Estimation of Drought Indices for Assessing the Impact of Climatic Variables on Groundwater Fluctuation over Upper Bhima Sub Basin

A B Jipkate1,a,*, D S Londhe2,b and Y B Katpatal3,c

1 M.Tech Scholar, Department of Civil Engineering, Visvesvaraya National Institute of Technology, Nagpur, Maharashtra, India
2 Research Scholar, Department of Civil Engineering, Visvesvaraya National Institute of Technology, Nagpur, Maharashtra, India
3 Professor, Department of Civil Engineering, Visvesvaraya National Institute of Technology, Nagpur, Maharashtra, India

Email: aakshyjipkate@gmail.com; bdigambarlondhe@students.vnit.ac.in; cybkatpatal@civ.vnit.ac.in

Abstract. Groundwater is an essential part of the hydrological cycle. The ultimate source of the groundwater is precipitation that occurs over the surface of the earth. Stress condition in groundwater reflects the vulnerability of drought events. In areas with ample soil moisture and without irrigation facilities, groundwater abstraction eventually leads to a decrease in agricultural yield. For the assessment of groundwater fluctuations, hydrological drought indices play a significant role in drought conditions. In Upper Bhima sub-basin, maximum area is under scarcity zone and partly under assured rainfall zone (Western part) and partly in transition zone I & II (Western part) with average annual rainfall of 690 mm. In the present study, standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI) and standardized water level index (SWI) is used to assess meteorological and hydrological drought conditions respectively. As SWI reflects aquifer stress, it is also used to understand groundwater decline and recharge in the present study region. SPI and SPEI are estimated by using precipitation and temperature data for yearly aggregated time scale, while SWI is obtained by normalising groundwater level data. Precipitation and temperature data are obtained from gridded reanalysis data product of NCEP – CFSR (spatial resolution approx. 38 km) for the period of 2002 – 2014. Groundwater level data is obtained from Central Ground Water Board for the period of 2002 – 2016. Spatio-temporal map of SPI, SPEI and SWI has been generated. No direct linear relationship has been observed between SPI and SWI; and between rainfall and SWI over the region. Hence, topography, aquifer properties, soil type and lithology may affect groundwater fluctuation in the region.

1. Introduction

Drought is natural hazards affecting an area with tangible and non-tangible repercussions gripping society. Frequent drought in Maharashtra has compelled researchers to analyze the origin and impact of these events. When drought occurred over the region shows decreasing water level due to inadequate rainfall, more evapotranspiration and more water use and commonly all these parameters are studies with the help of various drought indices develop by many scientists [1-5]. The present study attempts to
carry out detailed analysis of metrological data (obtain from the assimilated data product of the national Centre for the Environmental prediction-climate forecast system reanalysis of the upper Bhima region has been carried out for the period of 2002-2014). It shows that when one index recognizes normal drought condition at one place at same time same area shows severe drought conditions [6]. The drought is observed at different places of earth, while precipitation deficiency is the major causative parameter, water level beneath the ground and flow of water in the stream are the essential parameters impacting drought conditions. Flow in stream and groundwater, storage in reservoir shown longer-term rainfall anomalies.

In Maharashtra, precipitation mainly depends on the complex southwest monsoon. Therefore, deficit monsoon may lead to drought-like situations which especially affect small and marginal farmers as they have to witness crop loss due to erratic precipitation and drought. Less rainfall may cause a decline in groundwater level, leading to adverse surface and subsurface environmental effect [2]. Rainfall is only possible way for groundwater recharge in soil and rock in upper Bhima sub basin region. In this region western ghat received more rainfall compare to another region. Most of the people in these areas depend totally on groundwater resources for different purposes. Due to Frequent anomalies of more temperature with less rainfall in particular year reduces ground water, high ground water stress is observed in many parts of the region. The meteorological and hydrological drought both together adversely affects the development of the agriculture land and vegetation over the land and crop production in agriculture. Scarcity of water is observed in most of the Indian foreland basin, where groundwater resources are important source to hold agricultural practices, a large part of the study area experienced water deficit.

