DOI 10.1515/gein-2015-0003 GEOINFORMATICA POLONICA
14: 2015

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DEVELOPMENT OF INDEX TO ASSESS DROUGHT CONDITIONS USING GEOSPATIAL DATA A CASE STUDY OF JAISALMER DISTRICT, RAJASTHAN, INDIA*

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Keywords: drought, remote sensing indices, precipitation, NDVI, Jaisalmer

Abstract

The Jaisalmer district of Rajasthan province of India was known to suffer with frequent drought due to poor and delayed monsoon, abnormally high summer-temperature and insufficient water resources. However flood-like situation prevails in the drought prone Jaisalmer district of Rajasthan as torrential rains are seen to affect the region in the recent years. In the present study, detailed analysis of meteorological, hydrological and satellite data of the Jaisalmer district has been carried out for the years 2006‒2008. Standardized Precipitation Index (SPI), Consecutive Dry Days (CDD) and Effective Drought Index (EDI) have been used to quantify the precipitation deficit. Standardized Water-Level Index (SWI) has been developed to assess ground-water recharge-deficit. Vegetative drought indices like Vegetation Condition Index (VCI), Temperature Condition Index (TCI), Vegetation Health Index (VHI), Normalized Difference Vegetation Index (NDVI) and Modified Soil-Adjusted Vegetation Index 2 have been calculated. We also introduce two new indices Soil based Vegetation Condition Index (SVCI) and Composite Drought Index (CDI) specifically for regions like Jaisalmer where aridity in soil and affects vegetation and water-level.

OPRACOWANIE WSKAŹNIKA OCENIAJĄCEGO STOPIEŃ SUSZY Z WYKORZYSTANIEM DANYCH GEOREFERENCYJNYCH NA PRZYKŁADZIE OKRĘGU JAISALMER W RADŻASTANIE (INDIE)

Słowa kluczowe: susza, wskaźniki teledetekcyjne, opady, NDVI, Jaisalmer

Abstrakt

Okręg Jaisalmer w indyjskiej prowincji Radżasthan znany był z częstych susz, spowodowanych słabymi i pojawiającymi się zbyt późno opadami monsunowymi, wyjątkowo wysokimi temperaturami w lecie i niewystarczającą ilością zasobów wodnych. Jednakże ostatnio, w podatnym na suszę okręgu Jaisalmer w Radżasthanie, częstsze jest zagrożenie ze strony powodzi, spowodowanych ulewnymi deszczami. W niniejszej pracy przedstawiono szczegółową analizę danych meteorologicznych, hydrologicznych i satelitarnych z okręgu Jaisalmer, zgromadzonych w latach 2006‒2008. Aby ilościowo opisać deficyt opadów, użyto następujących wskaźników: standaryzowany wskaźnik opadów (*Standardized Precipitation Index* – SPI), ciągły wskaźnik dni suchych (*Consecutive Dry Days* – CDD) oraz efektywny wskaźnik suszy (*Effective Drought Index* – EDI). Aby ocenić deficyt wód grunto-

* This article titled "Development of an index to assess drought conditions using geospatial data – A case study of Jaisalmer district, Rajasthan, India" submitted to the journal Geoinformatica Polonica, have not submitted eles where nor published in any journal and is under consideration for publication with the Geoinformatica Polonica Journal.

wych, opracowano standaryzowany wskaźnik poziomu wód (*Standardized Water-Level Index* – SWI). Obliczono wskaźniki suszy wegetacyjnej takie jak: wskaźnik stanu wegetacji (*Vegetation Condition Index* – VCI), wskaźnik stanu temperatury (Temperature Condition Index – TCI), wskaźnik zdrowia wegetacji (*Vegetation Health Index* – VHI), znormalizowany różnicowy wskaźnik wegetacji (*Normalized Difference Vegetation Index* – NDVI) oraz zmodyfikowany wskaźnik wegetacji z uwzględnieniem poprawki na glebę – wskaźnik wegetacji 2 (*Vegetation Index* 2). Wprowadzono również dwa nowe wskaźniki: oparty na glebie wskaźnik stanu wegetacji (*Soil based Vegetation Condition Index* – SVCI) i złożony wskaźnik suszy (*Composite Drought Index* – CDI), uwzględniając specyfikę dla regionów takich jak Jaisalmer, gdzie suchość w glebie ma wpływ na wegetację i poziom wód.

1. INTRODUCTION

Drought is defined as phenomena of a prolonged period of dry conditions [1, 2] where a region observes a deficit in its water supply, whether surface or underground water. It is viewed as normal, repetitive climatic process, though few consider it as a rare and random event, occurring globally with varied scenarios in different regions. Drought, which is treated as a temporary condition, should not be confused with aridity, which is a permanent feature of areas with scanty rainfall. Since the intensity of drought conditions is dissimilar across the world, it is difficult to precisely define 'what is drought' keeping in view of their regional differences and disciplinary perspectives [3, 4]. For example, Libya identifies drought conditions in the country if annual rainfall is less than 180 mm, in contrast to Bali, which considers a period of six days without rain as drought [5].

Drought can be mainly of three types: Meteorological droughts occur, when the actual precipitation in an area is much less than the mean rainfall of that area. It is characterized based on the extent of dryness and length of dry episode. This kind of drought is regional specific as precipitation conditions vary across the regions worldwide. Hydrological droughts occur when the water reserves available in sources such as reservoirs, lakes, and stream flow fall below the statistical average. Hydrological droughts show up more slowly because it involves storing water that is used but not replenished. Agricultural Droughts are droughts that affect crop production and vegetation. This condition can also arise independently from any change in precipitation levels when soil conditions and erosion cause a shortage in water available to the crops.

