A Comparative Analysis of Regional Drought Characterization over Krishna River Basin in India Using Potential and Actual Evapotranspiration

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A Comparative Analysis of Regional Drought Characterization over Krishna River Basin in India Using Potential and Actual Evapotranspiration

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Abstract
Among the extreme events, droughts are the most widespread and slowly developing hydro meteorological events remain for a long duration affecting natural resources, environment and the people. Few studies included reference evapotranspiration to account for climatic water availability in drought characterization such as Standardized Precipitation–Evapotranspiration Index (SPEI). However, a drought prediction model should consider the
actual evapotranspiration to include the physical water availability and land surface changes of a region. The Budyko curve is used to estimate the actual evapotranspiration as a function of the aridity index. The drought index is based on the probability distribution of the difference between precipitation and Actual Evapotranspiration (AET), which represents the measure of the water surplus or deficit for a particular month. The gridded daily precipitation data from India Meteorological Department (IMD) available for the period of 1901 to 2015 at 0.25° X 0.25° resolution and the gridded daily average temperature at a resolution of 1° X 1° resolution was used in the study as temperature observational data sets. The regional drought prediction model developed in the study is applied on Krishna River basin in India. The monthly PET was estimated with the Thornthwaite equation using mean temperatures over the entire Krishna river basin. The AET is estimated at 12 month scale using Budyko equation, which combines the precipitation, AET and PET estimated from Thornthwaite equation. The performance of drought index is evaluated using historical droughts and projected variability under climate change. The results of the study reveal that inclusion of AET in the drought characterization along with PET and precipitation into account can drive the areas into moderate drought that would experience extreme drought under if only PET is considered.

**Introduction:**

Among the extreme events, droughts are the most widespread and slowly developing atmospheric hazards which remain for a long duration affecting natural resources, environment, and people. Furthermore, it corresponds to the failure of spatial and temporal precipitation and water availability and therefore consequent impact on agriculture, ecosystem and socioeconomic activities of human being. The global land surface in extreme drought is predicted to increase from 1-3% for the present day to 30% by the 2090s (IPCC AR4). More intense droughts and increased precipitation variability lead to increased stresses to water, agriculture and economic activities (IPCC AR5 WG2 Ch26 Exec. Summary). The frequency of severe and widespread multi-year droughts has increased in India during the recent decades due to the erratic summer monsoon and increase in air temperature and thereby creating huge damage to crops and society (Shah and Mishra 2014; Mishra et al. 2016). India has experienced 23 large-scale droughts starting from 1891 to 2009 and the frequency of droughts is increasing (Kumar and Gautam 2014). The severity of droughts has been reported as increasing in many parts of the Indian sub-continental basins under climate change (Mishra et al. 2014). The major factors for the persistence of droughts at river basin
scale are changes in water balance due to the alterations in the water supply (precipitation), energy (potential evaporation) and land surface characteristics (vegetation and topography).

In this context, several drought indices have been developed, which evaluate the deviation of climate variables in a given year from the normal conditions (Dai 2011; Liu et al. 2017). These drought indices serve as monitoring tools and operational indicators for regional water resources management. The most widely and tested worldwide drought index is Palmer Drought Severity Index (PDSI) developed by Palmer (1965) that considers precipitation, evapotranspiration and soil water holding capacity. The applicability of PDSI is limited due to the computational complexity, requirement of significant meteorological data and applicability on different time-scales. The Standardized Precipitation Index (SPI) developed by McKee et al. (1993), which is considered as simple and most widely used universal drought index by the World Meteorological Organization (WMO) is based on precipitation. SPI measures the drought index on different time-scales and enable to detect different drought types and it is widely accepted in the research community for drought monitoring and early warning (e.g. Hayes et al., 1999). Much effort has been devoted to developing techniques for drought analysis considering precipitation as the prominent variable in the context of Indian drought analysis (e.g., Bhalme and Mooley 1980; Parthasarathy et al. 1987; Chowdhury et al. 1989, SinhaRay and Shewale 2001; Guhathakurta 2003; Goswami et al. 2006; Ghosh and Mujumdar 2007; Pai et al. 2011; Mishra et al. 2012; Kumar et al. 2013). However, SPI can estimate the drought under lack of precipitation but not able to detect the drought conditions under higher than normal atmospheric evaporative demand (Vicente-Serrano et al. 2015). While, precipitation and temperatures are the main regional surface variables which are affecting under climate change due to the emission of greenhouse gases in the atmosphere, the increase in temperatures will directly have an impact on the severity of droughts (Abramopoulos et al. 1988). Furthermore, to study the climate change impacts on droughts for future scenarios, a drought indicator considering precipitation may not be sufficient. A drought indicator which can include both precipitation and temperature into account will be more suitable, particularly under extreme heat waves (Mishra et al. 2017). The Standardised Precipitation-Evapotranspiration Index (SPEI) has been proposed by Vicente-Serrano et al. (2010a, 2010b), which considers the Potential Evapotranspiration (PET) in addition to precipitation and it can be used at several time scales. Due to the consideration of PET, SPEI combines the sensitivity of the Palmer Drought Severity Index (PDSI) and the probabilistic and multi-temporal nature of SPI. In the recent years SPEI has
been widely used to evaluate drought events worldwide (Allen et al. 2011, Aadhar and Mishra 2017) as well as for Indian subcontinent (Kumar et al. 2013; Mallya et al. 2016; Nath et al. 2017).

