



Assessment of hydro-climatic trends in a drought-prone region of Maharashtra (India) with reference to rainfed agriculture

Rahul S. Todmal¹

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Abstract

The present investigation endeavored to understand trends in climatic, hydrological, and agricultural variables in the five semi-arid river basins of Maharashtra (India). For this, parametric and non-parametric statistical techniques were applied. The monsoon rainfall over the study area reveals no considerable increase during the past (1981–2013) and future (2020–2050). Although the construction of a large number of impoundment structures during the last two decades resulted in a significant rise in post-monsoon groundwater table (by 40 cm/decade), it caused a decline in surface runoff. The study area witnessed a significant increase in area under irrigated crops at the cost of rainfed crops, which resulted in a significant increase in groundwater withdrawal (GWW) by 70 cm/decade. The cropped area and productivity of irrigated crops heavily depend on rainfall and groundwater resources. Moreover, the Southern Oscillation Index (SOI) has a positive connection with the productivity of irrigated crops. On the other hand, a considerable increase in annual minimum temperature (AMNT), annual maximum temperature (AMXT), and annual mean temperature (AMT) (by 1.02, 0.50, and 0.82 °C, respectively) along with a rise of > 100 mm in potential evapotranspiration (PET) is registered during 1985–2015. The study indicates that the irrigated crops are more vulnerable to heat stress, as PHS (plant heat stress with > 34 °C) days show a considerable increase (2–5 days/decade). Furthermore, the climate projection suggest a significant rise of 1.05 °C in AMT by 2050, which is very likely to intensify the hydro-meteorological droughts and adversely affect the agricultural productivity of rainfed and irrigated crops as well. Briefly, the human-induced changes in cropping patterns (without a considerable increase in rainfall/water resource) from one side and the climatic changes (including extreme events) on the other side may exacerbate the regional water scarcity and food security challenges in the semi-arid region of Maharashtra (India) in the near-term future.

Keywords Climate change · Temperature rise · Rainfall-runoff · Groundwater · Agricultural crops · Plant heat stress

Introduction

Climatic changes can cause serious hydrological disasters (drought and flood) (TERI 2014) and aggravate agricultural distress, particularly in semi-arid regions (IPCC 2014). Maharashtra is one of the drought-prone states in India. Especially, due to low annual precipitation with high variability (Singh et al. 2021), the rain shadow zone of the state is vulnerable to drought disaster. The minor fluctuations in

rainfall affect the availability of water resources and agriculture, which is the predominant economic activity in this region (Todmal et al. 2018). The previous subdivisional and district-level studies registered increasing (Singh et al. 2021; Potdar et al. 2019) and decreasing (Kale et al. 2014; Kumar et al. 2010) trends in rainfall over the semi-arid region of Maharashtra (including the present study area), albeit the trends are not significant. Moreover, seasonality in rainfall is also observed to be increasing in this region (Guhathakurta and Saji 2013), which adversely affects rainfed agriculture. Under the scenario of climate change, the temperature rise is confirmed in different parts of India (Mondal et al. 2015). The state of Maharashtra is not an exception to this. During the last four decades, the state has witnessed a rise in annual mean temperature (AMT) by 0.4 to 0.8 °C (Dhorde et al. 2017). However, the regional studies (Jhajharia et al. 2014; Jedhe et al. 2018; Korade and Dhorde 2016; Nayak

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✉ Rahul S. Todmal
todmalrahul@gmail.com

¹ Department of Geography, Vidya Pratishthan's Arts, Science and Commerce College, Baramati, Maharashtra 413133, India

and Mandal 2012; Dhorde et al. 2017) have observed inconsistent trends and magnitudes of change in temperature at a local level. During the same period, the agricultural cropping pattern in Maharashtra is shifting toward commercial farming (Kalamkar 2011). Perhaps due to this reason, the production of food grains is notably decreased during the last two decades (Joshi and Tupe 2014).