Drought has a significant adverse effect on the socio-economic, agricultural, and environmental conditions of the affected area [6, 7, 8]. In this context, it is imperative to define and quantify drought characteristics to have a detailed understanding about its severity and the impact on the local conditions [9, 10].Thus it is vital to treat drought as a natural disaster and propose a mechanism to assess, analyze, mitigate and combat the situation wisely [11].

In the current scenario geospatial tools like remote sensing and Geographical Information System (GIS) proved to be better in assessing, monitoring and managing drought conditions of an area [12, 13, 14, 15, 16, 17, 18]. Satellite data sets like AVHRR (Advanced Very High Resolution Radiometer) and MODIS (Moderate Resolution Imaging Spectroradiometer) are widely accepted for better analysis of drought scenarios by various researchers [18, 19, 20, 21, 22].

A variety of drought analysis methods and indices using meteorological, hydrological and vegetation parameters such as rainfall, soil moisture, potential evapo-transpiration, vegetation condition and ground-water levels have been developed by many scientists [8, 23, 24, 25, 26, 27, 28, 29, 30]. The drought measuring parameters are not linearly related to one another and often have diminutive correlation among themselves. 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 [19].

Keeping in view of the advantages of geospatial technology, in the present an attempt has been made to evaluate the vegetative and hydrological stress using various indices for drought monitoring in Jaisalmer district of Rajasthan, India.

2. STUDY AREA

Jaisalmer district lies in the Thar Desert, which straddles the border of India and Pakistan (Figure 1). The district is located between 26°4 − 28°23′ N and 69°20′ − 72°42′E, spanning a geographical area of about 38401 km^2. Jaisalmer is almost entirely a sandy waste. The average rainfall is 201.05 mm and the average temperature is 34.2°C during summers and 15.61°C during

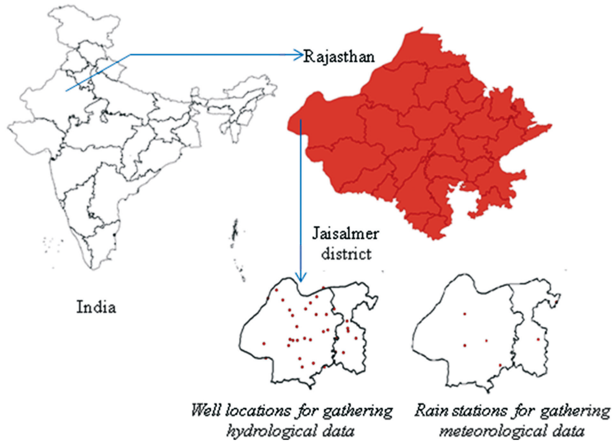

Figure 1. Map showing study area
Ryc. 1. Mapa przedstawiająca obszar badań; u dołu z lewej: rozmieszczenie studni, na podstawie których zbierano dane hydrologiczne, z prawej: rozmieszczenie stacji meteorologicznych do badania opadów deszczu

winters. Water is scarce, and generally brackish; the average depth of the wells is about 76.2 m. There are no perennial streams, and only one small river, the Kakni, which, after flowing a distance of 28 m spreads over a large surface of flat ground, and forms a lake called the Bhuj-Jhil. The climate is dry and healthy. Throughout Jaisalmer only rain crops are grown; spring crops of wheat, barley, etc., are very rare. Owing to the scanty rainfall, irrigation is almost unknown. More than 80% of the district is occupied by sandy soils [31].

Drought is frequent in the Jaisalmer district due to poor, limited and untimely rainfall. The monsoon is the only possible means for ground-water recharge in this arid area. Hence this scarcity of surface-water bodies makes people dependent entirely on ground-water resources. A continuous period of poor rainfall in combination with high temperature hinders replenishment of ground-water table thereby creating a hydrological stress on ground-water resources leading to severe drought in many parts.

In the present study, detailed analysis of seasonal drought dynamics has been carried out to identify drought patterns in meteorological, hydrological, and agricultural spheres for Jaisalmer district of Rajasthan. We aim to study various indices to identify drought characteristics like severity and spatial extent. These indices can be used to describe, quantify and map drought events, comparing them in space and time to provide a base for drought management. We also introduce a new index Composite Drought Index (CDI) to assess the arid conditions in Jaisalmer district.

3. MATERIALS AND METHODS

For the present study, we make use of MODIS data having 36 spectral bands with a spatial resolution of 1km and a temporal resolution of 15 days. Daily precipitation data and bi-monthly ground-water level data has been collected from Indian Meteorological Department. Data from 6 rain stations (Fatehgarh, Pokhran, Jaisalmer, Nokh, Ramgarh and Sam) and 35 wells in the Jaisalmer district was gathered for calculating meteorological and hydrological drought indices respectively (Figure 1).

The India Meteorological Department (IMD) designates four official seasons: (1) Winter, occurring from December to early April, (2) Summer or pre-monsoon season, lasting from April to June, (3) Monsoon or rainy season, lasting from June to September and (4) Post-monsoon season, lasting from October to December. The indices of interest are calculated for the above mentioned seasons for each year.

The following are the indices of interest to study drought patterns in Jaisalmer district.

3.1. Meteorological Drought Indices

Standard Precipitation Index (SPI) assesses the anomalous and extreme precipitation conditions based on the probability of precipitation for any desired time scale [29].

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

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 σ is its standard deviation.