To this end, the use of PET in the drought estimation can characterize the intensification of drying areas where precipitation is already under stress and also tries to drive the areas into a drought that would experience modest drying under only precipitation is considered alone (Cook et al. 2014). Although PET-based drought indices consider the climatic water demand, it is limited towards the inclusion of the effects of regional land surface changes and actual moisture availability in the drought estimation. The SPEI is based on the climatic water demand as it considers the difference between P and PET which is estimated based on empirical techniques such as Thornthwaite model (Vicente-Serrano et al. 2010a, 2010b). Such empirical techniques used to estimate the PET are based on the concept that the climatic moisture demand may exceed available moisture. Therefore, PET is the maximum possible moisture loss limited only by the energy endowment or it is the energy-driven ET (Shelton 2009). Further, the application of empirical equations for the estimation of ET may lead to an underestimation of PET in humid and tropical regions (Van der Schrier et al. 2011). Whereas, the Actual Evapotranspiration (AET) represents the transfer of moisture from the surface to the atmosphere in response to both the energy demand and available moisture supply. The drought indices estimated based on AET will consider both climatic water demand and actual available moisture. The efforts made in the literature to include AET in the drought indices are Drought Severity Index (DSI) (Mu et al. 1993) and U.S. Drought Monitor (USDM) (Svoboda et al. 2002). However, these indices use AET estimated using remote sensing datasets and vegetation information from normalized difference vegetation index (NDVI) and tries to account for land surface changes implicitly. Recently, Kim and Rhee (2016) developed Standardized Evapotranspiration Deficit Index (SEDI) using the Actual Evapotranspiration estimated from Boucette hypothesis and the structure of SPEI as a fully ET-based drought index without consideration of precipitation. The present study aims to study the hydro-meteorological drought index, named Standardized Precipitation Actual Evapotranspiration Index (SPAEI), based on precipitation as well as actual climatic water balance with the consideration of AET. The inclusion of AET in the drought index will also be useful to consider the joint effect of land surface changes or variability and water-energy balance. Therefore, a drought index that considers actual evapotranspiration as an input variable can account for the changes in the land surface such
as vegetation (Wang and Tang, 2014). Thus, the present study aims to study the SPAEI, based on actual evaporation estimated by the Budyko hypothesis and the structure of SPEI. The hypothesis of the study is that inclusion of AET in the drought characterization along with PET and precipitation into account can drive the areas into a moderate drought that would experience extreme drought under if only PET is considered. Further, the study aims to test how a drought index can outperform with the inclusion of AET along with precipitation, PET at a river basin scale. The proposed hypothesis was tested considering Krishna river basin, India, as a case study for which most of the basin is in an arid climate.

The paper is structured as follows. The description of study area is presented in Section 2. The methodology and data involved in the development of SPAEI drought indices is explained in Section 3. The changes in precipitation, potential and actual evapotranspiration and drought analysis results based on SPEI and SPAEI were presented in Section 4, followed by summary and discussion in Section 5.

2. Study Area
The study was conducted on Krishna river basin, which is fifth largest river system in India. Krishna River basin occupies an area of 2,58,948 km² which is 8% of the total geographical area of the country. Nearly 44 % lies in Karnataka, 26% of the basin falls in Maharashtra, about 15% in Telangana and another 15% in Andhra Pradesh within the range 73°17’–81°9’E and 13°10’–19°22’ N. The river originates in the Western Ghats and flows for about 1400 km before reaching to the Bay of Bengal. The major tributaries of the river are Ghataprabha, Malaprabha, Tunga-Bhadra, Bhima, Vedavathi, and Musi. There are two major cropping seasons: Kharif occurs from June to November and Rabi from December to March (George et al., 2011). Most of the Krishna river basin is covered by arid climate (Fig.1) with annual average precipitation in the basin as 784 mm, of which approximately 90% occurs during the South-West Monsoon from June to October (http://india-wris.nrsc.gov.in/wrpinfo/?title=Krishna). Some parts of the Krishna River basin, especially the Rayalaseema area of Andhra Pradesh, Bellary, Raichur, Dharwar, Chitradurga, Belgaum and Bijapur districts of Karnataka and Pune, Sholapur, Osmanabad and Ahmednagar districts of Maharashtra are drought-prone (Source: http://india-wris.nrsc.gov.in/wrpinfo/index.php?title=Krishna). Fig. 2 shows the number of drought-affected districts in each state of Andhra Pradesh, Maharashtra, Karnataka, and Telangana for the period of 2000 to 2016 based on the Farmer’s portal, Department of Agriculture & Cooperation and Farmers Welfare, Ministry of
Agriculture and Farmers Welfare, Government of India (Source: http://farmer.gov.in/Drought/Droughtreport.aspx#). The number of drought-affected districts is reported more in Maharashtra and few number of drought affected districts in the undivided state of Andhra Pradesh. Most number of drought affected districts are observed for the years 2002, 2009, 2014 and 2015 (Fig. 2) over Krishna River basin. Recently, severe drought has been experienced in the Krishna river basin during 2001 to 2004 where surface water resources were almost entirely committed to human consumptive uses, groundwater was over-abstracted and the discharge to the ocean almost nil (Venot 2008). A significant increase in the severity of droughts was reported over Krishna river basin during the period of 1948–2012 based on the study of Shah and Mishra (2016). The present study attempts to analyze the observed variability of regional drought occurrence over Krishna River basin including precipitation, potential evapotranspiration and actual evapotranspiration at the basin scale.