As the climate is a crucial physical factor for agriculture, scientific attempts have been made to understand the effects of temperature rise on the agricultural crop. Some of these studies (TERI 2014; Boomiraj et al. 2011; Singh et al. 2009; Hebbar et al. 2013; INCCA 2010; Kumar et al. 2011; Jena and Acharya 2016; Jayaraman and Murari 2014) have observed that the warmer condition negatively affects agriculture. In this context, the state of Maharashtra is very likely to experience 1 to 2 °C and 1.5 to 3 °C rise in temperature by 2050 and 2070, respectively, which has potential to significantly decline the productivity of rainfed as well as cash crops (Todmal 2021; TERI 2014). Particularly, sugarcane, rice, cotton (Kelkar et al. 2020), sorghum, and pearl millet (TERI 2014; INCCA 2010; World Bank 2003) are the most susceptible crops to adverse climatic changes. Along with rising temperature, an increase (by ~20%) in monsoon rainfall is also projected over Maharashtra (TERI 2014). However, the estimated bonus amount of rainfall in the form of heavy rainfall events can further aggravate agricultural distress (Todmal 2021).

On the other hand, notably declining streamflows in the semi-arid rivers of Maharashtra is another hydrological concern from the agricultural viewpoint. Particularly, in the Upper Bhima Basins (including the present study area), a notable decrease in surface runoff is registered (Biggs et al. 2007; Kale et al. 2014). Considering the current rate of surface water harvesting, further decline in water yield is expected in the Krishna Basin (Gosain et al. 2006; Jain and Kumar 2012). Although surface water harvesting brought a positive change in the groundwater table at the local level (Todmal 2020), due to limited surface irrigation, the groundwater is being over-exploited to cultivate cash crops and rainfed crops as well. It resulted in the deepening of the sub-surface water table in the rain shadow zone (GSDA 2014). Under such circumstances, the expansion of area under high water-requiring crops in Western Maharashtra may lead to intensification of hydrological (Surinaidu et al. 2013) and agricultural drought events in foreseeable future.

On this background, to cope with adverse climatic changes, it is important to rectify the existing hydro-climatic and agricultural policies with the consideration of present and future changes. Therefore, the present study endeavored to evaluate recent trends in rainfall, temperature, potential evapotranspiration, PHS days, surface, and sub-surface water resources in the drought-prone region of Maharashtra. The study also examined changes in the area

under rainfed and high water-requiring crops (cropping pattern). To discuss the future prospect of water resources and agriculture in the study area, an attempt has also been made to estimate trends in the near-term future climate (up to 2050).

Study area

Hydro-climatic setting

The Western Ghats is a predominant physical factor that determines the spatial distribution of rainfall over the state of Maharashtra. Its orographic effect causes scanty rainfall on the leeward side, which is < 750 mm (Fig. 1). High ambient mean daily temperature (> 22 °C) is another characteristic of this rain shadow zone, where the annual mean maximum temperature observed between 30 and 40 °C during summer season (IMD 2005). In the winter season, daily temperature ranges between 18 and 22 °C. As per Köppen's classification, the region has *a bsh* type of climate. On account of the warmer climate throughout the year, the rate of potential evapotranspiration (PET) is high (1500–1800 mm) (Todmal 2019). As the monsoon rainfall is erratic (coefficient of variability between 25 and 60%) (Guhathakurta and Saji 2013), this zone experiences drought conditions once in 3 to 5 years (Gore et al. 2010; Gadgil 2002). Therefore, the region is also known as a drought-prone region of Maharashtra.

For the present investigation, five river basins namely Sina, Karha, Yerala, Man, and Agrani from the rain shadow zone of Maharashtra were selected. These basins fall in the Madhya Maharashtra meteorological subdivision (Fig. 1) and collectively cover about 24,000 km² of area. Among them, the Sina, Karha, and Man are the part of Bhima River, which is the main tributary of the Krishna River. The Yerala and Agrani directly drain into Krishna River (Fig. 1). Each of the selected basins entirely (from source to confluence) falls in the rain shadow zone. The study area receives about 90% of annual rainfall (500 to 700 mm) in the monsoon months (June to October). Being a part of a severe to chronic drought-prone zone (Khambete and Biswas 1984), the basins under investigation are characterized by high (800 to 1100 mm) annual water deficiency (Dikshit 1983). As monsoon rainfall is the primary input in semi-arid hydrology, the selected rivers depict ephemeral or seasonal characteristics. During the non-monsoon period as well as drought year, stream discharge is observed to be nil (Kale et al. 2014). Although the monsoon rainfall is the only source to recharge the groundwater level, due to large number of surface impoundment structures, during the drought year the groundwater is available at least for drinking purpose (Udmale et al. 2014b; Todmal 2020).