In the present study, different drought indices have been carrying out to study the spatial pattern related to drought. Spatial maps of the different drought indices such as standardized precipitation Index (SPI), standardized precipitation Evapotranspiration Index (SPEI) and standardized water level Index (SWI) have been generated for upper Bhima sub basin area in Geographic Information System (GIS) environment. Rainfall controlled, groundwater recharge, activities related to agriculture, ecological change, and the present study focus on drought during monsoon period. Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) indicate drought related to meteorological conditions. Analysis pertaining to hydrological drought carry out with the help of Standard Water level Index (SWI). Among SPI, SPEI and SWI indices Correlation analysis is carried out.

2. Study Area

Bhima River is the main tributary of Krishna River. The whole Krishna river basin is divided into 7 sub basins. The total area of Upper Bhima sub basin is 46,066 km2. 17.58% area out of total area of Krishna river basin is covered by Upper Bhima sub basin. The major portion, i.e. 98.4% area of this sub basin, lies in Maharashtra's state and remaining 1.6% area lies in Karnataka. The study area lies between latitude 17.18 N - 19.24 N and longitude 73.20 E - 76.15 E [7]. Location map of the Upper Bhima Sub basin is shown in figure 1.

The whole study area is occupied mostly by Deccan plateau in the central and eastern parts and Western Ghat and Sahyadri mountainous ranges on the western region of the study area. As geomorphology taken into consideration of the study area, 25% area of the sub basin is highly dissected hills and valleys, 55% area is plateau and 20 % plain [8, 9]. Black cotton soils, lateritic soils, red soil, alluvium, alkaline soil and saline soils are the major soils types found in the study area [8, 9].

In hilly part, of the study area receive more precipitation, it is unsuitable for the development of ground water recharge in future as it has rocky topography thin soil cover and steep gradient which comes to heavy runoff and poor infiltration. The average gradient for foot hill zones varies between 6.00 to 30.00 m/km [8, 9], because of less infiltration, high runoff takes into picture. The good rechargeable zone are plains of river basin, valleys that are good for optimum ground water development.
3. Data and Methodology
In this research, precipitation and temperature data from the National Centre for Environmental Prediction Climate Forecast System Reanalysis (NCEP CFSR) with spatial resolution of T382 i.e. (approx. 38 km) for 2002-2014 was used to estimate the meteorological drought index. NCEP-CFSR contains assimilated data of the coupled atmospheric ocean model comprising of the NCEP Global Forecast System (GFS), spectral atmospheric model and ocean portion of the Geophysical Fluid Dynamics Laboratory modular ocean model [10] and groundwater level records collected from the Central Groundwater Board (CGWB) for the period 2002-2014 are used. Runoff data obtained from ERA-interim of resolution of 0.7 degrees [11]. Rainfall pattern over the study area at 10km resolution obtained from Global precipitation measurement GPM-TRMM data portal.

3.1 Standardised Precipitation Index (SPI)
SPI was developed by McKee et al. [5, 12] to give a better representation of wet and dry conditions in precipitation series. It quantifies precipitation deficit; the SPI is recommended as a drought index because it is simple and spatially invariant in its interpretation data; use for SPI estimation is mostly skewed. To normalize precipitation data Gamma and log-normal probability distribution function can be used. Thom found the Gamma distribution to fit the climatological time series well [13]. In the present study, precipitation data are normalized using Gamma function and it is defined by its frequency and probability density function. The SPI is computed by dividing the normalized seasonal precipitation and its long-term seasonal mean by the standard deviation. Thus,

\[ g(x) = \frac{1}{\beta^{\alpha}(\alpha)} X^{\alpha-1} e^{-\frac{x}{\beta}} \]

For \( X > 0 \)  

Where, \( \alpha > 0 \)
\( \beta > 0 \)
\( X > 0 \)

\( (\alpha) = \int_{0}^{\infty} y^{\alpha-1} e^{-y} dy \)

