Drought and flood dynamics of Godavari basin, India: A geospatial perspective

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Abstract
Assessing incidence and trends of droughts and floods can provide essential information for better water resource management, particularly in the context of ongoing climate change. The present study has examined the prevalence of drought and flood events of Godavari basin, India, for the last four decades using the Standardized Precipitation Evapotranspiration Index (SPEI) 3 months and 9 months, and their trends using Mann–Kendall’s test and Sen’s slope. The spatial distribution, frequency, and intensity of drought and flood episodes in the basin are not uniform. A 20-year breakdown, 1980–1999 and 2000–2019, shows a drastic increase in drought frequency in Manjra and Pranhita sub-basins, while Godavari Upper, Indravati, and northern part of Weinganga have registered increased flood frequency. The monthly trend of SPEI-3 shows that most of the sub-basins have registered a negative trend (increasing dryness) only during the winter months, while under the SPEI-9 scenario both Manjra and Pranhita registered strong negative trend throughout the year. Sen’s slope estimations detected an increasing trend in severity from SPEI-3 to SPEI-9. Dryness severity trend is highest in Pranhita, followed by Manjra, Wardah, and Lower Godavari sub-basins, and the increasing wetness severity trend is in Upper Godavari, while rest of the sub-basins do not show any significant trend. The interior districts of the basin are more prone to the high drought conditions in near future if the current trends persist. To sustain the future climate change challenges, the vulnerable districts need urgent structural and non-structural changes in their current water resource management practices.

Keywords Godavari basin · SPEI · Droughts · Floods · Water resource management practices

Introduction
Drought is the second-most geographically extensive climate-related hazards after floods covering nearly one-third of disaster-affected population globally (CRED 2018). Droughts/floods may cause substantial economic or social damage to individuals, property, or the environment (Wilhite 2005). On the basis of the degree of severity, the length of event, areal extent, total loss of life, economic loss, social effect, long-term impact, suddenness, and occurrence of associated hazards, drought was ranked first among all hazards (Bryant 1991; EM-DAT., n.d). Implications of climate change on the nature of these disasters are clearly visible with the fact that each year is surpassing their previous years in disaster graph. Year 2020, besides being ravaged by ongoing COVID-19 pandemic, had 23 per cent more floods than the annual average of 163 events and 15 per cent more economic losses in droughts than the annual average of 6.5 billion US$ around the globe (CRED 2021). The 2020 edition of the World Water Development Report (WWDR 2020) emphasizes that climate change will affect the availability, quality, and quantity of water in the planet, which will threaten the basic human rights to water and sanitation for potentially billions of people. With climate variability, the surface water, which acts as the principal freshwater supply globally, will become less reliable and predictable and the importance of groundwater will increase (Kundzewicz and Döll 2009), and over exploitation may lead to groundwater stress.

Approximately 53 per cent of agriculture in India is rain-fed (DoES 2016). Thus, droughts create severe water crisis problems for India’s rain-dependent farmers. The National Drought Mitigation Centre, USA, has defined drought under
three categories, namely meteorological, agricultural, and hydrological. A fourth category namely, socio-economic drought, incorporating the concept of water supply and demand has also been included in the classification of drought (Wilhite and Glantz 1985). Nearly one-third of the 328 million hectares geographical area of India is affected by droughts, which includes about 39 per cent of cultivable land and about 29 per cent of the population (Das et al. 2007). The 2015/2016 drought in India had affected 330 million people (CRED 2021). Studies on precipitation data reveal that India has recorded an increase in moderate drought’s intensity and its areal spread and also increased frequency of multi-year drought occurrences during recent decades (Niranjan et al. 2013; Mallya et al. 2016). Under climate change scenario, frequency and intensity of drought events are likely to increase (NIC 2009). The ‘Special Report on Drought, 2021’ (UNDRR 2021) has estimated that the effect of severe droughts is at 2–5% on India’s gross domestic product (GDP). Unlike drought that is slow growing and long-term prevailing, floods are instantaneous and may cause extensive damage in short time. Between 1998 and 2017, globally more than 2 billion people are affected due to flood hazards (CRED 2018). In India, the plains are affected by floods almost every year. According to Disaster Management in India report 2010, out of 40 million hectares of the flood prone area in the country, on an average, floods affect an area of around 7.5 million hectares per year. In 2020, flooding was responsible for the 3rd deadliest event of the year costing 1,922 lives, with an estimated economic loss of 7.5 billion US$ (CRED 2021). The impacts of a flood are strongly influenced by the hydraulic characteristics of the flood itself, the physical characteristics of the flooded area, and the preparedness for evacuation. The floods may be classified into coastal floods, flash floods, river floods, drainage floods (aka urban flooding), tsunamis, and tidal waves/bore (Jonkman 2005).