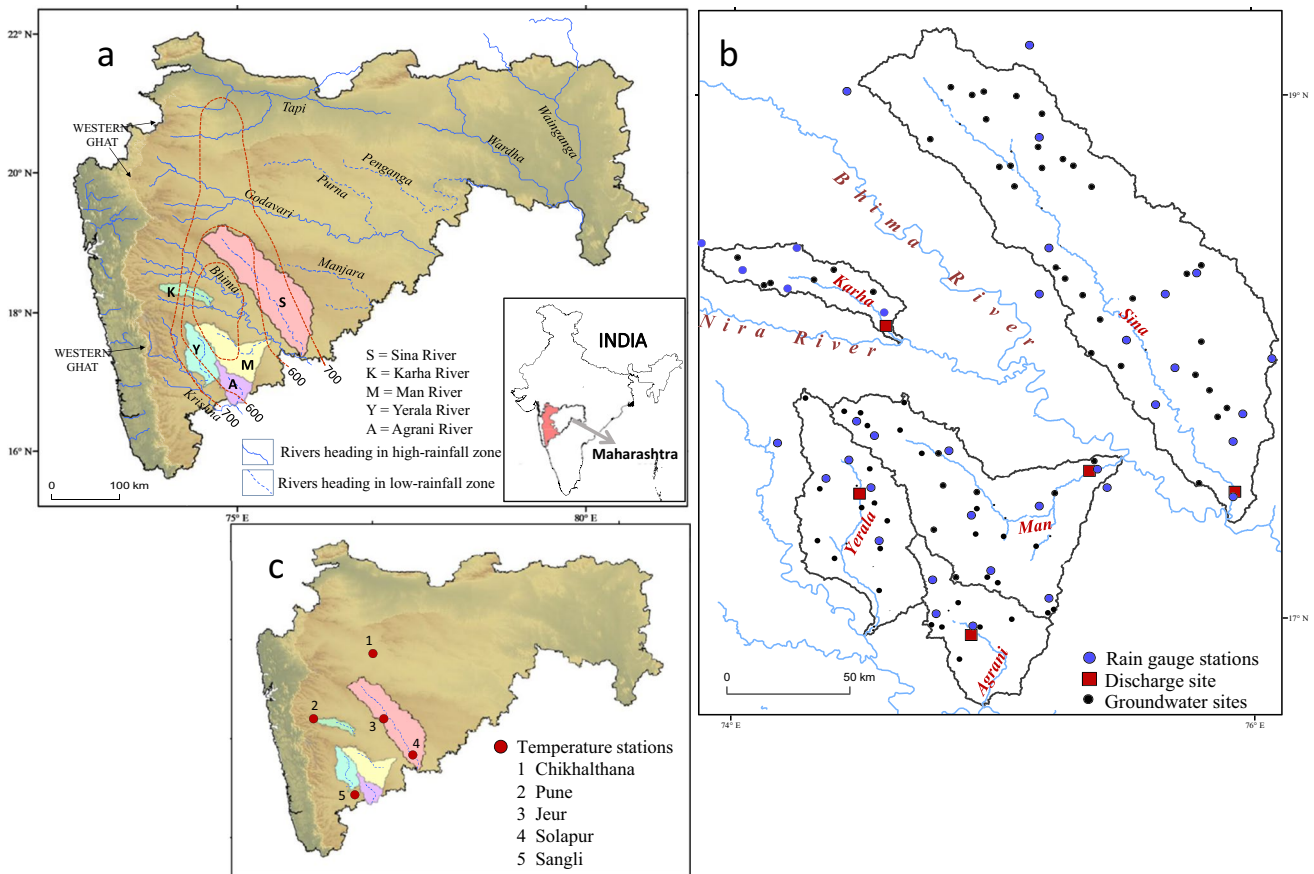


Fig. 1 a Location map of the study basins. Dashed red lines represent isohets (in mm). Distribution of the selected b rainfall, runoff, and groundwater c temperature stations over the study area. The pink