Where, \( (\alpha) \) is the Gamma Function

The cumulative frequency of precipitation for a given month and time scale for a particular station is given by:

\[ G(x) = \int_{0}^{\infty} g(x) dx \]
Since the Gamma function is undefined for \( x = 0 \), and the precipitation distribution may contain zeros, the cumulative probability becomes:

\[
H(x) = q + (1 - q)G(x)
\]

The cumulative probability \( H(x) \), is then normalised with mean ‘0’ and standard deviation ‘1’. SPI is computed by using formula,

\[
SPI = \frac{x_{ij} - x_{im}}{\sigma}
\]

Where, \( X_{ij} \) = seasonal precipitation at \( i^{th} \) rain gauge station and \( j^{th} \) observation;
\( X_{im} \) = long term seasonal mean;
\( \sigma \) = standard deviation.

Classification scheme of SPI and SPEI is given in Table 1

| SPI  | SPEI  | Drought Classes       |
|------|-------|-----------------------|
| > 2.00 | > 2.00 | Extreme wet           |
| 1.50 to 1.99 | 1.50 to 1.99 | Severe wet           |
| 1.00 to 1.49 | 1.00 to 1.49 | Moderate wet         |
| -0.99 to 0.99 | 0.99 to -0.99 | Normal               |
| -1.0 to -1.49 | -1.0 to -1.49 | Moderate dry         |
| -1.5 to -1.99 | -1.5 to -1.99 | Severe dry           |
| < -2.00 | < -2.00 | Extreme dry           |

3.2 Standardized precipitation Evapotranspiration index (SPEI)

SPEI is a multiscale drought index that combines precipitation and potential evapotranspiration (PET). SPEI represent a simple climatic water balance. The purpose of including PET in drought index calculation is to obtain a relative temporal estimation, therefore the method used to calculate the PET is not critical [14]. PET can be calculated by various methods such as Penman, Hargreaves, and Thornthwaite. Mavromatis [12] showed that using a simple or complex method to calculate PET provides similar results, when the drought is calculated. In this study, the Hargreaves method is used to calculate PET [11] which requires maximum temperature, minimum temperature and extraterrestrial radiation data.

\[
ET = 0.0023Ra(T + 17.8)(T_{max} - T_{min})^{0.5}
\]

Where, \( ET \) = Evapotranspiration (mm/day)
\( T \) = Mean temperature (°C)
\( T_{max} \) = Maximum temperature (°C)
\( T_{min} \) = Minimum temperature (°C)
\( Ra \) = Extra – terrestrial radiation (W/m²).

With the help of calculated PET, difference between precipitation (P) and PET for the month \( i \) is calculated using,

\[
D_i = P_i - PET_i
\]

Where, \( D_i \) = Water balance for \( i^{th} \) month

Water balance indicates a simple water increase or decrease calculation for the particular month. The calculated \( D_i \) values are collected at different time scales [14]. SPEI is calculated by using three parameter distributions.

\[
D_i^k = \sum_{j=1}^{k} D_{i-j}
\]

Where, \( i \) = year, \( j \) = month, \( k \) = time scale
A drought event for aggregated time scale is defined as a period in which drought indices are frequently negative and reach -1 or less. Drought intensity is arbitrarily defined for the value of indices with the following categories:

Time series variation of drought indices was studied to determine the dry and wet period and the correlation between SPI and SPEI was estimated over the study area. The spatial variation of resultant SPEI obtained from the above equation has been plotted. The drought-affected area signifies dry conditions in dry and wet years, which may be considered the worst situation.

### 3.3 Standardised Water-Level index (SWI)

SWI was developed to analyse the groundwater level. Groundwater level data are taken from CGWB, India. For the formulation of SWI index seasonal water level normalising and dividing by difference between seasonal water level and its long-term seasonal mean, by standard deviation. Thus,

\[
SWI = \frac{w_{ij} - w_{im}}{\sigma}
\]

Where, \( w_{ij} \) = seasonal water level for the \( j^{th} \) observations;
\( w_{im} \) = seasonal mean;
\( \sigma \) = standard deviation.

Similar to SPI an incomplete gamma function has been used for normalisation.