3. Data and Methods

The gridded daily precipitation data from the India Meteorological Department (IMD) available for the period of 1901 to 2015 at 0.25° X 0.25° resolution was used as precipitation observational dataset (Rajeevan and Bhate 2009). The gridded daily average temperature at a resolution of 1° X 1° resolution for the period of 1951-2014 was used as temperature observational data sets (Srivastava et al. 2009). The precipitation and temperature data used in the present study are available from India Meteorological Department (IMD). More details about the data are available from http://www.imd.gov.in/advertisements/20170320_advt_34.pdf. The temperature was interpolated to 0.25° X 0.25° resolution using the inverse distance weighting method. The daily precipitation and temperatures data sets obtained from IMD were aggregated over monthly time scale to serve as primary inputs to calculate SPEI and SPAEI at each grid at 0.25° X 0.25° resolution.

3.1 Development of Standardized Precipitation–Actual Evapotranspiration Index (SPAEI)

The drought index, SPEI is based on the climatic water balance, the accumulated monthly difference between precipitation and PET as follows:

\[ D = P - PET \]  

(Eq. 1)
Where \( P \) is the monthly precipitation (mm) and PET is the monthly potential evapotranspiration (mm). The PET can be estimated based on Thornthwaite (1948) model, which considers the monthly average air temperature and geographical location of the region of interest as input variables as follows:

\[
PET = 16k \left( \frac{10T}{I} \right)^a
\]  
(Eq. 2)

Where \( T \) is the mean monthly temperature (\(^{\circ}\)C); \( I = \) Heat index (given in Eq. 3); \( a = \) Location dependent coefficient (given in Eq. 4);

\[
I = \sum_{j=1}^{12} \left( \frac{T_j}{5} \right)^{1.5}
\]  
(Eq. 3)

Where, \( T_j \) is the mean monthly temperature during the month \( j \) (\(^{\circ}\)C) for the location of interest.

\[
a = 6.75 \times 10^{-7} T^3 - 7.7 \times 10^{-5} T^2 + 1.8 \times 10^{-2} I + 0.49
\]  
(Eq. 4)

\( K \) is the correction coefficient depending on the latitude and month, given as follows:

\[
k = \left( \frac{N}{12} \right) \left( \frac{NDM}{30} \right)
\]  
(Eq. 5)

Where \( NDM \) is the number of days of the month and \( N \) is the maximum number of sun hours.

\[
N = \left( \frac{24}{\pi} \right) \sigma_s
\]  
(Eq. 6)

where \( \sigma_s \) is the hourly angle of sun rising, which can be calculated as follows:

\[
\sigma_s = \arccos(-\tan \varphi \tan \delta)
\]  
(Eq. 7)

where \( \varphi \) is the latitude in radians. If \( \delta \) is the solar declination, in radians and \( J \) is the average Julian day of the month, then \( \delta \) can be estimated as follows:

\[
\delta = 0.4093 \times \left( \frac{2\pi J}{365} - 1.405 \right)
\]  
(Eq. 8)

Once, the PET is estimated, the values of \( D \) can be estimated for each month using Eq. 1. The estimated \( D \) values represents the water demand or surplus (P-PET), while the evapotranspiration is the result of complex relationship between atmosphere and surface water available, vegetation and soil characteristics (Brutsaert 1982). Moreover, conventionally it is assumed that available water and energy are the primary factors affecting
the rate of evapotranspiration (Budyko 1958). In this context, the use of PET in the drought assessment studies may not be able to include the actual surface available moisture. Further, the AET includes the interception, actual soil evaporation and actual plant transpiration (Homdee et al. 2016). If the difference between precipitation and AET is considered, it can account for the actual Residual Available Water (RAW) or water budget during drought conditions. Therefore, the water budget at a river basin scale can be expressed as:

$$\Delta S = P + Q_{in} + GW_{in} - GW_{out} - Q_{out} - AET$$  \hspace{1cm} (Eq. 9)