color in the inset map of India shows Madhya Maharashtra Subdivision. Base map of the Maharashtra State after Kale et al. (2014)

Agricultural setting

The agriculture in the present study area is mainly rainfed, as it is a part of the scarcity zone (agro-climatic zone) of Maharashtra (Deosthali 2002). The Karha, Man, and Agrani Basins cover part of the low-crop potential zone (LCPZ) which is one of the three LCP zones in India (Biswas and Nayar 1984). Cultivation of drought-resistant and short-duration crops is the characteristic of agriculture in the study area. Sorghum, pearl millet, gram, pigeon pea, edible oil seeds, and pulses are the rainfed crops that cover about 65 to 80% of agricultural area (GoM 1999). Among them, sorghum, pearl millet, and edible oil seeds are the dominant crops, cultivated over ~ 50%, 20%, and 10% of the area, respectively (Kalamkar 2011). On the other hand, the high water-requiring crops/cash crops such as sugarcane, onion, maize, and wheat are also cultivated (<20% area) in the areas where the surface irrigation facility is available. Despite enormous investment to increase the area under irrigation in the drought-prone region, less than 18% of the cultivated area is irrigated through surface water (Udmale

et al. 2014a). Therefore, during the lean monsoon and non-monsoon periods, almost 50% of the cultivated area depends on groundwater irrigation (GoM 2014).

Methodology

Collection and preparation of data

This investigation was carried out by using the rainfall, temperature, runoff, groundwater level, and agricultural data. The details of collected data are given in Table 1. The procedure to fill the missing values and preparation of collected data is provided in Appendix I. As mentioned earlier, the study area receives about 85% of annual precipitation during the monsoon months. Therefore, the station-wise rainfall data for the monsoon months (June to October) were collected. The monthly mean minimum and mean maximum temperature data were collected for the five selected stations, which represent the study area (Fig. 1). The annual PET values were estimated by using monthly mean temperature

Table 1 Details of data used in the present study

Parameters	Stations/talukas	Time span (duration)	Missing data	Source
Monsoon rainfall	40	1981–2013 (33 years)	7%	IMD, ADMS, HDUG
Temperature	5	1951–2015 (65 years)	4%	IITM
Monsoon discharge	5	1981–2010 (30 years)	0%	HDUG
Groundwater levels (pre-and post-monsoon)	73	(1981–2014) (34 years)	4%	GSDA
Projected rainfall and temperature data (CORDEX RCA4 model)		(2015–2050) (35 years)	0%	IITM
SOI and IOD (monthly)		1981–2015	0%	NOAA
Agricultural data	37	Cropped area (1981–2010)	2%	ADMS

Irrigated crops: sugarcane, maize, onion, and wheat

Rainfed crops: sorghum, pearl millet, gram, pigeon pea, pulses, and edible oil seeds

IMD India Meteorological Department, *HDUG* Hydrological Data Users Group, *ADMS* Agriculture Department of Maharashtra State, *IITM* Indian Institute of Tropical Meteorology, *GSDA* Groundwater Survey and Development Agency, *SOI* Southern Oscillation Index, *IOD* Indian Ocean Dipole, *NOAA* National Oceanic and Atmospheric Administration (www.noaa.gov)

