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RESEARCH ARTICLE

# An Estimation of Hydrometeorological Drought Stress over the Central Part of India using Geo-information Technology

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**Abstract**
Drought is a creeping natural hazard commencing from lack of rainfall and generally associated with various climatic aspects. Drought-related water deficiency has severe consequences upon environmental processes and socioeconomic activities. In the past few decades, a number of drought indices have been developed for assessing the extent, onset, duration and intensity of drought. The Bundelkhand region located in the central part of India has been affected by recurrent drought events during the past few decades. This study seeks to examine hydrometeorological drought stress of that area using remote sensing and meteorological indicators, i.e., standardized precipitation index (SPI), hydrology-based rainfall anomaly index (RAI) and standardized water-level index (SWI). Daily rainfall data from Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) and Tropical Rainfall Measuring Mission (TRMM) were integrated with station-based groundwater datasets (1998–2015) to analyze the hydrometeorological drought condition of the area. In addition, groundwater datasets were used to evaluate the long-term hydrological drought situation and compared with meteorological drought indices. The study reveals a good agreement among all hydrometeorological drought indices distinctly in few years (2002 and 2013). However, the findings were not coherent in all years due to high rate of runoff and poor groundwater recharge. In spite of having normal rainfall, the undulating terrains of this rugged land confine the infiltration process and cause hydrological drought stress in several parts of the area.

**Keywords** Drought assessment · SPI · RAI · CHIRPS · TRMM · SWI · Bundelkhand

## Introduction

Drought is considered as an extreme climatic phenomenon, having widespread impacts with large spatial and temporal scales and causes severe damage to crops, livestock and human society (Lin et al. 2013; Gupta et al. 2014). It is a creeping hazard with slow onset, indefinite commencement and termination. Unlike other natural hazards, drought has been considered as a most costly natural disaster (Hao et al. 2014) which affects large number of people comparing to other natural hazards across the world (Wilhite 2000). It has been categorized into three major groups: meteorological, agricultural and hydrological according to its concept of utilization.

Among various established indices of meteorological drought, the SPI is a popular and robust method for monitoring drought stress (McKee et al. 1993; Wilhite et al. 2000; Cancelliere and Rossi 2003; Patel et al. 2007; Raziei et al. 2009; Kumar et al. 2012; Mirabbasi et al. 2012; Dutta et al. 2013, 2015; Kundu et al. 2015, 2016). According to Guttman (1998), SPI is an excellent indicator to measure wetness or dryness in different timescales in comparison with the Palmer drought severity index (PDSI). Hayes (1999) illustrated that SPI is capable to monitor the

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spatiotemporal extent of drought situation. It can be estimated using mean seasonal rainfall in a particular range of diverse climate zones (Agnew 2000). Patel et al. (2007) found SPI with 3-month timescale suitable for identifying drought stress in Gujarat, a state of western India. It is proved to be one of the most reliable indicators for assessing the district-wise drought situation in India (Pai et al. 2011). In their study, Dutta et al. (2013) found SPI with lag three is most suitable for the prediction of agricultural drought. This index has been applied for assessing meteorological drought in hot sub-humid and semiarid regions of India using satellite-based long-term gridded rainfall datasets (Dutta et al. 2013; Kundu et al. 2015; Patel and Yadav 2015; Sahoo et al. 2015). Zakhem and Kattaa (2016) analyzed the characteristics of long-term hydrometeorological drought in the eastern Mediterranean region using cumulative SPI. Deo et al. (2017) compared SPI, RAI and rainfall decile drought index (RDDI) for assessing short-range drought (dry spells) scenario. Another study performed by Mossad and Alazba (2018) has used monthly precipitation data for SPI time series analysis and applied ARIMA and FBNN models for predicting drought stress in arid ecosystems. Dhurmea et al. (2019) analyzed drought climatology (dry and wet conditions) in the island of Mauritius using long-term SPI (1953–2007).

Hydrological drought is a shortage of surface and subsurface water volume, and thereby it is interrelated to agricultural (soil water deficit) and meteorological drought (rainfall scarcity and enhanced evapotranspiration) (Wilhite and Buchanan-Smith 2005). Several studies applied SWI for analyzing hydrological drought over different regions worldwide. Hydrological drought scenario has been examined for pre-monsoon and post-monsoon seasons using groundwater-level datasets in different regions of India (Bhuiyan 2004; Sahoo et al. 2015). In their study, Mishra and Nagarajan (2013) evaluated hydrological drought through SWI and well-based seasonal groundwater data of Tel watershed of Orissa. Mohammad et al. (2018) computed SWI using the mean seasonal groundwater level of 22 years for assessing hydrological drought severity in Yarmouk Basin (Jordan). Potopová et al. (2019) identified the effect of hydrological drought stress and agricultural practices using SWI and ground observation in the Prut river basin (Europe).