Where S is the storage volume, $GW_{in}$ ($GW_{out}$) is the ground water inflow (outflow) volume, $Q_{in}$ ($Q_{out}$) is the surface runoff inflow (outflow) volume. For sufficiently long time scales, the net change in storage volumes corresponding to ground water can be assumed to be zero. This will direct to a simplified water budget equation or actual residual water available (RAW) over a river basin, which can be expressed as follows:

$$RAW = P - AET \hspace{1cm} (Eq. 10)$$

Various empirical models have been developed for estimating AET which is based on the assumption that AET is limited by the water availability in terms of precipitation under very dry conditions and available energy under very wet conditions in terms of potential evapotranspiration (Budyko 1958; Fu 1981; Milly 1994; Zhang et al. 2004). In this context, Budyko (1958) has developed a relationship between three hydro-climatic variables for a basin: Precipitation (P), Potential Evapotranspiration (PET), and Actual Evapotranspiration (AET). The Budyko hypothesis states that the ratio of the AET over precipitation (AET/P) is fundamentally related to the ratio of the PET over precipitation (PET/P) (Budyko 1958; Fu 1981) as follows:

$$\frac{AET}{P} = 1 + \frac{PET}{P} \left[ 1 + \left( \frac{PET}{P} \right)^{\omega} \right]^{(1/\omega)} \hspace{1cm} (Eq. 11)$$

The parameter ‘$\omega$’ accounts for the effects of climate variability, basin characteristics such as soil, vegetation, terrain, etc. (Donohue et al. 2007). The present study used Budyko equation as implemented by Zhang et al. (2004) for estimating the AET, given as follows:

$$AET = \left[ P \left( 1 - \exp \left( -\frac{PET}{P} \right) \right) \right]^{0.5} PET \tanh \left( \frac{P}{PET} \right) \hspace{1cm} (Eq. 12)$$

The original Budyko equation (Eq. 10) has been developed for a long-time scales (e.g. Budyko 1974; Zhou et al. 2015). However, the Budyko framework can be applied over short
periods of monthly and annual scales (e.g. Zhang et al. 2008; Buytaert and De Bièvre 2012; Liu et al. 2017), if the parameter ‘\( \omega \)’, which represents the joint effect of climate and land surface is estimated. For a reasonable application of the Budyko equation as developed by Zhang et al. (2004) (Eq. 11), we used a 12-month scale for the estimation of drought indices. Any timescale lower than 12 months might result in the accumulated precipitation tending to zero, thus resulting (PET/P) value tending to infinity, which is not suitable for the implementation of Budyko (Eq. 11). Therefore, the monthly precipitation and PET estimated based on Thornthwaite model at monthly scale were aggregated as given as follows:

\[
P_i^k = \sum_{i-k+1}^i P_i \quad \text{where } k = 12
\]

(Eq. 13)

\[
PET_i^k = \sum_{i-k+1}^i PET_i \quad \text{where } k = 12
\]

(Eq. 14)

Where \( P_i^k \) and \( PET_i^k \) are the accumulated precipitation and PET in month \( i \). Next, the accumulated AET to a 12-month scale is estimated as:

\[
AET_i^k = \sum_{i-k+1}^i AET_i \quad \text{where } k = 12
\]

(Eq. 15)

Then, the climatic water balance (D) of SPEI and the actual Residual Available Water (RAW) of SPAEI in month \( i \) are given in the Eq. 15 and Eq. 16 respectively:

\[
D_i^{12} = P_i^{12} - PET_i^{12}
\]

(Eq. 16)

\[
RAW_i^{12} = P_i^{12} - AET_i^{12}
\]

(Eq. 17)

The present study adopted the structure of SPEI to produce standardized drought indices with \( D_n^k \) and \( RAW_n^k \) (Vicente-Serrano et al. 2010). The present study adopted a three-parameter log-logistic distribution to fit the \( D_n^k \) and \( RAW_n^k \) series following to Vicente-Serrano et al., (2010). The probability density function (pdf) \( (f(x)) \) and cumulative distribution function (CDF) \( (F(x)) \) of the three-parameter log-logistic distribution are given as follows:

\[
f(x) = \frac{\beta}{\alpha} \left( \frac{x-\gamma}{\alpha} \right)^{\beta-1} \left[ 1 + \left( \frac{x-\gamma}{\alpha} \right)^{\beta} \right]^{-2}
\]

(Eq. 18)

where \( \alpha, \beta \) and \( \gamma \) are the scale, shape and origin parameters respectively, for D and RAW values in the range of \(( \gamma > D, RAW < \infty )\). The parameters of the log-logistic distribution are obtained by following the L-moment procedure as follows:
\[ \beta = \frac{2w_1 - w_0}{6w_1 - w_0 - 6w_2} \quad (\text{Eq. 19}) \]
\[ \alpha = \frac{(w_0 - 2w_1)\beta}{\Gamma(1 + 1/\beta)\Gamma(1 - 1/\beta)} \quad (\text{Eq. 20}) \]
\[ \gamma = w_0 - \alpha \Gamma(1 + 1/\beta)\Gamma(1 - 1/\beta) \quad (\text{Eq. 21}) \]

where \( w_0, w_1 \) and \( w_2 \) are the probability weighted moments calculated based on Sheng and Hashino (2007), as follows:
\[ W_r = \frac{1}{n} \sum_{j=1}^{n-r} \sum_{r}^{n-j} x_j \quad r = 0, 1, 2 \quad (\text{Eq. 22}) \]

where \( n \) is the sample size and \( x_j \) is the ordered vector of observations in descending order.

