35.4
nm00–01	–27	–40.9	–18	–26.7	–19	–30.3
nm01–02	–3	–4.5	–44	–65.6	–20	–31.8
m2002	–32	–49.1	–40	–62.7	–33	–54.3

m1985, monsoon of 1985; nm85–86, non-monsoon of 1985–86, and so on.
VCIn, TCIn and VHIn represent the normal (mean of non-drought years) of VCI, TCI and VHI, respectively.

Table 8. Spearman's Rank Correlation between seasonal VHI depicting the 'recovery effect' in the Luni Basin.

	Spearman's *R*	
Season	Drought intensity	Drought–No-drought
m85/nm85–86	0.18	0.75
nm85–86/m86	0.05	0.87
m86/nm86–87	0.47	0.87
nm86–87/m87	0.36	0.94
m87/nm87–88	0.26	0.89
nm87–88/m88	0.60	0.89
m88/nm88–89	0.76	0.69
nm88–89/m89	0.29	0.55
m89/nm89–90	0.40	0.63
nm89–90/m90	0.52	0.74
m90/nm90–91	0.73	0.72
nm90–91/m91	0.58	0.61

m85, monsoon of 1985; nm85–86, non-monsoon of 1985–86.

4.4 *Resilience to drought*

Drought impacts are usually first apparent in agriculture (Komuscu 1999). However, the time-series of VHI shows that vegetation in the Luni Basin could withstand adverse meteorological conditions and maintained normal health for several seasons. Semi-arid ecosystems preserve the stimulation received by surplus water in a wet year (Schwinning *et al.* 2004, Martiny *et al.* 2005). Similar to semi-arid regions of Africa (Martiny *et al.* 2005, Philippon *et al.* 2005), the 'memory effect' of past rainfall is evident also in the arid Luni Basin. In spite of moisture and thermal stresses, vegetation in the Luni Basin maintained normal health after the monsoon of 1990 until the

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Table 9. Spearman's Rank Correlation between seasonal VHI depicting the 'memory effect' in the Luni Basin.

Season	Spearman's *R*
m90/nm90–91	0.72
nm90–91/m91	0.58
m91/nm91–92	0.52
nm91–92/m92	0.85
m92/nm92–93	0.98
nm92–93/m93	0.99
m93/nm93–94	0.99
nm93–94/m94	1.00
m94/nm94–95	0.99
nm94–95/m95	0.82
m95/nm95–96	0.77
nm95–96/m96	0.90
m96/nm96–97	0.95
nm96–97/m97	0.93
m97/nm97–98	0.99
nm97–98/m98	0.83
m98/nm98–99	0.84
m98–99/m99	0.87
m99/nm99–00	0.85
nm99–00/m00	0.64
m00/nm00–01	0.43
nm00–01/m01	0.63

m90, monsoon of 1990; nm90–91, non-monsoon of 1990–91.

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2001–02 non-monsoon season (figure 14). During these long 12 years, mild drought appeared in parts of the basin only during the 1991 and 2000 monsoons and the 2000–01 and 2001–02 non-monsoons. Consistently higher values of Spearman's Rank Correlation (table 9) confirm the presence of the memory effect in the vegetation of the Luni Basin. The present study observes that although vegetation health is directly influenced by rainfall, the response of vegetation to rainfall is not linear. In certain years and seasons, in spite of poor rainfall, the vegetation in the Luni Basin maintained health, and vice versa.

5. Conclusions

Analysis of the monsoon variation and spatio-temporal patterns of vegetative drought through rainfall, VCI, TCI and VHI time-series for the monsoon and the non-monsoon seasons reveals some interesting results. The monsoon was found to be inconsistent and rainfall pattern to be erratic in the rain-shadow zone of the Luni Basin. Rainfall attributed to the south-west and north-east monsoons was found to produce different rainfall patterns and amounts in the two distinct seasons. The south-westerly monsoon wind governs the monsoon rainfall, which constitutes more than 90% of total annual rainfall in the Luni Basin.

Insufficient rainfall accompanied by high heat-flow leads to frequent drought with varying intensity in this region. Vegetation may experience stress either due to a shortage of moisture from rainfall or due to high heat-flow or both. Accumulated stress may be sensitive either to moisture or temperature, and may lead to vegetative

drought even if one parameter is supportive. On the contrary, vegetation can resist drought in spite of intense moisture- or thermal-stress. The 'recovery effect' and the 'memory effect' are also evident in the patterns of the vegetation response to rainfall, indicating inertia in vegetation health. Manifestations of recovery effect and memory effect are dependent on phenological characters of vegetation and their sensitivity to aridity and temperature. This explains the weak or lack of correlation (Bhuiyan 2004, Bhuiyan *et al.* 2006) between a meteorological drought index, such as the Standardized Precipitation Index (SPI) (McKee *et al.* 1995), and vegetative drought indices. The present study shows that vegetation in the Luni Basin experienced frequent and prolonged drought in the previous decade, and excellent vegetation health in the next decade. The vegetation of the Luni Basin displays a long recovery effect during 1984–90 and a strong memory effect during 1990–2001.

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