Understanding the hydrometeorological drought is crucial for identifying the potential areas of agricultural drought stress. Although a lot of past studies have emphasized on drought monitoring, there is a gap in hydrometeorological researches. It has been also found that very few researches on meteorological drought have used satellite-based merged rainfall products. On this background, the present study aims to monitor the spatiotemporal pattern of hydrometeorological drought stress over the central part of India (Bundelkhand region).

## Study Region

Bundelkhand region is well known for its recurrent drought events and famines. As per Loveday (1914), the region was severely affected during "The Panic Famine" of 1873–1874. It lies at the heart of India, geographically between 23°20′N to 26°20′N latitude and 78°20′E to 81°40′E longitude. The total area of the region is 7.08 million hectares (Mha) and extended across thirteen districts: seven in Uttar Pradesh State and six in Madhya Pradesh State (Fig. 1). The central and northern part of the region is characterized by hard rocks with undulating plains (< 300 m) that cover up approximately 67% of the region. The soils are generally red–yellow and black (mix) in nature, containing less amount of organic matter. This region falls under hot semiarid and sub-humid agroecological zone with hot summer (April–June) and cold winter (December–January) seasons. It receives about 800–1000 mm rainfall during monsoon season (July–August). Most of the region is rain-fed, and less than 25% of the total area comes under the category of double-crop cultivation.