Next, the cumulative distribution function of log-logistic distribution can be calculated with the estimated parameters of Pearson-III distribution.
\[ F(x) = \left[ 1 + \left( \frac{x - \gamma}{\alpha} \right) \right]^{-1} \quad (\text{Eq. 23}) \]

With the values of \( F(x) \), the SPEI values were calculated as follows:
\[ \text{SPEI} = W - \frac{C_0 + C_1W + C_2W^2}{1 + d_1W + d_2W^2 + d_3W^3} \quad (\text{Eq. 24}) \]

where \( W = \sqrt{-2\ln(p)} \) for \( P \leq 0.5 \) \quad (\text{Eq. 25})

where \( P \) is the probability of exceeding a determined \( D \) value, \( P = 1 - F(x) \). If \( P > 0.5 \), then \( P \) is replaced by \( 1 - P \) and the sign of the resultant SPEI is reversed. The constants are \( C_0 = 2.5515517, C_1 = 0.802583, C_2 = 0.010328, d_1 = 1.432788, d_2 = 0.189269, \) and \( d_3 = 0.001308 \). Table 1 gives the range of SPEI and SPAEI values to identify the extreme weather as drought or wet conditions. By substituting the \( C_0, C_1 \) and \( C_2 \) values in Eq. 24, we found the SPEI and SPAEI values at various time scales.

The SPAEI can account for the hydrological drought also to some extent because it considers actual evapotranspiration as it is defined as a function of major hydrological variables (i.e. \( P, \) PET, and \( AET \)). Generally, SPEI can be expressed at different time scales as SPEI (6), SPEI (12), etc., where the number in the bracket indicates the timescale in months for which the \( P \)-PET values are accumulated and the estimated SPEI at these timescales.
Therefore, the ability of SPEI and SPAEI to reproduce drought and wet conditions has been compared at a river basin scale of Krishna River, India.

4. Results and Discussions

4.1 Climatic Water Balances

The daily gridded precipitation data is available from 1901 to 2015 and daily gridded temperature data is available from 1951 to 2014. A common data period of 1951 to 2014 was considered for the drought analysis, which is further divided into three time slices of 1951-1971, 1972-1992 and 1993-2014, over Krishna River basin. Dividing the entire 64 years (1951-2014) of data into three periods of 20 years was expected to provide a sufficient length of time series to understand the climate, water budget, and drought variability over the basin. The daily gridded precipitation data of precipitation and temperature of all over India were cropped at 0.25°X0.25° resolution for Krishna River Basin with 375 grid points. The spatial average monthly precipitation and temperature for the period of 1951 to 2014 is shown in Fig. 3. The average annual precipitation over Krishna river basin is 975 mm and varying between 650 to 1843 mm. The annual total precipitation has shown an increasing trend at a rate of 6.2 mm/decade with a significance level of 0.05 (Fig. 4). To examine the spatial pattern of precipitation changes, we have calculated the annual total precipitation for three periods of 1951-1972, 1973-1992, and 1993-2014 as shown in Fig. 5(a). The total annual precipitation amount was observed to be higher towards the Western Ghats boundary of the Krishna river basin. The spatial pattern of average air temperature over the basin is presented in Fig. 5 (b). The annual total AET estimated based on Budyko frame work (Eq. 11) is presented for three time periods of 1951-1972, 1973-1992, and 1993-2014 in Fig. 5 (c). Further, the average air temperature (Fig. 5 (b)) was used to estimate the monthly PET based on Thornthwaite model (Eq.2). Increasing trends were observed in the annual total PET and AET by 8.1 mm/decade and 4.9 mm/decade respectively (Fig.4). Moreover, the spatial variation of average air temperature (Fig. 5(b)) was found to follow the spatial variation of PET (Fig. 5(d)) for three time slices. Higher ranges of PET values were noted over the upper portion of the basin, particularly over Maharashtra, Telangana and Karnataka, where higher temperatures ranges were observed. Therefore, average air temperature and PET were essentially followed similar spatial variations over Krishna river basin. Whereas, the spatial variation of AET (Fig. 5(c)) has followed a combined effect of both precipitation (Fig. 5(a)) and temperatures (Fig. 5(b)). Therefore, the climatic water balances estimated based on AET
will be a more convincing factor to be considered in the drought characterization at river basin scale (Liu et al., 2017; Boer et al., 2016).