records. For this, the PET calculator based on Thornthwaite Method (1948) available online at <http://ponce.sdsu.edu/onlinethornthwaite.php> was applied. Assessment of hydrological changes in the study area was another objective of this investigation. For this, the monthly discharge data of five gauging sites (one from each basin) were collected. As about >95% of annual stream discharge is observed during the monsoon period, the discharge records were obtained from June to October. The groundwater levels recorded during post-monsoon (POGW) and pre-monsoon seasons (PRGW) (usually recorded in the month of October–November and April–May, respectively) were considered. The annual groundwater withdrawal (GWW) was estimated by subtracting POGW level values from the succeeding year's PRGW levels. In order to understand the recent agricultural changes in the study area, data regarding agricultural crop productivity and cropped area under rainfed and irrigated crops were acquired for 37 talukas (subdivision of the district), which cover the study basins (Table 1). For the assessment of physical connections of hydro-climatic variables with agricultural productivity and cropped area, average monsoon rainfall, runoff, POGW, and GWW for the entire study area were considered. Moreover, the Southern Oscillation Index (SOI) and Indian Ocean Dipole (IOD) Index data were collected from the website of the National Oceanic and Atmospheric Administration (NOAA), USA. The linear correlation and regression model was applied to estimate the relationships between the abovementioned hydro-climatic and agricultural variables. It is well recognized that high temperature has a negative effect on the growth and yield of agricultural crops (Luo 2011). The temperature above the optimum range is considered as Heat Stress (Kotak et al. 2007). This study attempted to understand the crop-wise trends in PHS days. Generally, the temperature above 30 °C

is considered to be a critical temperature for crop growth (Agrimet. IMD 2003; Gaur et al. 2013; Murari et al. 2018; Swami et al. 2021; Lobell et al. 2012; Lobell et al. 2013; Luo 2011; Ong and Monteith 1985). Therefore, the days with temperature > 30 °C, > 32 °C, and > 34 °C were considered as PHS Days. For this, the daily maximum temperature values for the entire study area between 1971 and 2015 were estimated by averaging the grid data acquired from India Meteorological Department (IMD). The yearly days with temperature above threshold values during the crop duration were counted. For this, the duration of each selected crop was taken into consideration as per the crop weather calendar for Maharashtra (Agrimet. IMD 2003). Additionally, this study also endeavored to estimate future climate change over the study area. For this, projected rainfall and temperature data (2015–2050) CORDEX RCA4 Model based on representative concentration pathway (RCP) 4.5 were collected from IITM (<http://cccr.tropmet.res.in>). The details of considered climate projection models are given in Appendix II.

Trend analysis

Generally, the hydrological and climatic data are not normally distributed (Kundzewicz and Robson 2004). As the parametric statistical techniques are based on the assumption of normality, this type of test may fail to detect real trends in time series. In this study, therefore, parametric and non-parametric statistical techniques were applied to understand the hydro-climatic and agricultural changes. However, the study considered the rate of per unit change (*b* value) in selected variables estimated by the parametric techniques. The following data series of variable duration

(25 to 65 years) were derived from the prepared data to carry out the trend analysis:

- Monsoon rainfall (station-wise and for the entire study area)
- Station-wise 1-day maximum monsoon rainfall
- Temperature (AMNT, AMXT, and AMT for selected five stations)
- Average monsoon runoff, average PMGW level, and GWW for the entire study area
- Agriculture (cropped area for the selected talukas and entire study area)
- Crop-wise PHS days with $> 30\text{ }^{\circ}\text{C}$, $> 32\text{ }^{\circ}\text{C}$, and $> 34\text{ }^{\circ}\text{C}$ temperature (daily maximum).
- Projected climate data (monsoon rainfall and AMT for the entire study area and Madhya Maharashtra subdivision)

The trends in the abovementioned data series were detected by applying the linear regression method. To verify the obtained results, the Mann–Kendall and Spearman's *Rho* which are the non-parametric tests were used. In addition to this, an attempt has also been made to understand the year of abrupt change in hydro-climatic and agricultural variables. For this, cumulative deviation a parametric technique was applied and the obtained results were confirmed by cumulative sum (CUSUM) and Worsley likelihood ratio tests, which are non-parametric methods. Moreover, based on the derived year of step-change, the data series were divided and treated as two samples to compare by using Student's *t* and rank sum tests. It helped to verify the change after the step-change year. These two tests were also applied to compare the change in agricultural cropped area over the entire study area between 1980–1990 and 1990–2010.