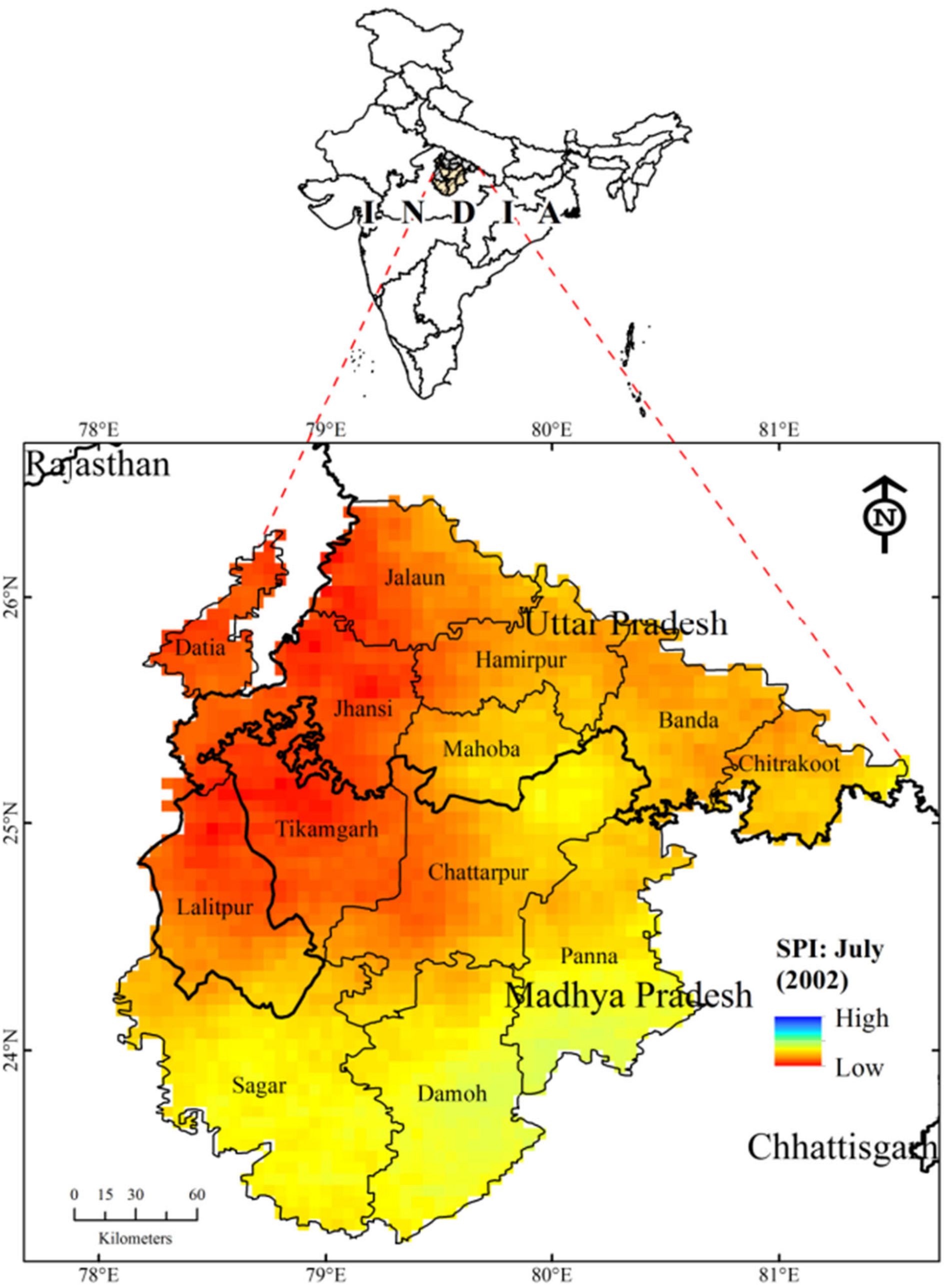
## Materials and Methods

### Datasets

With the advancement of satellite-based meteorological observations, the application of gridded precipitation datasets like TRMM and CHIRPS has become popular. Unlike the scattered in situ station-based datasets, they provide seamless data and reduce the chance of error (Mossad and Alazba 2018). TRMM, an international joint project of NASA and JAXA, provides superior estimates of monthly rainfall at 0.25° × 0.25° spatial resolution. It has been widely used by the scientific community since its launching in 1997. The high spatial and temporal resolution makes it popular for studying tropical rainfall (Sassa et al. 2014), hydrological models (Li et al. 2012; Meng et al. 2014), hydrological predictions (Su et al. 2008) and drought assessment (Naumann et al. 2012). Monthly TRMM-based precipitation datasets collected for a period 1998–2015 have been used for estimating RAI.

CHIRPS datasets, prepared by the United States Geological Survey (USGS) and the Climate Hazards Group at the University of California, Santa Barbara, USA, have been proved to be a reliable precipitation dataset for analyzing long-term trend, water stress and drought

**Fig. 1** Study area




monitoring (Shukla et al. 2014; Funk et al. 2015; Tote et al. 2015; Dinku et al. 2018). It is a merged product of three diverse datasets, (1) global precipitation climatology at 0.05° (5.3 km) resolution, (2) satellite-based climate model precipitation estimates and (3) in situ precipitation observations. In this study, the monthly CHIRPS data for the period 1998–2013 have been used for estimating SPI.

Groundwater-level data were collected from the Central Ground Water Board (CGWB), Ministry of Water Resources, Govt. of India. They provide a Web-enabled interface for accessing station-based groundwater-level data of the country from Water Resources Information System known as India-WRIS, a joint scheme of the Central Water Commission (CWC), Ministry of Water Resources and Indian Space Research Organization (ISRO), Govt. of India. Groundwater-level data from 271 stations across the Bundelkhand region were collected for the period, 1998–2013. In order to analyze the spatiotemporal extent of hydrological drought through the standardized water-level index, groundwater-level data of post-monsoon season have been used.

## Methods

### Standardized Precipitation Index (SPI)

Standardized precipitation index propagated by Mckee et al. (1993) is a robust index for the time series analysis of cumulated precipitation and characterization of meteorological drought (Caparrini and Manzella 2009). The raw precipitation of a station is generally fitted to a probability (gamma) distribution, which is then altered to an ordinary distribution in such order that the mean SPI is zero (Edwards and McKee 1997). The gamma distribution function can be expressed as follows (Eq. 1):

$$g(x) = \frac{x^{\alpha-1} \cdot e^{-\frac{x}{\beta}}}{\beta^{\alpha} \cdot \Gamma(\alpha)} \quad \text{for}\, x > 0 \tag{1}$$

where $\alpha > 0$ is a shape parameter, $\beta > 0$ is a scale parameter, $x$ is the precipitation amount, and $\Gamma\ (\alpha)$ is the gamma function.

### Rainfall Anomaly Index (RAI)

Rainfall anomaly index is one of the most efficient and simple meteorological drought indexes used successfully by the researchers (Van Rooy 1965; Dutta et al. 2015; Kundu et al. 2016). Average annual rainfall of Bundelkhand region was collected for a period of sixteen years (1998–2013), and rainfall anomaly of every year was estimated using long-term mean rainfall of study region. The years with negative RAI indicate less rainfall than long-term mean rainfall and vice versa. Significant negative departure from long-term mean indicates a deficit of rainfall and drought-related water stress. The RAI is expressed as follows (Eq. 2):

$$\text{RAI} = (R - \mu)/\sigma \tag{2}$$

where, $R$ = rainfall; $\mu$ = long-term average rainfall; $\sigma$ = standard deviation

### Standardized Water-Level Index (SWI)

It has been widely used by the researchers for analyzing hydrological drought (Sahoo et al. 2015; Kundu et al. 2016). The severity of hydrological drought can be assessed by the levels of SWI as mentioned in Table 1. The SWI expression specified by Bhuiyan (2004) is as follows (Eq. 3):

$$\text{SWI} = (Wij - \text{Wim})/\sigma \tag{3}$$

where $Wij$ is the water level (seasonal) for the $i$th well and $j$th observation,Wim is the long-term mean (seasonal) and $\sigma$ is the standard deviation (Bhuiyan et al. 2006).