Effective Drought Index (EDI) is calculated based on Effective Precipitation (EP) data, considering the loss of precipitation due to evaporation and runoff. Byun and Wilhite [32] suggested the following equation for EP.

$$EP_i = \sum_{i}^{n=1} \left(\sum_{n}^{m=1} P_m \right) / n$$

where i is the number of days of the time window, n running from 1 till i and P_m denotes the precipitation of m days ago in mmd^{-1}. EDI is calculated as,

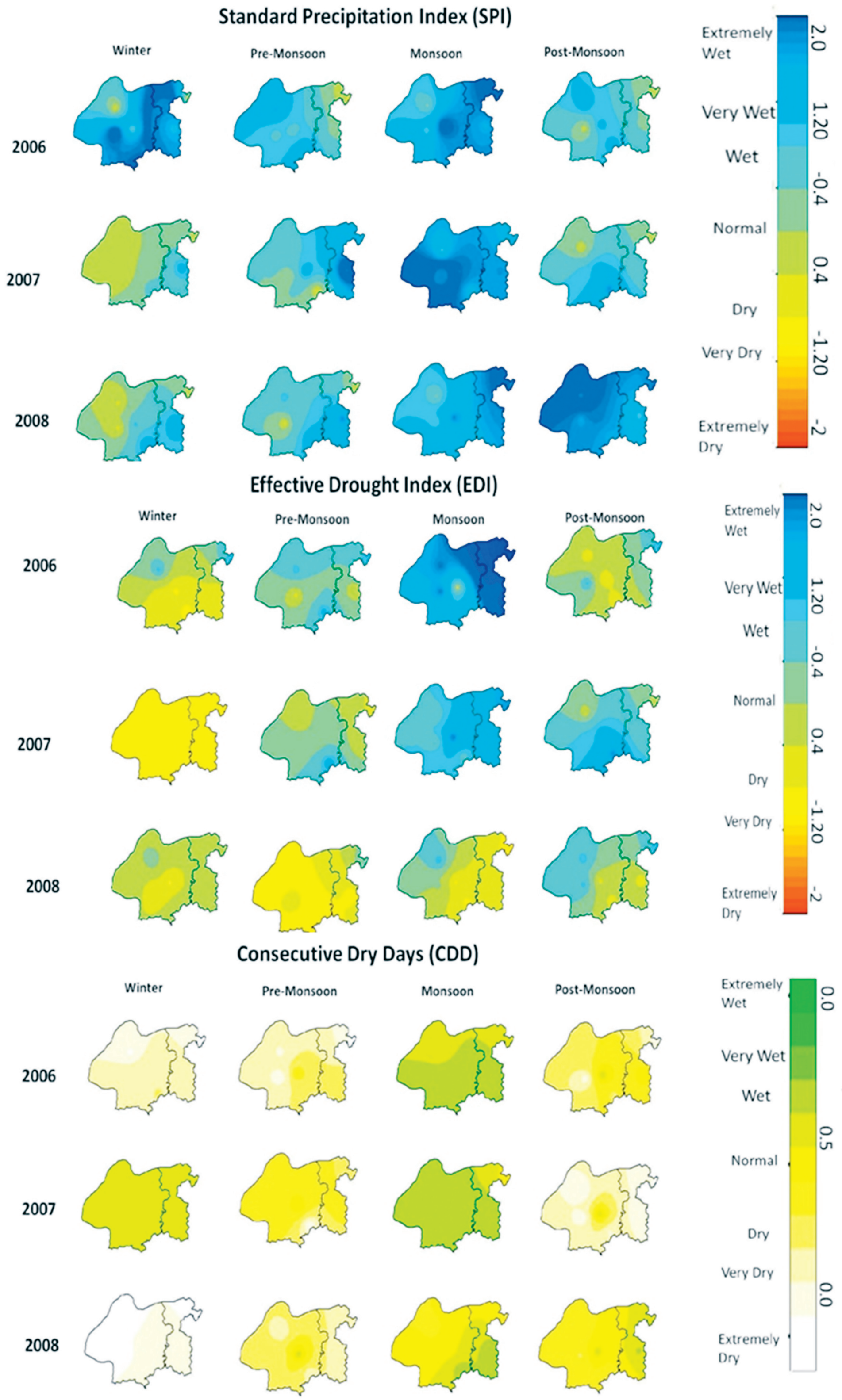

Figure 2. Meterological drought indices

Ryc. 2. Wskaźniki meteorologiczne suszy; u dołu skali – najniższa ilość opadów, u góry skali – najwyższa

EDI = (EPi – μ) / σ

where μ is the mean of effective precipitation, which is subtracted from the EP and divided by σ, the standard deviation of the EP.

Consecutive Dry Days (CDD) The number of Consecutive Dry Days (CDD) is the number of dry days between two wet days

$$C(n) = \sum_{n-L}^{n} 1$$

where C(n) is the number of consecutive dry days and L is the last wet day.

Meteorological Drought Mapping:

SPI, EDI and CDD (Figure 2) have been used to quantify the precipitation deficit from 2006 to 2008. The geographical coordinates of rain stations and well locations were collected and precipitation values were normalized. For the computation of SPI, long-term mean is calculated using seasonal rainfall data for maximum available years, i.e. of 35 years (1973–2008). To calculate the CDD we used the ratio of maximum number of consecutive dry days in the season and the total number of days. Since drought is a regional phenomenon, to demonstrate its spatial extent, SPI, CDD and EDI values of the 6 rain-gauge stations in Jaisalmer district have been interpolated using moving average technique in ILWIS (Integrated Land and Water Information System) software.