Results

Trends in monsoon rainfall

The results obtained from parametric and non-parametric statistical tests are summarized in Table S1. The majority of selected stations (about 60%) reveals a decreasing trend in rainfall; however, only 8% (3 stations) of them are statistically significant. It should be noted that 23 out of 25 stations with decreasing trend fall in all the basins excluding the Yerala. Perhaps due to the averaging effect, the average monsoon rainfall over the entire study area exhibits no significant change (Table S1 and Fig. 3). The study conducted by Kale et al. (2014) registered comparable trends in rainfall over the semi-arid region of Maharashtra. The rainfall over the Madhya Maharashtra experiences spatial variation (from west to east direction) due to the orographic effect.

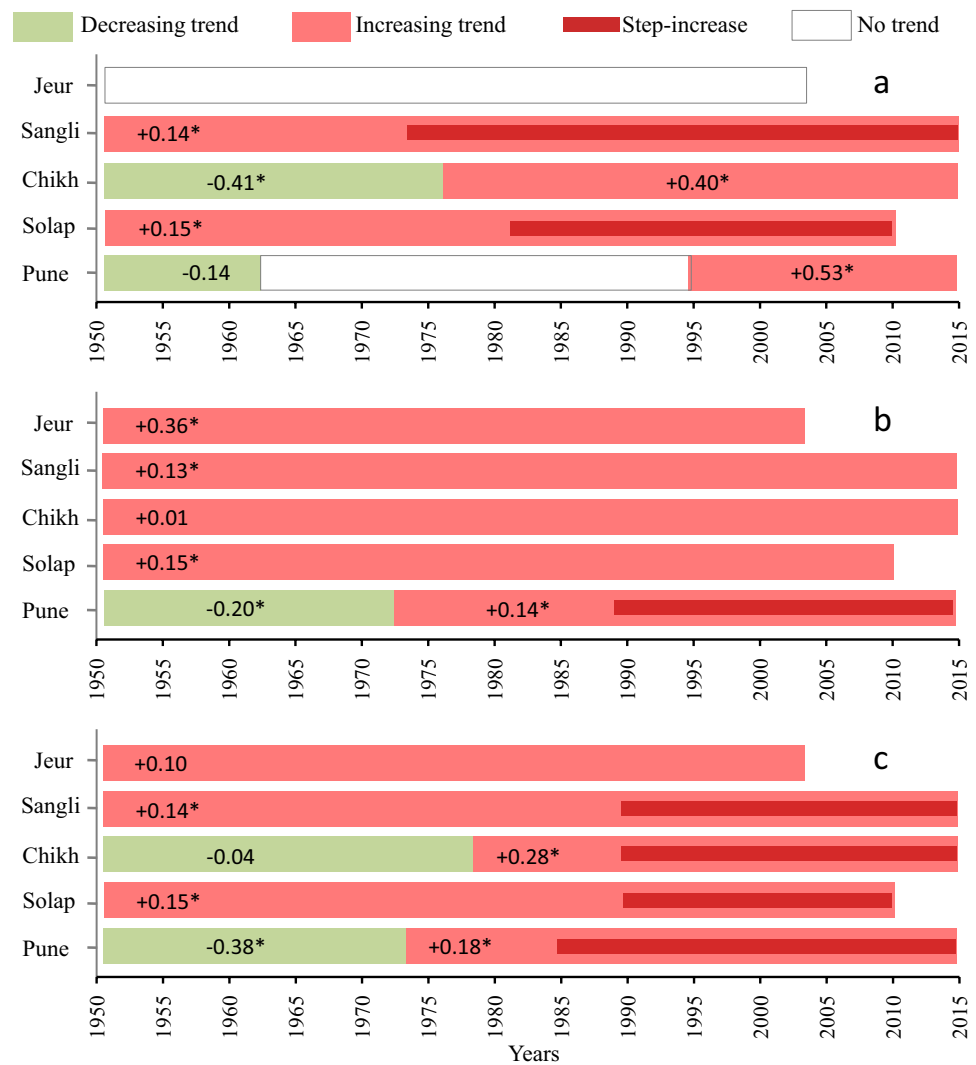
Therefore, an attempt was made to examine the spatial variation in the initiation of abrupt change in monsoon rainfall by plotting the years of step-changes for selected rain gauge stations against their longitudes (Fig. S1a). The two distinctive clusters of stations with increasing and decreasing trends can be noticed. The western part of the study area (in the vicinity of the Western Ghats) shows an increasing rainfall trend (the Yearla and western Karha Basins), particularly after 2003. The Man and Agrani Basins fall in the chronic drought-prone and low-crop potential zone of Maharashtra (Todmal 2020). Interestingly, another cluster of stations with a declining trend (particularly after 1997–2002 period) exactly falls in this zone (Fig. S1a).