**Table 1** Categorization of hydrological drought based on SWI

| SWI | Drought classes |
|---|---|
| > 2.0 | Extreme |
| > 1.5 | Severe |
| > 1.0 | Moderate |
| > 0.0 | Mild |
| < 0.0 | No-drought |

## Results and Discussion

### Meteorological Drought Assessment

Standardized precipitation index is considered as a useful and robust index for understanding the spatiotemporal extent of long-term historical droughts. SPI-based meteorological analysis was carried out for the years 1998 to 2013 that reveals occurrences of drought-related stress in several years (Fig. 2). It is notable that extremely dry condition with SPI $< -2$ was observed in the year 2002. This year was declared as the drought year in India as a major part of the country was affected due to severe drought. The Bundelkhand region was not an exception as we observe in the SPI map of 2002. In addition, the study reveals evidences of mild-to-moderate meteorological drought stress in 2004, 2007 and 2009. In those years, the districts of the northern and northeastern region significantly affected due to lack of sufficient rainfall. It was observed that more than 90% of the total area except Chitrakoot and Sagar districts was under mild-to-moderate drought stress in 2003 and almost similar condition prevailed during August and September months of 2012 (Fig. 3). On the other hand, a reverse situation observed in 2007, which was considered as a normal year.

The RAI developed by Van Rooy (1965) is another useful index for identifying positive and negative departure of rainfall. Several studies proved that vegetation growth of an area depends upon the amount of rainfall it receives. Long-term RAI from 1998 to 2015 was used to analyze the spatial and temporal pattern of rainfall, and the years with remarkable low rainfall were identified. The study found that RAI values were significantly less in the years 2002, 2006 and 2007, indicating acute rainfall deficit and meteorological drought stress in most of the areas (Fig. 4). RAI values were estimated less than $-1.5$ in those years, whereas the values were positive ($> 1.5$) in the years 1999, 2003, 2011 and 2013. It was found that the results from RAI were quite identical with SPI as it reveals the incidence of severe drought and normal condition in 2002 and 2013, respectively. It is worthy to mention that previous researches on droughts of Bundelkhand also agreed with the occurrences of severe drought condition in 2002 (Patel and Yadav 2015; Thomas et al. 2016).