Further, the present study made an effort to understand the monthly water balance over the Krishna river basin based on both PET and AET. The areal averaged monthly average precipitation, climatic water demand (D) and actual residual available water (RAW) for the historical data of 1951 to 2014 were compared (Fig. 6). The climatic water demand based on PET (P-PET) and AET (P-AET) reaffirmed the acute unevenness in seasonal precipitation distribution over Krishna River basin. From January to May the amount of available precipitation is less thereby representing water deficiency months and negative water balances. Starting from June, when the monsoon season begins the basin slowly getting to accumulate the storage with positive values of (P-PET) and therefore high amounts of (P-AET) till the end of monsoon season up to October. During post-monsoon and winter months (November, December, January, and February), pre-monsoon (March-May) season, acute water shortfall was observed, due to inadequate precipitation occurrence, therefore, climatic water demand in terms of PET was noticed to be more in these months. It should be noticed that the monthly climatic water balance based on AET is following the monthly variations of precipitation over the Krishna river basin. In general, it was noticed that for the Krishna river basin, the spatio-temporal variation of precipitation followed AET more than PET. Further, climatic water balances based on PET has shown negative water balances and AET with positive water balances over the basin. Therefore, based on spatio-temporal variations of precipitation, PET and AET (Fig. 5 and 6) the drought indices assessed based on RAW (P-AET) will be more promising in terms of water availability and actual climatic water balances.

The monthly D (P-PET) and RAW (P-AET) values were used in the estimation of drought indices of SPEI and SPAEI respectively at various time scales of 6-, 12-, 18, and 24-months for the period of 1951 to 2014. The three-parameter log-logistic distribution was applied to model the series (P-PET) and (P-AET) for various time scales. Furthermore, the fitted three parameter log-logistic distribution is validated with the Kolmogorov-Smirnov (K-S) goodness of fit test for both the climatic water balance time series of D and RAW. The K-S rejection for the overall basin including all valid grid points was obtained as 6% and 8% for SPEI and SPAEI respectively at a significance level of 0.01.
4.2 Drought Characterization

To assess SPEI and SPAEI, for meteorological drought detection, the years when the annual precipitation is less than 75% of the annual average of 1951 to 2014 were considered based on the IMD definition of drought year (http://imd.gov.in/section/nhac/wxfaq.pdf). Four drought years were identified based on the deviation of annual precipitation from the normal precipitation of the period 1951-2014. Based on Fig. 7 (a), these drought years have been identified as 1972, 1985, 2002 and 2003. These drought years are among the major documented drought events over Indian monsoon region (De et al. 2005; Mallya et al. 2016). Among these, the 2002 drought is one of the severest in India, affected 56% of its geographical area, livelihoods of 300 million people (https://public.wmo.int/en/bulletin/flood-and-drought-management-through-water-resources-development-india). Fig. 8 shows the time series of SPEI and SPAEI calculated for 6, 12, 18 and 24 months correspondingly. The SPEI and SPAEI values accumulated at 6 months represent the monsoon seasonal precipitation variations over the basin. The SPEI is able to reconstruct most of the drought years at 6 months scale as moderate and severe, whereas, SPAEI has recognized them as mild drought years. Further, as SPAEI considers the actual water budget into account, all years were identified under moderate droughts. The SPEI and SPAEI values accumulated at 6 months represent the monsoon seasonal precipitation variations over the basin. The SPEI is able to reconstruct most of the drought years at 6 months scale as moderate and severe, whereas, SPAEI has recognized them as mild drought years. The SPEI-6 (SPAEI-6) values for the most severe drought years of 1972 and 2003 was noted as -1.76 (-0.94) and -2.0 (-0.96) respectively. The SPEI-12 (SPAEI-12) values for the drought years of 1972 and 2003 was obtained as -2.4 (-1.5) and -2.1 (-1.4) respectively. The SPEI-18 (SPAEI-18) values for the drought years of 1972 and 2003 were obtained as -2.1 (-1.5) and -2.2 (-1.4) respectively. The SPEI-24 (SPAEI-24), which shows the multi-year droughts, the values for the 2003 and 2004 were obtained as -1.6 (-1.3) and -2.0 (-1.4) respectively. Over all, the severities of the drought indices at various time scales were found to be more with SPEI compared to SPAEI. Therefore, the drought indices developed in the present study has revealed that inclusion of AET with Budyko frame work will reduce the intense droughts characterization. Furthermore, the drought indices developed in the study has drive the moderate drought years, which were considered as severe with SPEI, which is consistent with the hypothesis of the present study.
Coming to the comparison of the number of drought events capturing over a particular period with SPEI and SPAEI, the present study mainly considered on the moderate and severe droughts over Krishna river basin. Figs. 9 and 10 show the number of moderate (SPEI/SPAEI value between -1.0 and -1.49) and severe (SPEI/SPAEI values of greater than -1.50) drought events at 6, 12, 18 and 24-month scale with SPEI and SPAEI for three time periods of 1951-1971, 1972-1992 and 1993-2014. Both moderate and severe drought events have increased over Krishna river basin from 1951 to 2014 based on both SPEI and SPAEI drought indices. More pronounced increase in the number of drought events was noticed for periods of 1972-1992 and 1993-2014 compared to 1951-1971. Such increasing behavior of drought events in the recent years were also observed over all India (Sharma and Mujumdar 2017), particularly over parts of coastal south-India (Mallya et al. 2016). The increase in number of drought events were observed to increase more towards the east and south portions of the basin, particularly over majority of south Indian states of Maharashtra, Karnataka, Telangana and Andhra Pradesh. Coming to the comparison at each individual time scales of number of drought events with SPEI and SPAEI over the basin, for all time scales the SPAEI has identified less number of grid points as moderate and severe compared to SPEI (Figs. 9 and 10).