SWI shows a reduction in water level and indirect measurement of the groundwater table. For measurement of groundwater level ground surface as datum into observation well, positive values such as greater than two indicate that extreme drought conditions similarly less than zero indicate no drought condition.

| SWI   | Drought Class       |
|-------|---------------------|
| > 2.00| Extreme drought     |
| >1.5  | Severe drought      |
| >1.0  | Moderate drought    |
| >0.0  | Mild drought        |
| <0.0  | No drought          |

Overall methodology adopted for the analysis is as shown in figure 2.
4. Results and Discussion

4.1 Spatial Variation for the Precipitation Pattern and Drought Indices

The spatial variation of annual precipitation for the period of 2002-2014 is shown in Figure 3. The climate of the Upper Bhima Sub Basin is highly desperate because of the interaction between the monsoon and the Western Ghat mountain range [15]. Variation of rainfall over the study area ranges from 415 mm/year to 4240 mm/year with an average of 688 mm/year, mountain ranges, and thick forest covering the whole Western Ghats of the study area rainfall reaching up to 4500 mm per year. The eastern part's rain is less compared to the Ghat region part where it is less than 500 mm per year and is again increases towards the east; therefore, the central part receives the lowest rainfall [15].

Figure 3. Spatial Variation of Annual Precipitation (mm) over Upper Bhima Sub Basin

Spatial variation of SPI, SPEI and SWI for normal drought years specifically during 2004, 2006, 2010 and 2013 is shown in Figure 4 and for critical drought years, i.e. 2002, 2003, 2005 and 2008 in Figure 5. SPI and SPEI values in critical drought years show extreme drought, but SWI value shows no hydrological drought in some study areas. In the year 2004, spatial variation of SPI and SPEI shows that no drought occurred in the south-eastern region of the study area, but SWI shows mild condition drought. In the year 2006, spatial variation of SPI and SPEI shows that there is no drought in the western part of the region at the same time SWI (> 2) shows extreme hydrological drought for same region. For the year 2010, spatial variation of SPI and SPEI shows that some portion of the western ghat under moderate drought condition but SWI (< -2) spatial variation shows no drought condition in the same region. In the year 2013, spatial variation of SPI and SPEI indicates that there is no drought in the western ghat of the study area and for the same region, SWI also shows that there is no hydrological drought in the region.
In the year 2002, 2003, 2005 and 2008 spatial variation of SPI and SPEI shows complete drought condition over the study area. These are the critical years with respect to precipitation deficit for the
same time period. SWI shows some region shows no drought condition. Some regions show extreme drought conditions in the region.

![Image of SWI maps for different years]

**Figure 5.** Spatio-temporal variation of drought indices for Critical Drought Years

4.2 Spatial variation of runoff

Average runoff map for study period shown in figure 6 illustrates that the hilly region of western Maharashtra shows the highest runoff. This may be attributed to highest precipitation in the study area and highly undulating topography. In the year 2008, 2009 and 2010 eastern part of the study area has been showing relatively wet conditions and positive values of SWI which indicates lowering of groundwater level. Hence, other than runoff factors, like soil characteristics, make this region more droughts vulnerable. Runoff pattern has been extracted from ECMWF web user for ERA-interim
(https://apps.ecmwf.int/datasets/data/interim-land/type=fc/). After retrieving runoff pattern, results for the study area has been visualized in GIS environment by using extraction by mask technique and map algebra for average runoff response over the period.

![Average Runoff](image)

*Figure 6.* Spatial variation of average runoff

4.3 Correlation analysis of SPI, SPEI AND SWI

Pearson correlation analysis between SPI, SPEI and SWI has been performed. The statistical summary of the Pearson correlation analysis is given in Table 3. From these three indices, SPI and SPEI show strong correlation with $r = 0.958$. The correlation between SPI and SWI shows weak correlation among them with $r = 0.272$. There is no strong correlation between SWI with SPI and SPEI. This may be due to the fact that indices signify meteorological drought while SWI is used for monitoring groundwater level deficit and index. There may be a time lag between groundwater level responses to depict dry conditions due to meteorological parameters like precipitation.

|       | SPI   | SPEI  | SWI   |
|-------|-------|-------|-------|
| SPI   | 1     | 0.958 | 0.272 |
| SPEI  | 0.958 | 1     | 0.193 |
| SWI   | 0.272 | 0.193 | 1     |

5. Conclusion

The Pearson correlation analysis based on monthly SPI, SPEI and SWI was employed to analyze the spatio-temporal analysis of drought in Upper Bhima Sub-basin for 2002-2014. Correlation between drought indicators and SWI were examined to explore the potential causal factors of drought variation and groundwater fluctuations in the study area.