About 60% and 40% of stations in the study area show decreasing and increasing trends in 1-day maximum rainfall, respectively (Table S1). Around 50% of stations with a declining trend exhibit a significant step-decline, although the year of step-change varies station-wise. Therefore, the average for the entire study area registered a decline in maximum rainfall (particularly after ~2000), albeit the trend is not statistically significant. Alike to monsoon rainfall, only 8% of stations registered a significant increase and decrease. Being a part of a chronic drought-prone and LCP zone, a considerable decline in maximum rainfall is observed in the Man and Agrani Basins (Fig. S1b). However, stations in the vicinity of Western Ghats displayed an increase in peak rainfall events (particularly after ~2004).

Trends in temperature

Figure 2 displays trends in AMNT, AMXT, and AMT over the study area between 1951 and 2015. Broadly, the area under investigation has witnessed a rise in temperature, as all the selected stations registered a significant increase in temperature, particularly during the post-1970 period. It should be noted that the interior peninsular region (including the present study area) underwent an abrupt change in temperature after 1971 (Mandal et al. 2015). The station-wise temperature records considered in the present study depict a significant increase in AMNT (Fig. 2a). All the selected stations, except Jeur, exhibit rise in minimum temperature by 0.10 to 0.53 $^{\circ}\text{C}$ per decade (Fig. 2a). Epochal variations in AMNT trends (increasing and decreasing) can be observed at Chikhalthana and Pune Stations. During the 1950–1975 and 1976–2015 periods, a significant decreasing and increasing trends, respectively are registered at Chikhalthana with a comparable rate of change. Similarly, a variety of phases with decreasing, stable and increasing trends in long-term AMNT records are registered at the Pune Station. This anomalous temporal pattern in AMNT is likely due to the vicinity of Western Ghats. It should be noted that the same station experienced a significant rise in AMNT with a considerably higher pace during the last 20 years. On the other

Fig. 2 Station-wise trends in **a** annual mean minimum, **b** annual mean maximum, and **c** annual mean temperature. Positive and negative values in bar denote increasing and decreasing decadal rates, respectively in temperature (in °C). * represent statistically significant trends at a 0.05 level. Solap = Solapur, Chikh = Chikhalthana. Temperature stations and representative areas: Pune (Karha Basin), Chikhalthana, Jeur and Solapur (upper, middle, and lower Sina Basins, respectively), Sangli (Yerala, Agrani and Man Basins), Solapur (Man Basin)