Several drought indices were developed regionally and globally, based on a range of climatic and socio-economic variables and parameters, in the past. Some of them are: rainfall anomaly index (Van Rooy 1965), crop moisture index (Palmer 1968), surface water supply index (Shafer and Dezman 1982). Palmer hydrological drought index (Karl 1986), Palfai aridity index (Palfai 2002; Mezősi et al. 2016), aggregate drought index (Keyantash and Dracup 2004), decile index (Morid et al. 2006), and atmospheric crop moisture index (Uang-aree et al. 2017). Standardized precipitation index (SPI) (McKee et al. 1993) and Palmer drought severity index (PDSI) (Palmer 1965) are the most popular drought indices among all. However, both have certain limitations (Mishra and Singh 2010). Fixed time scale, inability to represent different drought types (Vicente-Serrano et al. 2010a), complex computation, and limited application where observations are scarce (Smakhtin and Hughes 2004) do not make PDSI a good choice to represent drought conditions. SPI, on the other hand, though considers precipitation and captures the multi-scalar nature of droughts, completely ignores temperature, an indicator highly correlated with the severity of drought (Abramopoulos et al. 1988; Fischer et al. 2007) and global warming scenarios. Recently, the Standardized Precipitation Evapotranspiration Index (SPEI), which considers both temperature and precipitation, has been proposed to quantify the drought conditions (Begeueria et al. 2010; Vicente-Serrano et al. 2010a, 2010b). SPEI is capable of depicting the multi-temporal nature of hydrological, meteorological, and agricultural drought based on the probability of precipitation and potential evaportranspiration (P-PET) differences (Vicente-Serrano et al. 2010a) and therefore allows a more holistic approach to explore the effects of climate change on droughts. SPEI has been applied in many regional studies (Li et al. 2015; Bezdan et al. 2019; Ayugi et al. 2020; Qaisrani et al. 2021) and was found satisfactory to capture the multi-scalar characteristic of drought conditions. The index is also applied in India at the country level (Kumar et al. 2013; Dhangar et al. 2019) and regional levels (Alam et al. 2017; Malik and Kumar 2021).