3.2 Agricultural Drought Indices

Normalized Difference Vegetation Index (NDVI) (Figure 3) reflects the vegetation health and vigor conditions along with green percent cover and biomass through

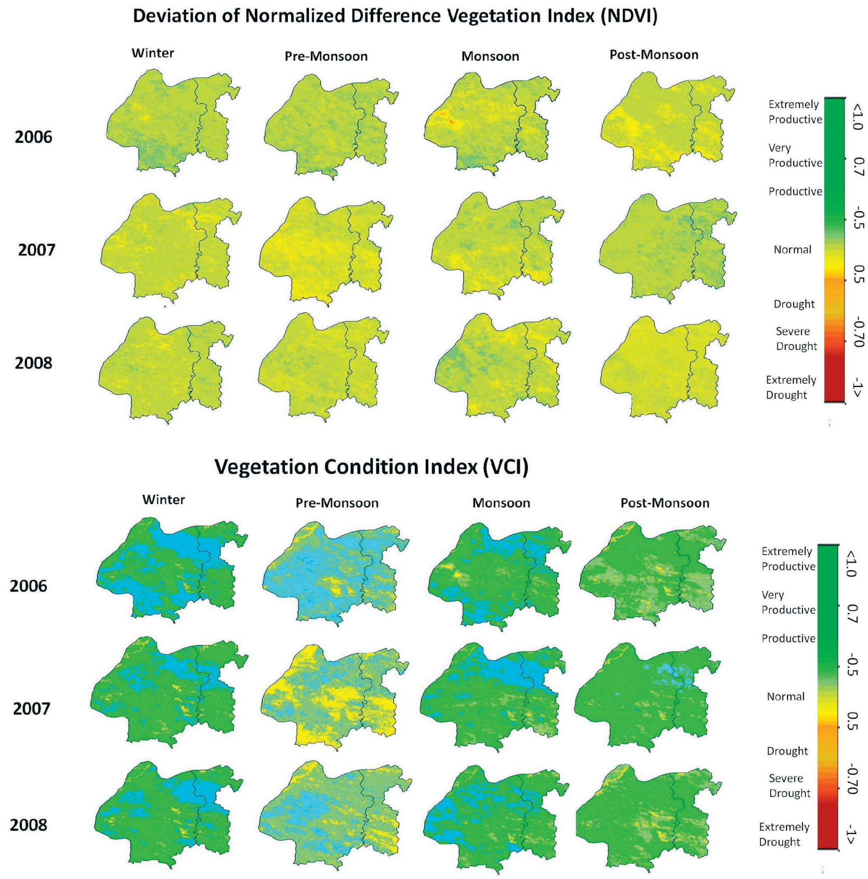

Figure 3. Agricultural drought indices – NDVI and VCI

Ryc. 3. Rolnicze wskaźniki suszy – NDVI I VCI; kolor niebieski i zielony – najwyższa produktywność, kolor czerwony – silna susza the ratio of responses in red and near infrared bands [33, 34, 35, 36]. It is calculated as:

$$NDVI\ (\%) = 100 * (\rho_{nir} - \rho_{red}) / (\rho_{nir} + \rho_{red})$$

Where ρ_{nir} and ρ_{red} is reflectance in the near infrared band and red band respectively.

Vegetative Condition Index (VCI), (Figure 3) is related to the long-term minimum and maximum NDVI (21)

$$VCI\ (\%) = 100 \times (NDVI - NDVI_{min}) / (NDVI_{max} - NDVI_{min})$$

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

Temperature Condition Index (TCI) represents the relative change in thermal condition in terms of brightness temperature [21] whose values are obtained from the thermal band (band 31 of the MODIS data).

$$TCI\ (\%) = 100 * (BT_{max} - BT) / (BT_{max} - BT_{min})$$

where BT, BT_{min} and BT_{max} are the seasonal average of weekly brightness temperature, absolute multi-year minimum and maximum respectively (Figure 4).

Vegetation Health Index (VHI), While VCI and TCI are characterized by varying moisture and thermal conditions of vegetation, VHI represents overall vegetation health (Figure 4) and is calculated as [37].