Furthermore, to study the spatial drought characterization, the extent of moderate and severe droughts represented as percentage of grids with SPEI and SPAEI < -1 at 12-month time window was analyzed as shown in Fig. 7 (b) and Fig. 7 (c) respectively. Here, the moderate drought areal extent was estimated based on the number of grid points with SPEI/SPAEI values between -1.0 and -1.49 out of total number of 375 valid grid points over Krishna river basin. Similarly, for the estimation of severe drought areal extent the SPEI/SPAEI values of greater than -1.50. The percentages of annual moderate and severe drought affected areas were observed to be increasing over the Krishna river basin for the period of 1951-2014. The areal extents of moderate and severe droughts were observed to be more for the drought years of 1972, 1985, 2002 and 2003 for both SPEI and SPAEI. The moderate drought areal extent with SPAEI was observed to be more compared to SPEI for Krishna river basin (Fig. 7(b)). For 1972 drought year, the moderate drought spatial extent was noted as 78% and 74% for SPEI and SPAEI respectively. About 82% (60%) and 79% (67%) of area was identified as moderate drought areas for SPEI (SPAEI) for the drought years of 2002 and 2003 respectively. Whereas, percentage of the severe drought areas were observed to be more evident with SPEI compared to SPAEI (Fig. 7(c)). For about 29% and
7% of area was categorized as severe drought affect area with SPEI and SPAEI respectively for the year 1972. Whereas, about 12% (2%) and 50% (7%) of area has identified as under severe drought with SPEI (SPAEI) for the drought years of 2002 and 2003 respectively. That is, the driving of areal extents between SPEI and SPAEI for severe droughts is more evident, then the moderate drought areal extents. Therefore, with SPEI more percentage of area is falling under severe drought conditions, which were identified as moderate drought areas otherwise with SPAEI, which is again consistent with the hypothesis of the present study.

Furthermore, to support such research findings, the spatial drought characterizations for the major drought years of 1972, 1985, 2002 and 2003 were presented in Fig. 11. The years 1972 and 2003 were noted as most severe historic droughts occurred over Krishna river basin as most of the basin was classified under extreme drought. While, for the 1972 drought year, the upper portion of the basin, particularly, Maharashtra, North Karnataka, Telangana were classified under extreme drought regions with SPEI, the SPAEI drought index drive few of those regions into moderate. Such noticeable deviation in the drought categorization from extreme to moderate can also be seen for the drought years of 2002 and 2003. Therefore, the proposed drought indices based on AET is able to drive the areas into moderate, which or otherwise categorized under severe drought regions in the drought analysis.

In order to measure the length and intensity of drought, a threshold value must be considered for both SPEI and SPAEI. The present study considered a threshold of -1 for both SPEI and SPAEI and the drought duration is identified as the period of months which is continuous negative, started from the SPEI/SPAEI values are more then -1 and ends when the SPEI/SPAEI values turns out to be positive. The duration and intensities of droughts were studied for the two consecutive drought years of 2002 and 2003 over the river basin for 6, 12, 18 and 24 months scales (Fig. 12). The SPEI at 6 month drought duration was noted as from May to August and May to September for year 2002 and 2003 respectively with intensity as moderate. Whereas, the SPAEI has identified 2002 and 2003 as normal conditions from March to September and February to September respectively. Similarly, for SPEI12 the duration of moderate drought months were noted from September 2002 to December 2003, whereas, SPAEI12 has identified the same period as normal conditions. Such similar drought durations were observed for 18 and 24 month time scales of SPEI and SPAEI. Therefore, it can be revealed from the present analysis that use of AET may not have a major impact on the drought duration assessment. In fact, it is the drought severity, which will have more pronounced impact by the inclusion of AET compared to PET in the drought characterisation.
5. Summary and Discussion