River Godavari, the longest of peninsular rivers, accounts for nearly 9.5 per cent of the total geographical area of India. The basin’s lower reaches and coastal areas are prone to cyclone and flood hazards, while the rain-shadow and plateau areas are prone to droughts. This basin has witnessed numerous extreme events of droughts and floods in last 100 years. A local climate modeling study has projected decreasing rainfall trends in the basin (Hengade and Eldho 2019). Yaduvanshi et al. (2020) have observed that extreme rain indices like consecutive dry days, highest one-day precipitation, rainfall > 10 mm, and rainfall > 20 mm show significant increase trend in recent decades. With less access to surface water due to frequent droughts, the dependency on groundwater has increased significantly in last few decades. According to ‘Groundwater Scenario Report’ of Govt. of Andhra Pradesh, Andhra Pradesh and Telangana states alone, the well population has increased from 0.8 million to 2.5 million, and area irrigated through groundwater increased from 1 million to 3.4 million hectares in just last three decades. As per Central Ground Water Commission report, with insufficient-cum-erratic rainfall and increased extraction, the groundwater level is falling in the basin. With increasing vulnerability and inefficient water resource management, climate change will further worsen the situation in most cases. The ‘Special Report on Drought, 2021’ (UNDRR 2021) has highlighted that in developing countries since the institutions treat drought as an episodic and outlier event and choose to respond only when drought emergencies arise, it perpetuates the drought vulnerabilities and its related crisis. In recent times, most of the scholars have investigated either the climate variability or projected drought scenarios.
of the basin at various scales (Bhavani et al. 2017; Masoor et al. 2020; Dixit et al. 2021; Kumar et al. 2021), but ignored the need to study the drought and flood dynamics of this huge basin under a single frame for better understanding the water resource management equations. The creation of a better knowledge base on the spatial and temporal variability of droughts and floods is necessary to improve hazard mitigation and preparedness. Water resource management helps a community to adapt the climate variability by reducing vulnerability and increasing resilience through implementing pro-active measures (Estrela and Vargas 2012; Mortazavi et al. 2012). Therefore, the objectives of the paper are: 1) to assess frequency and intensity of drought and flood events of Godavari Basin using SPEI and 2) to examine the trend of these events at sub-basin level using Mann–Kendall’s test during last four decades.

Materials and methods

Study area

The Godavari basin, the second largest basin of India, spreads over 312,812.00 Sq. Km of peninsular India. The longest river of the Deccan Plateau, River Godavari, originates near Trimbakeshwar of Nashik district at the height of 1067 m amsl, virtually bisects the plateau of Maharashtra, and flows for a length of about 1465 km before draining into the Bay of Bengal. The upper reaches of the basin are occupied by the Deccan Traps; the middle part of the basin is principally Archean granites and Dharwars; and the downstream part is occupied mainly by the Cuddapah and Vindhyan metasediments and rocks of the Gondwana group. The basin is very dissected and rugged in the north-eastern part too. The entire basin slopes toward the floodplains to the east that are very flat (0 to 3%) and often experiencing inundation. It covers 55 districts from the states of Maharashtra, Andhra Pradesh, Madhya Pradesh, Orissa, West Godavari, Nagpur, Pune, Nasik and Rangareddy that are very flat (0 to 3%) and often experiencing inundation. It covers 55 districts from the states of Maharashtra (48.7 per cent), Telangana (18.8 per cent), Chhattisgarh (12.4 per cent), Madhya Pradesh (7.8 per cent), Orissa (5.7 per cent), Andhra Pradesh (4.9 per cent), Karnataka (1.4 per cent), and Puducherry (0.01 per cent) (India-WRIS 2014). The term ‘district’ represents an administrative unit of an Indian state. The overall catchment comprises of 466 watersheds clustered into 8 sub-basins: Upper, Middle and Lower Godavari, Weinganga, Pranhita, Manjra, Indravati and Wardah. Around 37 per cent of the total basin area lies in the elevation zone of 500–1500 m (Fig. 1a). The Godavari basin has a tropical climate and is divided into three climatic regions arid, semiarid and humid (Fig. 1b). The average annual maximum and minimum temperature recorded was 32.85 °C in and 20.53 °C, respectively, in the basin (India-WRIS 2014). The average annual rainfall is 1096.92 mm, 85 per cent of it happens between the months of June and September from south-west monsoon (Fig. 1c). The basin frequently experiences droughts and floods. As per 1986 ‘Drought Area’ map prepared by National Atlas Thematic Mapping Organization, NATMO, Nasik, Ahmednagar, Bir, and Osmanabad were the drought prone districts. East Godavari, West Godavari, Nagpur, Pune, Nasik and Rangareddy are the most densely populated districts of this basin. There are about 59,293 tanks, most of them are small, nearly 870 reservoirs and nearly 286 major/medium irrigation projects in the basin.