$$VHI = 0.5(VCI) + 0.5(TCI)$$

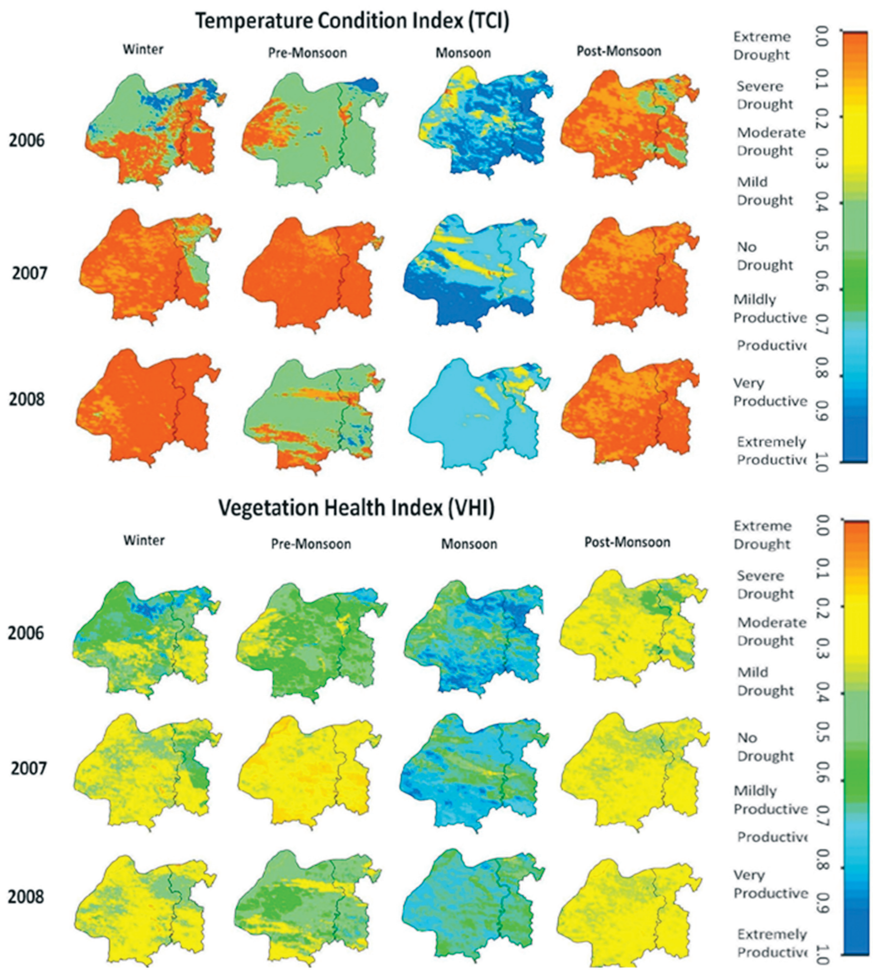

Figure 4: Agricultural drought indices – TCI and VHI
Ryc. 4. Rolnicze wskaźniki suszy – TCI i VHI; kolor niebieski – najwyższa produktywność, kolor czerwony – ekstremalna susza

Modified Soil-Adjusted Vegetation Index 2 (MSAVI2), addresses the soil moisture problem of NDVI (Figure 6). It is calculated as:

$$MSAVI2 = (2 * \rho_{nir} + 1 - \rho\ (2 * \rho_{nir} + 1)2 - 8 * *(\rho_{nir} - \rho_{red})) / 2$$

where ρ_{nir} and ρ_{red} is reflectance in the near infrared band and red band respectively.

Agricultural Drought Mapping: Satellite data with a temporal resolution of 10 days was averaged for a season. The images were geo-referenced prior to this. The region of interest was then extracted followed by calculation of indices. Data with a deviation of NDVI values is calculated with respect to the mean NDVI.

VCI, VHI, TCI and MSAVI 2 maps have been generated by plotting pixel values having 1 km spatial resolution, and have been classified to represent various drought intensities.

3.3. Hydrological Drought Indices

Standardized Water-level Index (SWI) proposed to monitor anomaly in ground-water level as a correspondent of aquifer-stress [19]. The SWI is computed by normalizing seasonal ground-water level and dividing the difference between the seasonal water level and its long term seasonal mean, by standard deviation (Figure 5).

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

where, W_{ij} is the seasonal ground-water level at the i^{th} well and j^{th} observation, W_{im} the long-term seasonal mean and σ is its standard deviation.

Hydrological Drought Mapping: SWI value has been classified and used as a reference to map hydrological drought severity. It has been computed using the mean seasonal water levels of 5 years (2004 − 2008). SWI values of the wells have been interpolated in a GIS environment to generate SWI maps of the region using a similar technique used in SPI.

3.4. Generic Drought Indices

Drought in Jaisalmer district mainly affects the vegetation condition, soil moisture and the groundwater level. This leads to its high arid climate. We introduce the following indices to assess such conditions.

Soil based Vegetative Condition Index (SVCI) related to the long-term minimum and maximum MSAVI2. Using MSAVI2 we account for the soil moisture conditions for vegetative growth (Figure 6).

$$SVCI(\%) = 100 \times \frac{MSAVI2 - MSAVI2_{min}}{MSAVI2_{max} - MSAVI2_{min}}$$

where $MSAVI2$, $MSAVI2_{min}$ and $MSAVI2_{max}$ are the seasonal average of smoothed weekly MSAVI, absolute multi-year minimum and maximum respectively.

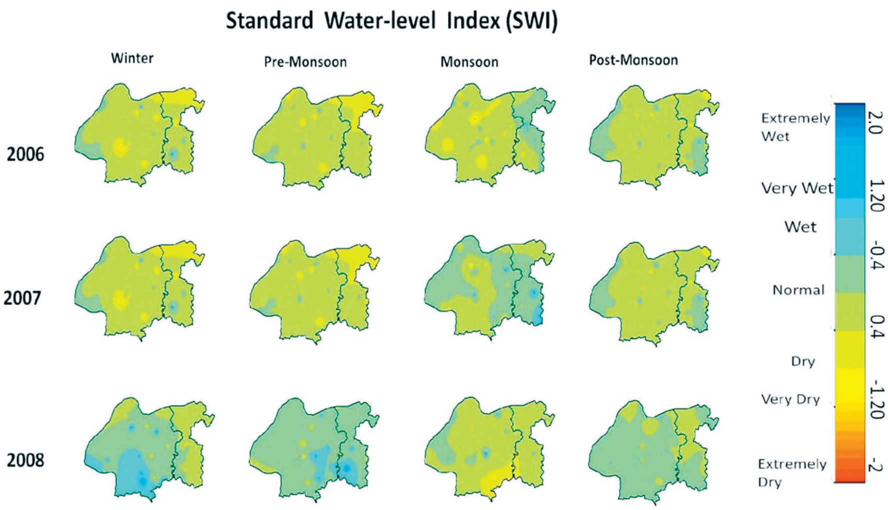

Figure 5. Hydrological drought index

Ryc. 5. Hydrologiczne wskaźniki suszy; kolor niebieski – duży opad, kolor czerwony – silna susza