The hypothesis of use of climatic water balance based on AET in the drought characterization will drive the extreme drought variability into moderate was tested in terms of severity, spatial extent, duration and frequency. For this, the present study developed a drought indices which can combine the structure of Standardized Precipitation and Evapotranspiration Index (SPEI) and actual evapotranspiration, which is estimated by Budyko hypothesis, the Standardized Actual Precipitation Evapotranspiration Index (SPAEI). The drought characterization based on two climatic water balances, one is with potential evapotranspiration and other with actual evapotranspiration were compared for Krishna river basin, India. For calculating SPEI and SPAEI at different time scales of 6, 12, 18 and 24 months, for a period of 1951 to 2014, the monthly precipitation and temperatures at 0.25 degree resolution have been used. Results showed that both SPEI and SPAEI have captured the historical drought years of 1972, 1985, 2002 and 2003 which are also the major drought events all over India. For the recent consecutive drought years of 2002 and 2003, about 82% (60%) and 79% (67%) of moderate, about 12% (2%) and 50% (7%) of severe area has noted with SPEI (SPAEI) respectively over the river basin. Such findings conclude that driving of areal extents between SPEI and SPAEI is more evident for severe droughts, then the moderate drought areal extents. Further, the drought indices, SPAEI, developed in the present study has drive the moderate drought years, which were considered as severe with SPEI, which is consistent with the hypothesis of the present study. The research findings also reveal that use of AET may not have a major effect on the drought duration assessment. In fact, the drought severity, areal extent and frequency which will have more pronounced effect by the inclusion of AET compared to PET in the drought characterization. The results of the study revealed that SPEI overestimates the drought intensity as it is based on unlimited water supply, whereas, the SPAEI is a reliable measure as it agrees better with the natural water budget of a river basin. Nevertheless, the proposed methodology to estimate the monthly and annual AET are based on Budyko hypothesis (Budyko, 1958) and the empirical equations generated by Zhang et al. (2004). The parameter which represents the basin characteristics of vegetation and climate change in the estimation of AET was considered as stationary. However, to consider the joint effect of climate and land surface variability, a dynamic parameter of Budyko-type formula can be applied (Liu et al. 2017). Even though, few studies stressed on the use of AET in the drought indices (Joetzjer et al. 2013; Homdee et al. 2016) none of the studies integrated Budyko frame work with SPEI to develop a drought indices
which can be more robust in terms of capturing regional water budget and atmospheric anomalies. Further, employing a regional hydrological model to simulate the AET at river basin scale and accounting for the dynamic parameter of Budyko-type formula can be a potential future research problem. As most difficult variables to measure in the regional water balance assessment (Lettenmaier and Famiglietti 2006) are potential and actual evapotranspiration in addition to precipitation and streamflow, these variables deserves more attention towards estimation and understanding the variability. Given the concern of increasing droughts worldwide under climate change evaluation of variability associated with retrospective drought events will be valuable towards the understanding of regional drought pattern in terms of severity, area extent and duration. Such analysis will provide as a basis of possible future droughts and potential vulnerabilities.

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References


Allen KJ, Ogden J, Buckley BM, Cook ER, Baker PJ, 2011: The potential to reconstruct broad scale climate indices associated with southeast Australian droughts from A throat axis species, Tasmania. Climate Dynamics 37: 1799–1821,


IPCC. Managing the Risks of Extreme Events and Disasters to Advance Climate Change


Boer M.M., Bowman, D.MJS., Murphy, B. P., Cary, G. J., Cochrane, M. A., Fensham, R. J.,


https://doi.org/10.1088/1748-9326/aa93.


https://doi: 10.1007/s11069-011-9867-8


https://doi:10.1002/joc.3370070106


Ray, K. S., & Shewale, M. P., 2001: Probability of occurrence of drought in various sub-
divisions of India. *Mausam*, 52(3), 541-546.


Table 1 Criteria for Identification of Drought and Wet

<table>
<thead>
<tr>
<th>SPEI/SPAEI Value</th>
<th>Weather Category</th>
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<tbody>
<tr>
<td>≥2.00</td>
<td>Extreme Wet</td>
</tr>
<tr>
<td>1.99 to 1.50</td>
<td>Severe Wet</td>
</tr>
<tr>
<td>1.49 to 1.00</td>
<td>Moderate Wet</td>
</tr>
<tr>
<td>0.99 to -0.99</td>
<td>Normal Condition</td>
</tr>
<tr>
<td>-1.00 to -1.49</td>
<td>Moderate Drought</td>
</tr>
<tr>
<td>-1.50 to -1.99</td>
<td>Severe Drought</td>
</tr>
<tr>
<td>≤ -2.00</td>
<td>Extreme Drought</td>
</tr>
</tbody>
</table>
Figures

Fig. 1 Map for the Krishna River basin. (a) Location of the catchment in India. (b) Climate classification
Fig. 2 Number of Drought Affected Districts in each state in Krishna basin

(Source: Farmer’s portal, Department of Agriculture & Cooperation and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government of India)
Fig. 3 The spatial average monthly average temperature and precipitation over Krishna River Basin for 1951-2014
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Fig. 6 Monthly Variation of Precipitation, (P-PET) and (P-AET) over Krishna River Basin
Fig. 7. (a) Annual precipitation of Krishna river basin compared to long term average annual precipitation, (b) Areal extent of moderate droughts represented as percentage of grids with SPEI and SPAEI < -1 at 12-month time window (c) Areal extent of severe droughts represented as percentage of grids with SPEI and SPAEI < -2 at 12-month time window.
Fig. 8 Time series of SPEI and SPAEI for different accumulated periods 6, 12, 18, and 24 months for the period of 1951 to 2014 over Krishna river basin
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