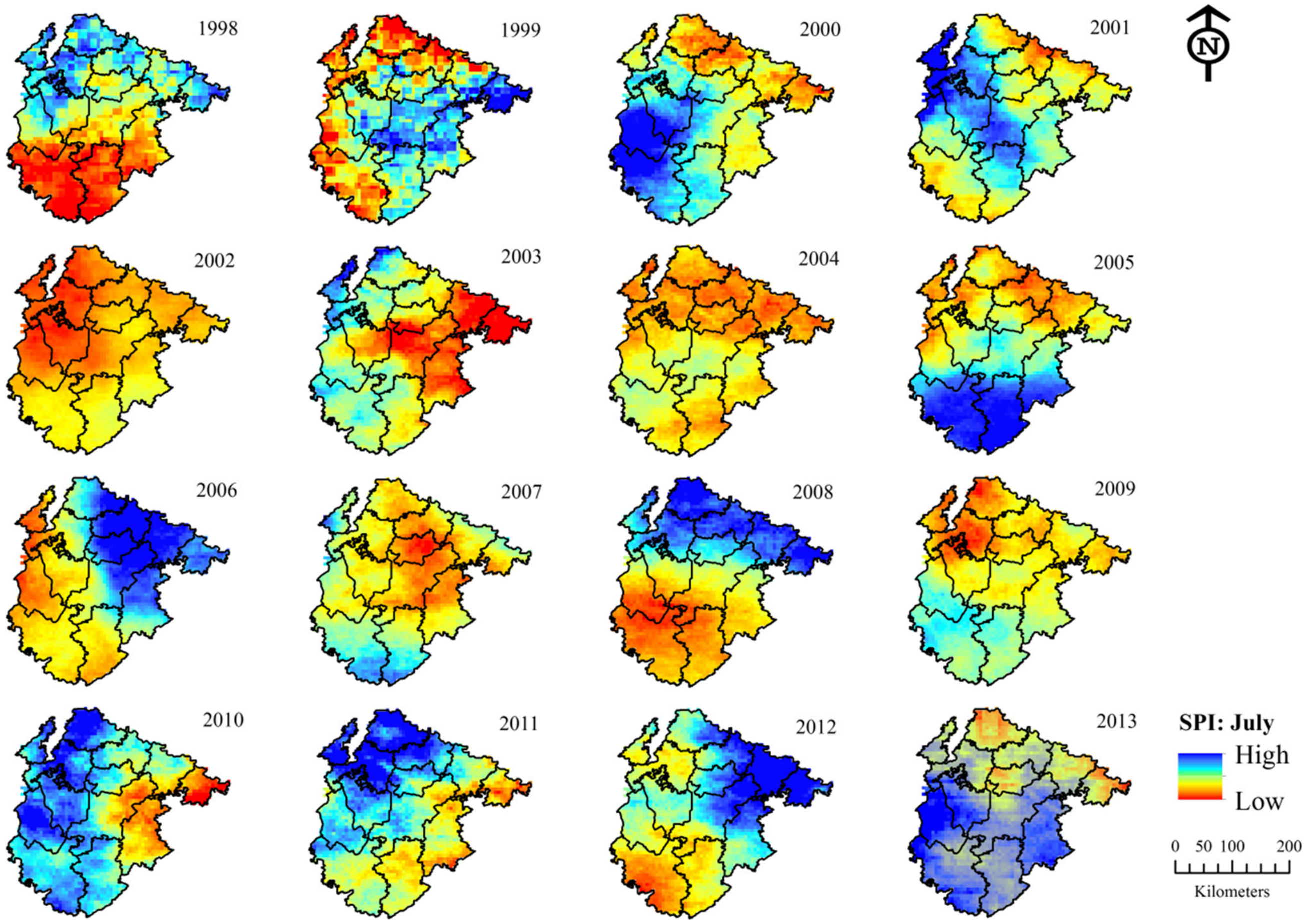



**Fig. 2** Long-term spatial pattern of SPI for the month of July

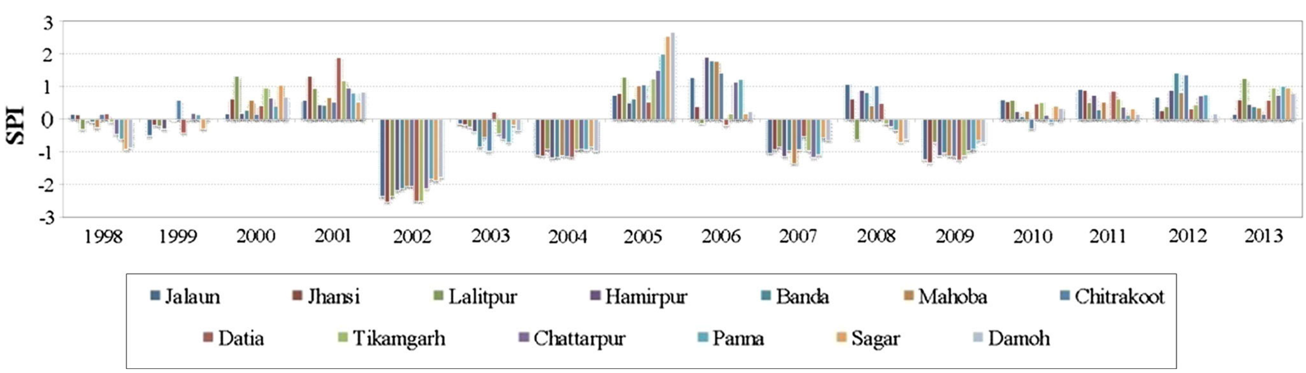



**Fig. 3** Year-wise mean SPI

The year-wise average RAI depicts recurrent drought stress happened during the period 1998 to 2015 over the study region (Fig. 5). Meteorological condition of an area is considered as the most important and triggering factor responsible for outbreak of drought. Deficit of precipitation from its long-term mean can be a useful indicator of drought as it significantly affects soil moisture, surface and groundwater and most importantly rain-fed agriculture. The availability of water for a plant is determined by the rainfall received by an area. The agricultural lands those are dependent upon monsoonal rainfall experience water stress and consequent loss of production during the hydrometeorological drought years.