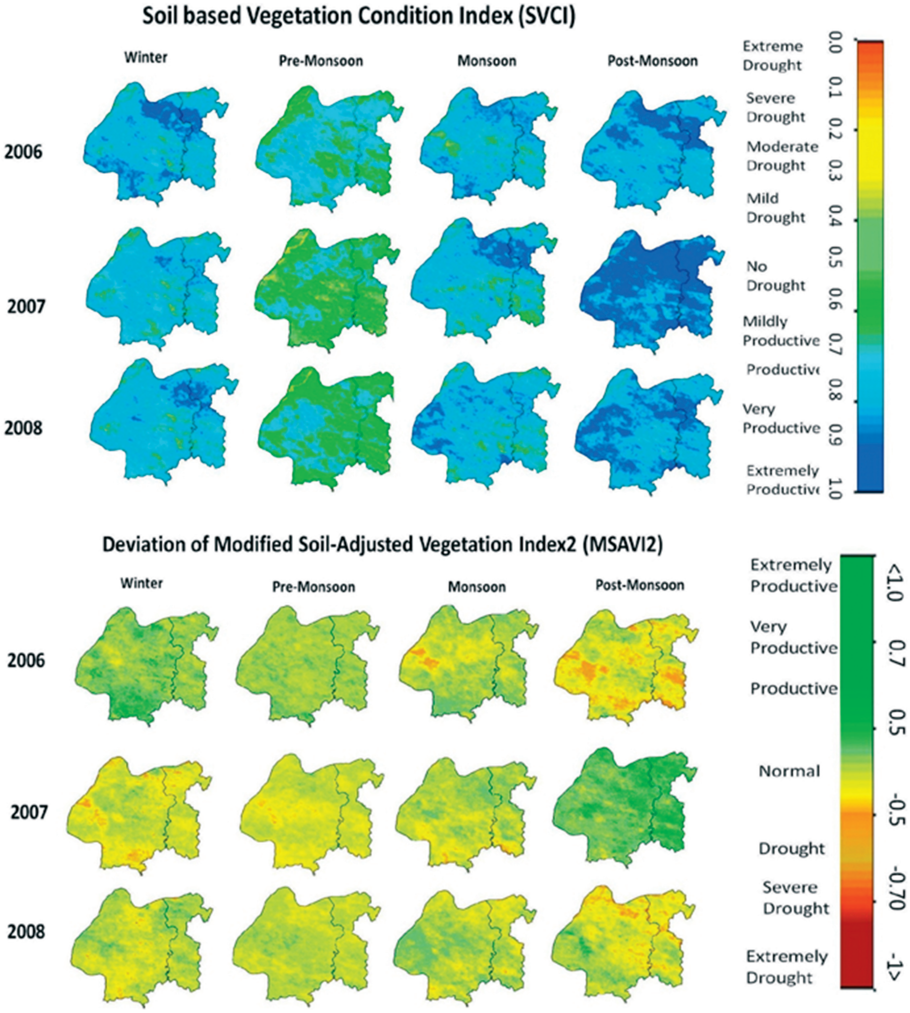

Figure 6. Generic drought indices
Ryc. 6. Ogólne wskaźniki suszy; kolor niebieski i zielony – najwyższa produktywność, kolor czerwony – silna susza

Composite Drought Index assesses overall drought conditions using fluctuations in vegetation and water-table (Figure 7). It is a composite of indices: SVCI, TCI and SWI. CDI index does not measure physical parameters of vegetation or soil; neither does it attempt to simulate the physical phenomena. It is a statistical comparison, it measures how much the present conditions deviate from the reference level, which is the multi-year long-term average, characteristic for the given period.

$$CDI\ (\%) = \alpha SVCI + \beta TCI + \gamma(\delta SW\ I + \eta)$$
$$\alpha + \beta + \gamma = 1$$

where α, β, γ are weight coefficients for the three indices, δ and η are scale coefficients for SWI to match the scale of TCI and SVCI. We use δ = 0.2 and η = 0.4. Coefficients are calculated as follows:

$$\alpha = \frac{Variance\ of\ agricultural\ yield}{Mean\ of\ agricultural\ yield} = 0.3046$$

$$\beta = \frac{Variance\ of\ temperature}{Mean\ of\ temperature} = 0.1377$$

$$\gamma = \frac{Variance\ of\ water\ table}{Mean\ of\ water\ table} = 0.5577$$

where, mean and variances are calculated for long term period.

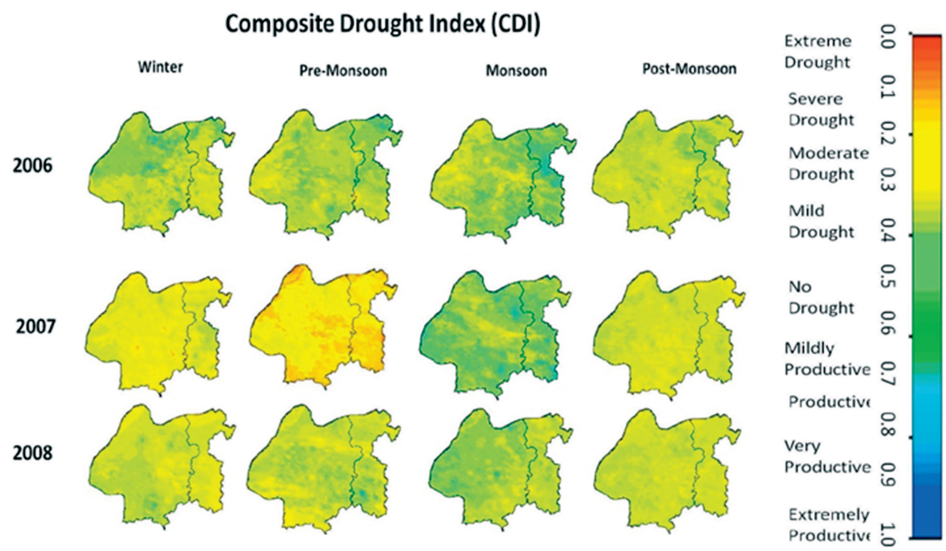

Figure 7. New Index to assess overall drought conditions
Ryc. 7. Nowy wskaźnik oceny wszystkich warunków związanych z suszą; kolor niebieski – najwyższa produktywność, kolor czerwony – największa susza

4. RESULTS AND DISCUSSIONS

Meteorological drought: All the four seasons of 2006–2008 were mostly drought free. The region observed very less rainfall days in the non-monsoon seasons. However, heavy rains were observed during specific days in the winter of 2006 and 2008. The results show that the region has been observed extremely wet flood-like conditions during monsoon of 2006 and 2007. In June and August 2006, the usual drought prone district of Jaisalmer was hit by flash floods. Rains due to cyclone Phet caused havoc in the district. Pokhran in Jaisalmer reported one of the highest rainfalls of the season during these days. The post-monsoon season of 2008 observed high departure of rainfall in December [Indian Meteorological Department]. Departure from rainfall was also seen in winter of 2007. Our results appropriately show these unusually high rainfall patterns for these times.