Spatial variation of SPI map indicates that meteorological drought in upper Bhima region is random in fashion. In most of the year the drought changes its position. Spatial variation of SWI show that over upper Bhima region, ground water level changes for a successive year and the movement is the change from West to East, South to North and vice versa. Spatial map of different drought indices shows no direct correlation linearly between meteorological drought and hydrological drought in the region.
Mainly SPI takes rainfall deficit into consideration, a major cause for drought development but not consider the impact of drought. As it may be region free from water stress in case of negative SPI Value. Thus, the negative SPI values mean drought present over the region not always true drought may appear with respect to the hydrological sphere despite positive SPI result of Pearson correlation coefficient, which shows that precipitation and temperature have relatively low correlation with ground water level. Almost no significant correlation is detected between drought and the SWI.

References
[1] Palmer W C 1965 Meteorological Drought Research Paper No. 45 US Department of Commerce Weather Bureau pp 58
[2] Palmer W C 1968 Keeping track of crop moisture conditions, nationwide: the new crop moisture index Weatherwise 21 156–161
[3] Shafer B A and Dezman L E 1982 Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. Proc. Western Snow Conference (Fort Collins) pp 164–175
[4] Keyantash J and Dracup J A 2004 An aggregate drought index: assessing drought severity based on fluctuations in the hydrologic cycle and surface water storage Water Resour. Res. 40 W09304
[5] McKee T B, Doesken N J and Kleist J 1993 The Relationship of Drought Frequency and Duration to Time Scales Conference on Applied Climatology. American Meteorological Society, (Anaheim CA)
[6] Bhuiyan C 2004 Various drought indices for monitoring drought condition in Aravalli terrain of India. Proc. XXth ISPRS Conférence Int. Soc. Photogrammes. Remote Sens (Istanbul)
[7] Londhe D S and Katpatal Y B 2020 Comparative Assessment of Evapotranspiration in Bhima Sub-Basin Using Spatial Analysis for Normal and ENSO Years J. Agromet. 22(2) 179-185
[8] Gunnell Yanni 1997 Relief and climate in South Asia: the influence of the Western Ghats on the current climate pattern of Peninsular India Int. J. Clim. 17 1169 – 1182
[9] Report on Krishna Basin by Central Water Commission and National Remote Sensing Centre 2014 http://india-wris.nrsc.gov.in/Publications/Reports/Krishna20Basin.pdf
[10] Saha S, Moorthi S, Wu X, Wang J, Nadiga S, Tripp P and Iredell M 2014 The NCEP climate forecast system version 2 J. Climate, 27(6) 2185–2208
[11] Dee D P et al. 2011 The ERA-Interim reanalysis: configuration and performance of the data assimilation system Q.J.R. Meteorol. Soc.137 553–597
[12] McKee T B, Doesken N J and Kleist J 1995 Drought Monitoring with Multiple Time Scales Conference on Applied Climatology American Meteorological Society (Dallas Texas)
[13] Edward D C and McKee T B 1997 Characteristics of 20th Century Drought in the United States at Multiple Time Scales Climatology Report Department of Atmospheric Science, Colorado State University, Fort Collins 97-2
[14] S M Vicente-Serrano, S Beguería, and J I López-Moreno 2010 A Multiscal Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index J. Climate 23 1696–1718
[15] Garg Kaushal et al. 2012 Spatial Mapping of Agricultural Water Productivity using the SWAT Model in Upper Bhima Catchment India Irri. Drain. 61 60 – 79