Standardized Precipitation Evapotranspiration Index (SPEI)

This study has extracted the 1°×1° global gridded SPEI dataset developed by Vicente-Serrano et al. (2010a) for the Godavari basin from 1980 to 2019. The SPEI evaluates monthly difference between precipitation (P) and Potential Evapotranspiration (PET) over multiple time scales up to 48 months (Vicente-Serrano et al. 2010b). SPEI calculation was done based on the Thornthwaite equation for estimating PET, using mean temperature data obtained from the NOAA NCEP CPC GHCN_CAMS gridded dataset and monthly precipitation data obtained from the first guess’ Global Precipitation Climatology Centre (GPCC).

With a value for PET, the difference between the P and PET for the month i is calculated:

\[ D_i = P_i - PET_i \]

Vicente-Serrano et al. (2010a) expounded the details on the mathematical equation for computing the SPEI. SPEI can indicate the severity of dry/wet conditions using a (+/-) scale, where a negative (positive) value represents dry (wet) conditions. The scale can be classified into four categories of dry/wet events: extreme (SPEI > -2.00), severe (-1.50 > SPEI > -1.00), moderate (-1.00 > SPEI > -0.50), and mild (0 > SPEI > +0.99). In this study, a threshold of SPEI ≥ 1.0 was considered to signify dry events and SPEI ≥ 1.0 as wet events over the Godavari basin. Here ‘dry’ represents ‘drought’ episodes and ‘wet’ represents ‘flood’ episodes. This study has considered SPEI-3 and SPEI-9 for the drought and flood analysis of the Godavari basin. SPEI-3 reflects a seasonal estimation of dry/wet conditions. SPEI-9 can be effective in showing the long term dryness/wetness patterns over distinct seasons, further reflecting the agricultural-cum-hydrological consequences of drought. It compares the dry/wet conditions for nine consecutive months with that recorded in the same nine consecutive months in all previous years of available data. It may be the delayed and prolonged effects of meteorological drought (Nicholson 2000; Wu et al. 2002).
Theory of Runs

In this study, drought/flood duration and severity were extracted from the SPEI-3 and SPEI-9 series as the drought characteristics factors by using the ‘Theory of Runs.’ Proposed by Yevjevich (1967) the theory is recognized as one of the most effective methods for analyzing time series, and was applied in numerous hydrological and meteorological studies (Griffiths 1990; Peel et al. 2004; Martínez et al. 2010; Razmkhah 2017). ‘Theory of Runs’ is a method to identify drought/flood episodes, estimate the average drought length over the desired time period and study their properties for their characterization (Moyé et al. 1988). ‘Run’ denotes a series of the same phenomena that satisfies certain threshold level. This threshold level helps to identify the beginning, continuation or end of dry/wet events. In this study, a threshold of SPEI ≤ -1.0 was considered to signify dry events and SPEI ≥ 1.0 as wet events over the Godavari basin.

Dry/wet events duration \(d\) denotes the period from the beginning to the end of the dry/wet event. The severity, intensity, and frequency for both dry and wet events over the study area were defined by Eqs. (1)–(3):

Severities \(S\) for dry/wet condition is the cumulative sum of the SPEI \(\geq/-/+\) 1.0 value based on the duration extent (Eq. 1).

\[
S = \sum_{i=1}^{480} \text{Index}
\]  

(1)

Intensity \(I\) of an event is the average severity during the study period (Eq. 2). Events with shorter duration and higher severity will have larger intensities.

\[
I = \frac{S}{d}
\]  

(2)

Frequency \(F_g\) of the drought/flood event occurrence during the study period is defined in Eq. (3):

\[
F_g = \sum_{i=1}^{480} \text{Index}
\]  

(3)

Fig. 1 Godavari Basin: a) Physiography (SRTM DEM), b) Aridity Index (World Atlas of Desertification, Office of the European Union, 2018), c) Box and whisker plot of monthly rainfall (1980–2019)
\[ F_g = \frac{n_g x 100}{N_g} \quad (3) \]

where \( n_g \) is the number of months with dry/wet events (SPEI < -1/ -1.0), \( N_g \) is the total of the months in the study period, and \( g \) is a grid cell.