Hydrological drought: Decline of water level takes place in small pockets both during the monsoon and the non-monsoon periods depending upon rainfall, temperature and draft. During the years 2006–2008, major parts of the Jaisalmer district were free from water-stress. One of the reasons for this is the increase in precipitation, which helped replenish water-levels. Water levels are seen to rise in winter and pre-monsoon season of 2008.

Agricultural drought: During pre-monsoon of 2007, the vegetation experienced the stress and loss of vegetation health (VHI<0.2).We see a decline of both favorable vegetation and temperature conditions during this period. MSAVI2 shows that post-monsoon season of 2006 witnessed mild drought in patches of Jaisalmer district. Winter of 2006 sees improvement in vegetation conditions enhanced by an increase in precipitation and mild temperature conditions. The monsoon season is majorly seen as productive across all indices whereas winter pre-monsoon and post-monsoon seasons experience vegetative stress.

Relative Dynamics: SPI maps indicate that stress due to deficit of rainfall has been low in the Jaisalmer due to heavy rains. This is a departure from historic trends of Jaisalmer. Meteorological drought scenario in the region changed continuously with the season depending upon rainfall amount and spatial distribution. Drought in the ground-water system develops only slowly from meteorological droughts through recharge deficit, and over-exploitation of ground-water resources further enhance. The ground-water levels are seen to be replenished in the winter and pre-monsoon season of 2008 due to higher precipitation as seen in SPI maps. Vegetative drought, neither follows any spatio-temporal pattern nor shows a linear relationship with meteorological and/or hydrological droughts. CDI index shows consistency with the overall conditions shown by agricultural indices. SVCI maps show that overall soil conditions have been favorable for crop production, which is second by the improvement in water-table conditions as shown in the SWI. However the temperature conditions are not so favorable in winter 2007, this has been reflected in CDI map. Thus CDI index assesses overall drought conditions using fluctuations in vegetation conditions, temperature and water-table

5. CONCLUSIONS

The SWI maps show that aquifer-stress shifts its position from time to time. The SPI maps indicate that meteorological dry or wet conditions appear in the Jaisalmer district in a random fashion and have a short lifespan. Vegetation conditions remain normal for longer duration. The time-series maps of different indices show no linear correlation among meteorological, hydrological, and vegetative droughts in the Jaisalmer region. Speed of drought development and drought duration also vary widely. Thus, assessment of drought conditions varies greatly on the parameters used. These parameters take into account the possible causes but not their impact. Despite of negative SPI, a region could be free from water-stress and may maintain normal vegetation. Moreover, drought may appear in regions showing favorable hydrological and vegetation index values in spite of positive SPI.

SWI and VHI, however, represent the negative impact of adverse meteorological and hydrological conditions on water and vegetation, therefore they present better basis for analysis of drought. We take the idea of these indices and form a new amalgamation of them, which is specific to the study area. CDI index thus takes into account the soil moisture for vegetation, the optimal temperature and the groundwater fluctuations and provides a better drought assessment mechanism by setting up a location specific reference level.

6. ACKNOWLEDGEMENTS

We extend our sincere thanks to Indian Meteorological Department (http://www.imd.gov.in/) and US Geological Survey organization (http://earthexplorer.usgs.gov/) for providing the data for this study.

REFERENCES

[1] Dalezios NR, Blanta A, Spyropoulos NV (2012) Assessment of remotely sensed drought features in vulnerable agriculture. Nat. Hazards Earth Syst. Sci., (12): 3139–3150.

[2] Matalas NC (1963) Probability distribution of low flows. USGS Professional Paper 434-A, U.S. Government Printing Office, Washington D.C

[3] Dracup JA, Lee KS, Paulson EG Jr (1980) On a definition of drought. Water Resour. Res. 16 (2), 297–302

[4] UNDP-DDC/BCPR and UN – ISDR, 2005: *Drought Risk and Development Policy Discussion Paper*, Expert Workshop Drought Risk and Development (January 31 – February 2, 2005), at www.undp.org/drylands/docs/drought/Drought discussion Paper.pdf.

[5] Dracup JA (1991) Drought Monitoring, Stochastic Hydrology and Hydraulics 5 (4): 261–266

[6] Nagarajan R (2004). Drought Vulnerability Assessment Using Geoinformatics. Bombay, CSRE, Indian Institute of Technology

[7] Heim Jr. RR (2002) A Review of Twentieth- Century Drought Indices Used in the United States, B. Am. Meteorol. Soc., (83): 1149–1165.

[8] McVicar TR, Jupp DLB (1998). The Current and Potential Operational Uses of Remote Sensing to Aid Decisions on Drought Exceptional Circumstances in Australia: a Review, Agr. Systems (57): 399–468

[9] Knutson C, Hayes M, Phillips T (1998) How to Reduce Drought Risk Preparedness and Mitigation Working Group of the Western Drought Coordination Council, Lincoln, Nebraska (http://drought.unl.edu/handbook/risk.pdf).

[10] Smakhtin VU, Hughes DA (2004) Review, Automated Estimation and Analyses of Drought Indices in South Asia. IWMI Working Paper N. 83 – Drought Series Paper N 1. Colombo, Sri Lanka

[11] Wilhite DA., Hayes MJ, Knutson CL, Smith KH (2000): *Planning for Drought: Moving from Crisis to Risk Management*, Journal of American Water Resources Association 36(4):697–710.