## Hydrological Drought Assessment

Meteorological drought adversely affects surface water level, especially the availability of water in reservoirs and

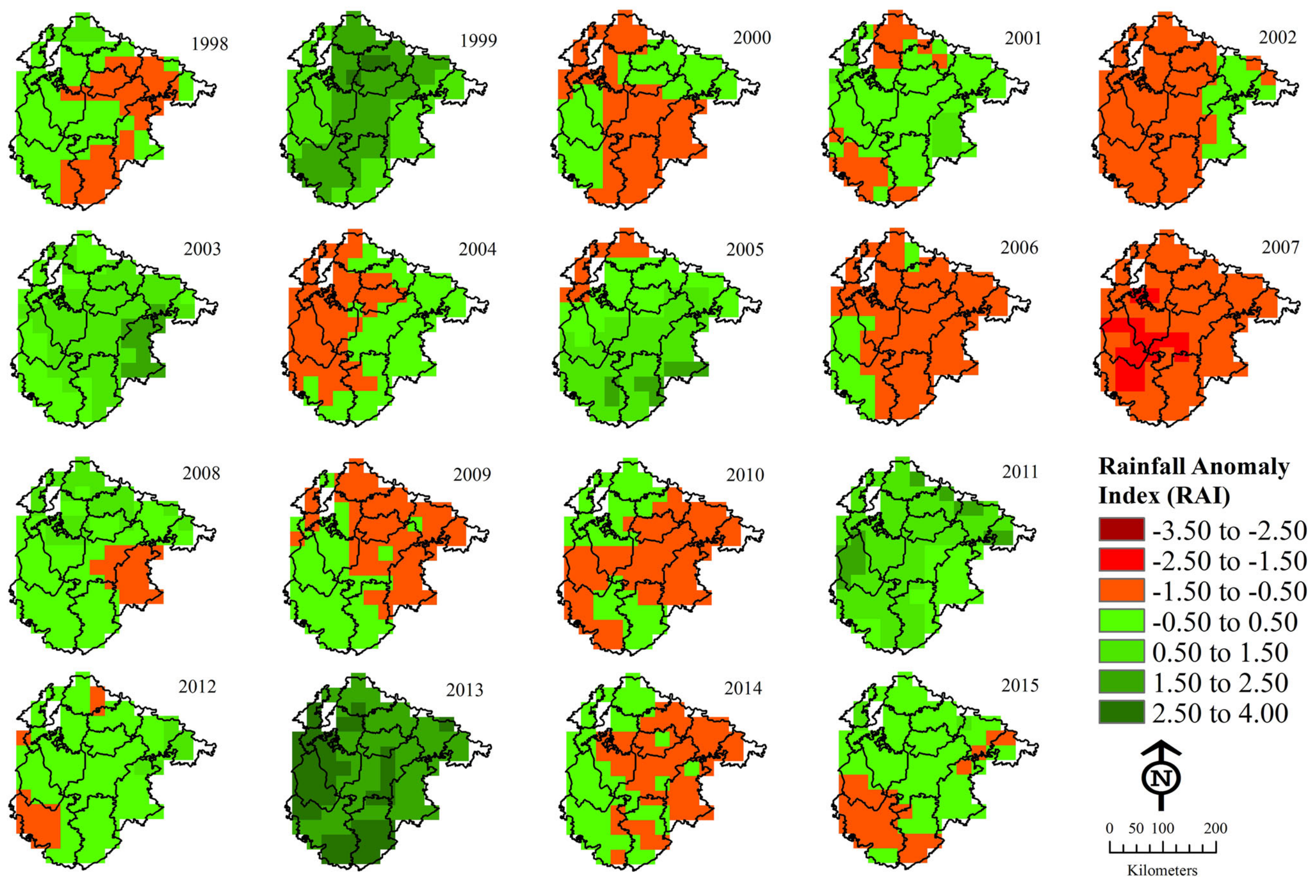
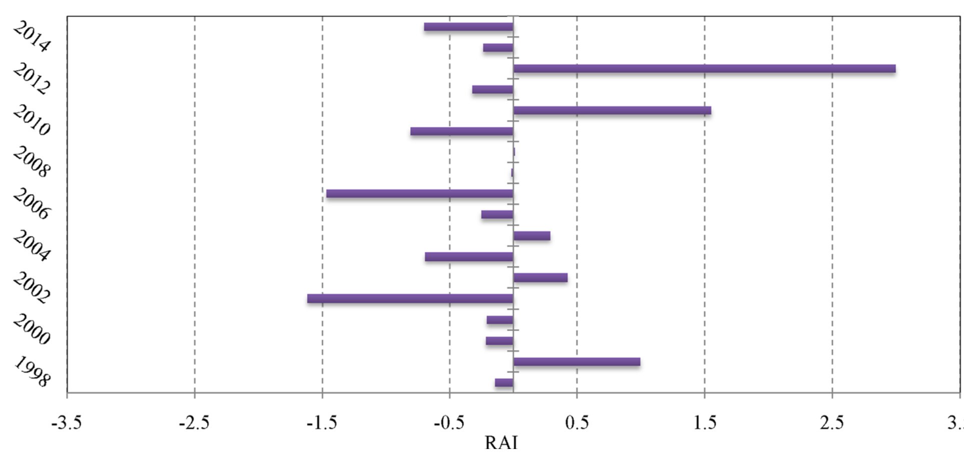