**Assessment of dryness/wetness trends**

This study has used Mann–Kendall (MK) test to detect the existence of a short-term and long term-trend in any data against the null hypothesis of no trend. Nonparametric MK test (Mann 1945; Kendall 1975) has been used widely for detection of dry/wet trend was tested at three different significance levels \( \alpha: 0.1, 0.05 \) and \( 0.01 \). MK test exploits the normal approximation (Z statistics). A Z-score at a given significance level

\[ Z = \frac{S}{\sqrt{\text{VAR}(S)}} \quad (8) \]

where \( Z \) is a grid cell distribution. The variance of \( S \) approximates to normal

\[ \text{VAR}(S) = \frac{1}{18} [n(n-1)(2n+5)] \quad (6) \]

The values of \( S \) and \( \text{VAR}(S) \) are used to compute the test statistic \( Z \) as follows:

\[ Z = \begin{cases} 
\frac{S-1}{\sqrt{\text{VAR}(S)}} & \text{if } S > 0 \\
0 & \text{if } S = 0 \\
\frac{S+1}{\sqrt{\text{VAR}(S)}} & \text{if } S < 0
\end{cases} \quad (7) \]

The Sen’s slope estimator, another non-parametric procedure, uses a linear model to detect the magnitude of the trend (Sen 1968). The Sen’s method is not greatly affected by gross data errors or outliers, and also it can be computed when data are missing. This method has been widely used in several hydro-meteorological time series (Lettenmaier et al. 1994; Yue and Hashino 2003; Partal and Kahya 2006; Gocic and Trajkovic 2013).

The magnitude of the time series trend is calculated by:

\[ \beta = \text{Median} \left( \frac{x_j - x_k}{j - k} \right), j > k \quad (8) \]

where \( \beta \) is Sen’s slope estimate. \( \beta > 0 \) indicates upward trend in a time series, otherwise downward during the time period.

The methodological framework of the present study is represented in Fig. 2.

**Result and Discussion**

**Dry/Wet episodes in Godavari Basin**

Figure 3 provides an overview of historical analysis for SPEI 3- and 9-month for the years 1980 to 2019 over the Godavari basin. The distribution of drought and wet events were categorized under mild, moderate, severe, and extreme frequencies. SPEI-3 has identified extreme drought episode only during 2009, while 1992, 2002–03, and 2019 as strong episode. 2002–03 are found to be consecutive years that experienced meteorological droughts. Strong wetness episodes are identified only during 1990–91. Under SPEI-9 scenario, 2009–10 and 2015–16 were found to be two consecutive drought episodes of extreme nature. Similarly 1999–2000 and 2018–19 were found to be the two consecutive droughts of strong nature, along with isolated drought years 1991, 1996, and 2009. The main cause of strong to extreme nature of droughts during the mentioned years is the below normal precipitation (IMD). It is a matter of concern that frequency of the consecutive droughts has increased in the recent decades.