[12] Hicham Ezzine, Ahmed Bouziane, Driss Ouazar. (2014) Seasonal comparisons of meteorological and agricultural drought indices in Morocco using open short time-series data. International Journal of Applied Earth Observation and Geoinformation (26): 36–48.

[13] Naumann G, Barbosa P, Carrao H, Singleton A, Vogt J (2012) Monitoring Drought Conditions and Their Uncertainties in Africa Using TRMM Data. J. Appl. Meteor. Climatol., (51): 1867–1874

[14] Du L, Tian Q, Huang Y, Liu J (2012) Drought monitoring based on TRMM data and its reliability validation in Shandong province, Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering (28): 121–126.

[15] Caccamo G, Chisholm LA, Bradstock RA, Puotinen ML (2011). Assessing the sensitivity of MODIS to monitor drought in high biomass ecosystems, Remote Sens. Environ., 115: 2626– 2639

[16] Thiruvengadachari S, Gopalkrishna HR (1993) An integrated PC environment for assessment of drought. International Journal of Remote Sensing (14):3201–3208

[17] Tian G (1993) Estimation of Evapotranspiration and Soil moisture and Drought Monitoring using Remote Sensing in North China Plain. In Space and Environment, Special Plenary Session. In International Astronautical Federation, 44th IAF Congress Graz, Austria, pp. 23–31

[18] Johnson GE, Achutuni VR, Thiruvengadachari S, Kogan FN (1993) The role of NOAA satellite data in drought early warning and monitoring: Selected case studies. Chapter 3. In Drought assessment, management, and planning: Theory and case studies, ed D. A. Wilhite, 31–48. New York, NY: Kluwer Academic Publishers

[19] Bhuiyan C (2004) Various drought indices for monitoring drought condition in Aravalli terrain of India. Proceedings of the XXth ISPRS Conference, Istanbul, 12–23 July 2004, pp. 907–912

[20] Tian G, Jupp DLB, Qin Y, McVicar TR, Li F (1998) Monitoring Soil Moisture and Drought Using AVHRR Satellite Data II: Applications. CSIRO Earth Observation Centre, Canberra, ACT

[21] Kogan FN (1995) Droughts of the late 1980s in the United States as derived from NOAA polar orbiting satellite data. Weather in the United States. Bulletin of American Meteorological Society (76): 655–668

[22] McVicar TR, Tian G, Jupp DLB, Li F (1993). Soil moisture and drought monitoring using remote sensing. In Proceedings of the 14th Asian Conference on Remote Sensing Tehran, Iran, pp. A.5.1 – A.5.6

[23] Anderson MC, Hain C, Wardlow B, Pimstein A, Mecikalski JR, Kustas WP (2011) Evaluation of drought indices based on Thermal remote sensing of evapotranspiration over the continental United States, J. Climate (24):2025–2044.

[24] Kanellou E, Spyropoulos N, and Dalezios NR (2011) Geoinformatic Intelligence Methodologies for Drought Spatiotemporal Variability in Greece, Water Resour. Manage. (26): 1089–1106

[25] Thenkabail PS, Enclona EA, Ashton MS, Legg C, Jean De Dieu M (2004) Hyperion, IKONOS, ALI, and ETM+ sensors in the study of African rainforests . Remote Sensing of Environment (90): 23–43

[26] Eklundh L (1996) AVHRR NDVI for Monitoring and Mapping of Vegetation and Drought in East African Environments, Meddelanden fran Lunds Universitets Geografiska Institutioner, 126, Lund University Press, Lund, Sweden, 187 p.

[27] Vogt JV, Viau AA, Beaudin I, Niemeyer S, Somma F (1998). Drought Monitoring from Space Using Empirical Indices and Physical Indicators, Proc. Int. Symp. on Satellite-Based Observation: A Tool for the Study of the Mediterranean Basin , Tunis, Tunisis, 7 p.

[28] Gosh TK (1997) Investigation of Drought Through Digital Analysis of Satellite Data and Geographical Information Systems, Theor. Appl. Climatol . (58): 105–11

[29] McKee TB, Doesken NJ, Kleist J (1993) The Relationship of Drought Frequency and Duration to Time Scales, Proc. 8th Conf. on Appl. Clim ., 17–22 Jan. 1993, Anaheim, CA, 179–18

[30] Shafer BA, Dezman LE (1982). Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. In: Proceedings of the Western Snow Conference, Fort Collins, CO, pp. 164âA˘ S¸ 175.

[31] Chatterji PC, Kar A. (Eds.) (1992). Integrated natural and human resources appraisal of Jaisalmer district. CAZRI, Jodhpur, P.156.

[32] Byun HR, Wilhite DA (1999). Objective quantification of drought severity and duration. J. Climate (12): 2747–2756.

[33] Tucker CJ (1979) Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment (8) :127–150

[34] Teillet PM, Staenz K, Willams DJ (1997) Effects of spectral, spatial, and radiometric characteristics on remote sensing vegetation indices of forested regions. Remote Sensing of Environment (61): 139–1

[35] Baret F, Guyot G (1991) Potentials and limits of vegetation indices for LAI and APAR assessment. Remote Sensing of Environment (35):161–173

[36] Thenkabail PS, Gamage MSDN, Smakhtin VU (2004) The Use of Remote Sensing Data for Drought Assessment and Monitoring in Southwest Asia, Research Report, International Water Management Institute (85): 1–25

[37] Kogan FN (1990) Remote sensing of weather impacts on vegetation in non-homogeneous areas. Int. J. Remote Sensing, 11(8): 1405-1419