**Fig. 4** Spatiotemporal pattern of rainfall anomaly index (RAI)

**Fig. 5** Year-wise RAI pattern (1998–2015)




tanks. Besides, it determines the groundwater storage as all these components are interlinked with each other. The spatiotemporal variation of standardized water-level index (SWI) was estimated in the study to analyze the hydrological drought condition over the Bundelkhand region. The station-wise water-level data were interpolated for estimating the district-wise SWI. For SWI analysis, water-level data of post-monsoonal season were taken into account. The spatiotemporal analysis of SWI reveals moderate to mild drought condition in most of the years during the period 1998–2013. However, extreme drought stress was evident in the year 2002 as SWI values were distinctly high (> 2) all over the area. The study reveals a shortage of groundwater in most of the years, indicating the occurrences of recurrent hydrological drought in the area (Fig. 6).

The district-wise variation in SWI was shown to assess the spatiotemporal extent of water stress during the drought

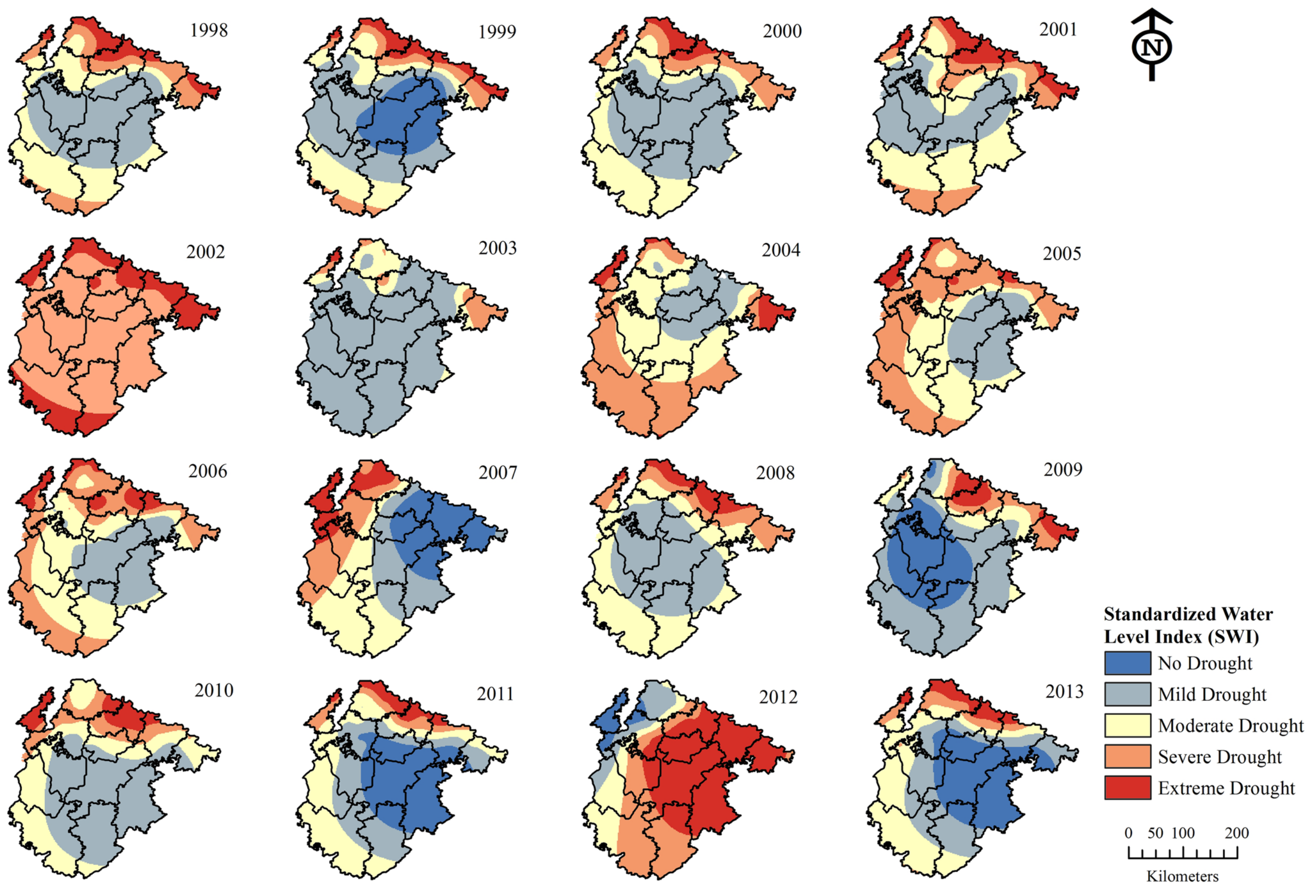



**Fig. 6** Year-wise spatial pattern of SWI (1998–2013)

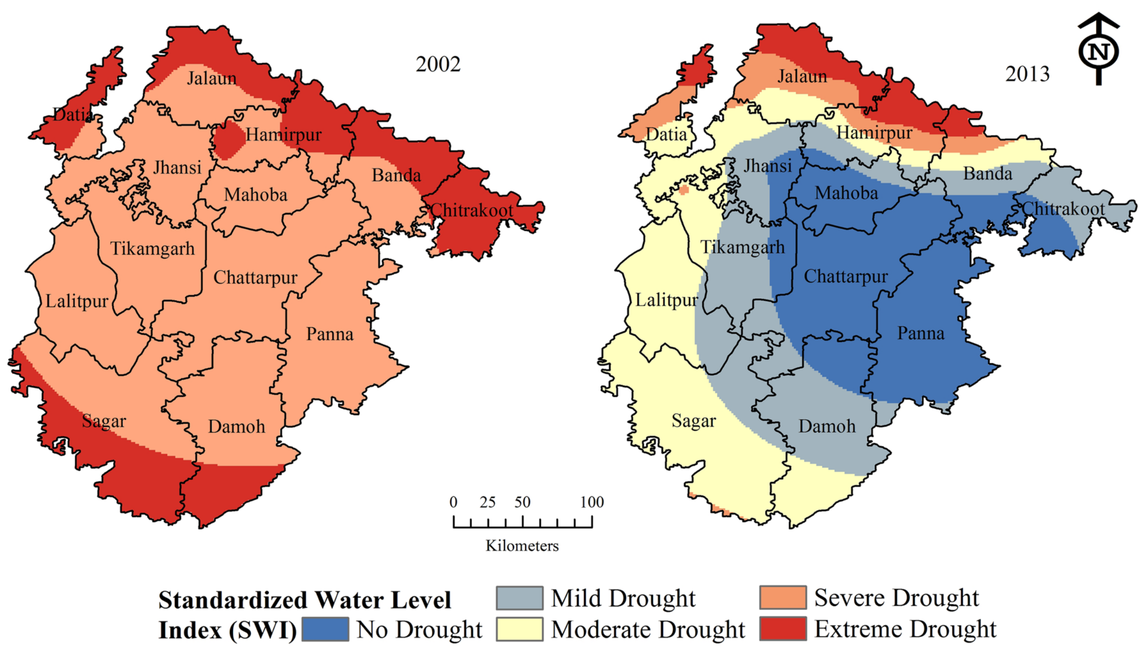



**Fig. 7** Spatial pattern of SWI for drought (2002) and normal year (2013)

year 2002 and normal year 2013 (Fig. 7). It shows a good agreement with the findings of meteorological drought indicators SPI and RAI. However, lack of sufficient groundwater recharge and high rate of runoff play a significant role in hydrological drought in this region.

## Conclusions

The present study aims to assess the hydrometeorological drought stress over the Bundelkhand region lying in the central part of India by using meteorological and hydrological drought indices. Station-based groundwater level data and satellite-based merged rainfall products have been used in the study. The SPI estimated from long-term satellite-based