**Frequencies: drought (DF) and flood (FF)**

The spatial distribution of drought and flood episodes in the basin is not uniform. Figure 4 shows the drought and flood frequency under SPEI 3- and 9-month scenarios in last four decades. For SPEI-3, the drought frequency (DF) varies between 10 and 30 per cent, while for SPEI-9 DF varies between 10 and 40 per cent. Manjra and Pranhita sub-basins have experienced highest frequency of drought episodes, and Godavari Upper the least. A 20-year breakdown of the frequency distribution shows that a drastic increase in DF has taken place between 1980–1999 and 2000–2019 time frames for Manjra and Pranhita. Under SPEI-3, the entire basin has registered an increase in DF during 2000–2019 than earlier two decades. In SPEI-9, except Indravati, the rest of the sub-basins have experienced rise in the DF between 2000 and 2019. More than two fold increase in DF
has been recorded in Pranhita sub-basin in recent decades compared to 1980–1999. The return time of drought in the interior Godavari basin was 5 years during 1980–1999 that has decreased to 3 years in recent decades. Regarding the flood frequency (FF), decreased frequency in the central part of the basin has been recorded for both SPEI 3 and SPEI 9-months. Godavari Upper, Indravati, and northern part of Weinganga have registered an increase in FF during the recent decades compared to 1980-1999. FF in Upper Godavari has increased by more than double during recent decades under SPEI-9 scenario. The return period of flood in the Upper Godavari sub-basin was 5.5 years during 1980–1999 that has decreased to 3.5 years in recent decades.

**Intensities: drought (DI) and flood (FI)**

Figure 5 shows the drought and flood intensities under SPEI 3- and 9-month scenarios in last four decades. Severe DI prevails over central part of the basin for both SPEI 3 and SPEI 9-months. Similarly, the Godavari Upper and Lower sub-basins have severe FI for both SPEI 3 and SPEI 9-months scenarios. The central parts of the basin experience moderate FI under SPEI-3 but a severe FI under SPEI-9. Although FF has reduced in the last four decades in central Godavari basin, the intensity of wetness index is quite high for the years that have encountered the flood events.

**Temporal trends of Dry/Wet episodes in Godavari sub-basins**

The basin-wise short-term and long-term dryness/wetness trends for each month is important from agriculture point of view. It helps to pro-actively adapt appropriate mechanism to overcome the future challenges of droughts and floods. Figure 6 shows the sub-basin-wise monthly SPEI 3- and 9-month trend results based on the application of MK test (Z parameter) for different time series. In this figure, color code represents the negative/positive trend at three significance levels, α: 0.01, 0.05 and 0.1. Both negative/downward (increasing dryness) and positive/upward (increasing wetness) trends have been represented along with the no trend months. In SPEI-3 except Indravati, rest of the sub-basins show a negative trend during the winter months (January/February/December). Manjra and Pranhita sub-basins have
registered negative trend during the monsoon months (June – August). A positive trend (increasing wetness) has been recorded only in Upper Godavari sub-basin during July to September months ($\alpha \leq 0.05$), while Indravati sub-basin has registered increased wetness during the month of October ($\alpha = 0.1$). Annually no significant trend is found for Indravati, Godavari Middle, and Godavari Upper sub-basins, while rest of the basins have shown significant downward trend (Fig. 7). Under SPEI-9 scenario, both Manjra and Pranhita register strong negative (increasing dryness) trend throughout the year. Wardah sub-basin has April and August months, and Godavari Lower has November and December months that have recorded increasing dryness trend. Godavari Upper is the only sub-basin that has recorded strong positive trend during monsoon and post-monsoon months. Godavari Middle, Indravati and Weinganga have shown no dryness/wetness trend in any of the months. Annually, Manjra and Pranhita registered strong negative trend ($\alpha = 0.01$); Godavari Upper has recorded positive trend ($\alpha = 0.1$); and rest have no trends (Fig. 8).

Sen’s slope estimations detected an increasing trend in severity from SPEI-3 to SPEI-9. Dryness severity trend is only visible in Upper Godavari, while rest of the sub-basins do not show any significant trend. If the dryness trend persists in near future, then Bidar, Madak, Ranga Reddy, Osmanabad, Warangal, Nizamabad, Karimnagar, Khammam, Adilabad, Yavatmal, Chandrapur, Wardha, Bhandara, West Godavari and Bijapur districts will be worst affected due to drought situations.

**Discussion**

Drought and flood studies at basin level in India have mainly considered rainfall anomaly (Gore and Sinha Ray 2002). This study has, therefore, considered SPEI 3- and 9-months using precipitation and temperature data for drought and flood occurrence and trend analysis in Godavari basin in smaller spatial scale. The SPEI 3 and SPEI 9- months have appropriately identified the distribution of short- and long-term drought situations of the Godavari basin over last 40 years. Prolonged SPEI-3, representing the short-term dryness for a few consecutive months, leads to long-term dryness was captured by SPEI-9. Since the agricultural drought is commonly related to the deficit in soil moisture and has direct implications on crop yield, increasing dryness trend
during monsoon and winter months under SPEI-9 is a major concern. Moreover, the episodes of drought of moderate to severe nature have increased by 2 to 3 folds in many parts of the basin in last 20 years than before. The basin falls in six agro-ecological zones, where interior part of the basin is characterized by moderate rainfall (500 – 1000 mm annually) with high variability (coefficient of variation greater than 20 per cent) and dry spell in winter and hot summer. The increasing dryness may have severe implications on agricultural output in near future.

As per 2010 estimation, the per capita water availability of Godavari basin was 1486.01 cubic m, which was less than the national average (1608.26 cubic m). And it was estimated that by 2050 it will be 1053 cubic m (CWC 2013). As per global standards, a region having per capita water availability less than 1700 cubic m is considered as water stressed, and less than 1000 as water scarce. Thus, Godavari is already a water stressed region and increasing dryness trend may push it to the verge of water scarce. Therefore, when the NATMO’s 1986 ‘Drought Atlas’ captured the drought situations being concentrated in Upper Godavari and Manjra sub-basins, the present study has found that dryness has extended toward interior parts of the basin comprising the districts Bidar, Madak, Ranga Reddy, Osmanabad, Warangal, Nizamabad, Karimnagar, Khammam, Adilabad, Yavatmal, Chandrapur, Wardha, and Bhandara. Water resources mismanagement, both surface and groundwater, will further increase the drought risk of these districts. Large part of Godavari is under agricultural land utility (59 per cent), and tank irrigation in the basin had a great bearing to the development of its agricultural economy and livelihoods of diverse communities on the whole in past. However, in last few decades, wells and bore-wells assumed primacy in the irrigation systems of the basin due to the availability of credit facilities and electricity at subsidized rates, deteriorating conditions of the tanks and the change in land use in the tank catchments (ISEC 2006; Pingle 2011; Kumar and Vedantam 2016). Thus, it is necessary to immediately
undertake the work of streamlining the usage of surface and ground water for irrigation, industry and municipal supply.

A closer look into the relationship between the rainfall and ground water depth of the basin may give better insights toward managing the water resources. In past three decades, Upper Godavari, Lower Godavari, Pranhita and Indravati sub-basins have experienced positive trend in annual rainfall, while rest have recorded negative trend (Fig. 9). Similarly, groundwater situation is highly variable in the basin where in some of the sub-basins the ground water depth is greater than 7 m below ground level (m bgl) throughout the year. Manjra sub-basin has registered highest fall in ground water levels in last three decades. The correlation between rainfall and ground water depth shows that except Manjra and Weinganga, rest of the sub-basins experiences reduction in ground water depth with increase in rainfall. Weinganga does not show any significant correlation. Manjra that already receives very less rainfall and have geo-morphometric constraints to groundwater recharge, at one point of time groundwater exploitation was rampant. As per the 4th minor irrigation census data (2006–07), in a single district of Beed located in Manjra sub baseline area irrigated by ground water was 1463.24 sq. km., whereas the surface water accounted for about 82.43 sq.km; thus, ground water accounted for 94% of net irrigated area (Dhonde 2014). Such regions need systematic creation of surface water resource management and ground water recharge infrastructures.