CHIRPS rainfall data proved to be useful for identifying meteorological drought stress over the region. There was a good agreement in drought assessment of SPI, RAI and SPI in few years. However, the findings were not coherent in other years. This area is characterized by undulating plains and rugged topography that confine the rainfall to be penetrated in the soil layers. Most of the rainfall received by this area drains out as surface runoff, resulting in poor storage of groundwater. The deficit in groundwater is evident from the SWI maps. In spite of having normal rainfall, this area experienced mild-to-moderate drought in few years. The hydrometeorological drought assessment of the area unveils the root cause behind the recurrent droughts of Bundelkhand region. The unique topography of this region plays an important role in frequent outbreak of drought and poor agricultural productivity. The increasing frequency of droughts can also be linked with erratic monsoon. Lack of irrigational facilities is common in most of the areas, and as a result, a large part of the area still depends upon monsoonal rainfall for agriculture. The areas without irrigational facilities are mainly single cropped area; thus, emergence of hydrometeorological droughts adversely affects agricultural productivity and socioeconomic condition of the area as a whole. The study agrees with the findings of previous researches on drought assessment of the region (Gupta et al. 2014; Patel and Yadav 2015; Kundu 2018). The hydrometeorological drought assessment using multi-temporal satellite-based and in situ datasets can be useful for policy-makers and planners to adopt positive measures toward reducing the frequency of droughts in Bundelkhand. Moreover, the assessment of hydrometeorological drought is significant considering the complex and cumulative impacts of climate change in such vulnerable region.

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