Recently, understanding the significance of the tanks to climate adaptation and water management, state governments of Maharashtra and Telangana have initiated the tank rejuvenation and farm pond creation programs namely, Gaalmukt Dharan, Gaalyukt Shivar Yojana (GDGS) 2017, ‘Magel Tyala Shet Tale (Farm Pond on Demand)’ scheme 2016 and Mission Kakatiya (MK) 2015. However, no fund has been allotted for the maintenance of the renovated tanks. Instead of heavily investing on developing new infrastructure, restoring traditional water tanks is more viable (Gujja et al. 2009) with community participation. A comparative study conducted on the semi-arid regions of Marathawada, Vidarbha and
Saurashtra has found that the groundwater levels in Saurashtra have increased immensely compared to other two regions during the same study period, and attributed it to the community-led construction of rainwater harvesting and artificial recharge structures in the region (Patel et al. 2020). It has further mentioned that groundwater recharge situation in Marathawada and Vidarbha has not equally flourished even after efforts by the Government as expected because it involved little community participation and focused more on regulation.

While the highly urbanized districts like Thane, Nasik and Ahmadnagar are experiencing increased number of heavy rainy days (IMD 2020) and subsequently increased occurrences of flood situations; Parbhani, Hingoli, and Nanded, lying downstream, have suffered extreme water stress situation during the same period. It’s high time that

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**Fig. 6** Sub-basin-wise monthly SPEI-3 and SPEI-9 trends. At $\alpha=0.01$, January month of 4 out of 8 sub-basins have recorded increasing dryness under SPEI-3, and Manjra and Pranhita have recorded increasing dryness under SPEI-9 for July and August months under SPEI-9. Upper Godavari is only sub-basin with increasing wetness at $\alpha=0.05$ during SW monsoon months under both SPEI-3 and 9 months.
Fig. 7 Sub-basin-wise annual trend of SPEI-3. Pranhita, Manjra, Wardah and Godavari lower have recorded significant negative trends.
Fig. 8 Sub-basin-wise annual trend of SPEI-9. Godavari Middle, Indravati and Weinganga show no significant trends; Godavari Upper shows significant positive trend; while rest shows significant negative trends.
the tendency to view flood and drought risks separately be avoided, and must consider them to be the part of an integrated multi-hazard risk reduction strategy. Revisiting the indigenous water management practices with community participation like ‘Jal Khet’ – rainwater harvesting structures in Diwas districts of Malwa region; the Ramtek model, traditional water harvesting structures of Ramtek in Maharashtra, may provide an insight to the need for encouraging such practices.

**Conclusion**

Increased climate variability has great implications on the incidence of extreme hazards like droughts and floods. Occurrences of these hazards are not new to Godavari basin, but the present study has shown that their intensity and frequency have increased in recent decades. Moreover, their trends are not uniform throughout the basin; when upper Godavari sub-basin registered increased wetness, Manjra and Pranhita sub-basins recorded increased dryness. UN-Water, 2021 under SDG Target 6.5 suggests that implementation of integrated water resources management at all levels, including through transboundary cooperation as appropriate, is necessary to balance competing water demands from across society and the economy. Understand the ongoing climate variability and weather extremes, it is highly essential that regions of water excess and regions of water stress of a basin should be studied under the single framework of water resource management for optimality and sustainability. With this objective present study has attempted to map the trend, intensity and frequency of both drought and flood episodes of the basin. Use of high resolution climate data may provide better insights to the drought and flood severity at watershed level, though such data availability are limited in open source domain. Even at the coarser resolution SPEI-3 and 9 months have well captured the spatio-temporal dimensions of drought/flood events at sub-basin level within Godavari basin. Such mapping methods can help regional planners and disaster managers to access the prevailing water resource management practices and accordingly recommend both structural and non-structural changes required to sustain the future climate change challenges.

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**Conflict of interest** The author declares no competing interests.

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