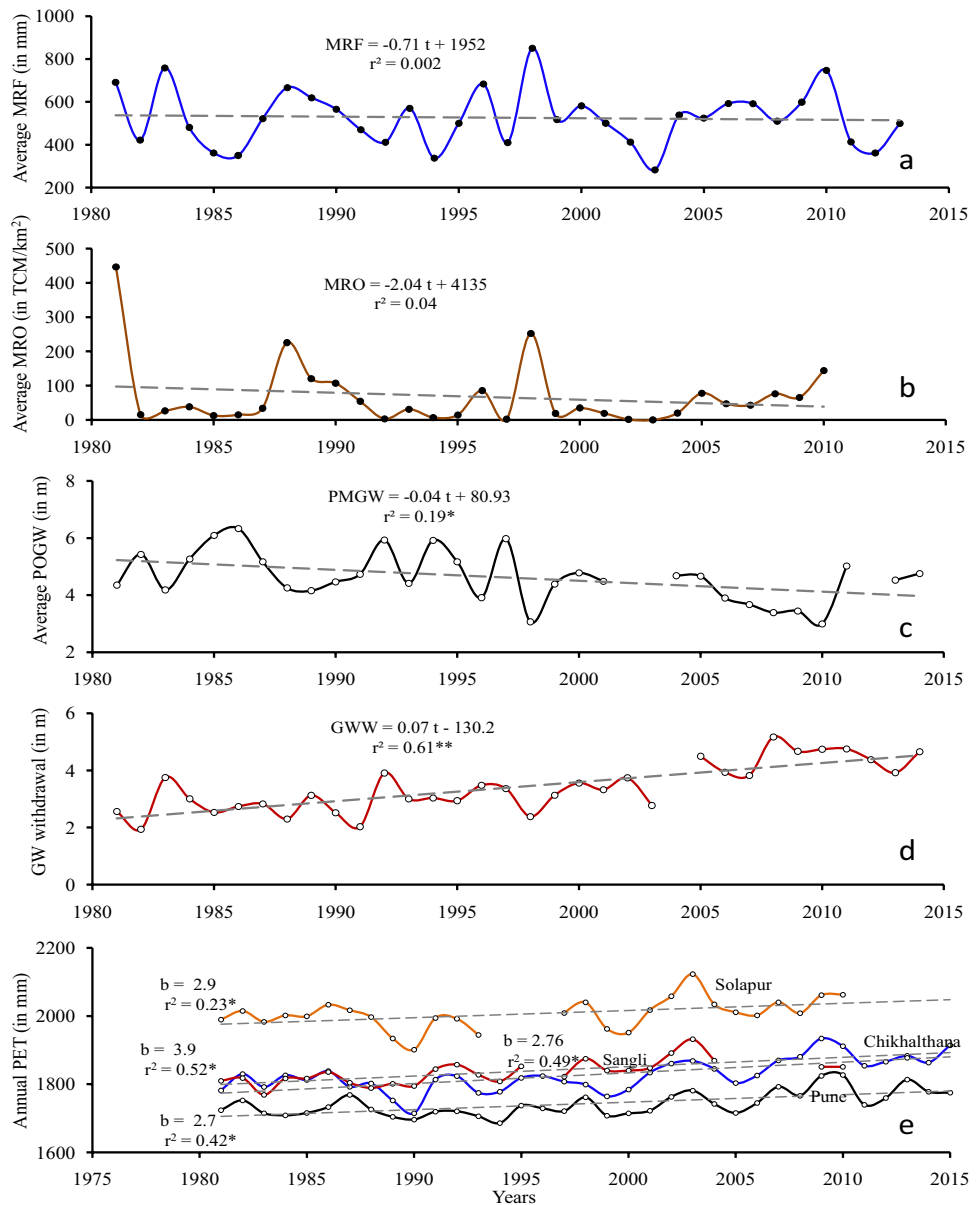


hand, the Sangli and Solapur Stations show a gradual rise in AMNT between 1951 and 2015. However, these stations registered a significant rapid warming after 1974 and 1982, respectively (Fig. 2a). These results are in good agreement with the findings that emerged from the study conducted by Singh et al. (2013). Although there is no trend in AMNT at Jeur Station, the coefficient of variability is increased (from 1.5 to 35%) notably after 1972. Alike AMNT, the study area experienced a significant rise in AMXT during the last 65 years, as all the stations registered an increasing trend (Fig. 2b). The results obtained from the study carried out by Mandal et al. (2015) support this observation. It is confirmed that the AMXT over India has increased (by 0.91 °C) during the last century (Arora et al. 2005). As compared to this, the present study area witnessed an additional rate of rise in AMXT. Since 1951, Solapur and Sangli registered a rise of about 0.90 °C. Warming of > 1.5 °C with a maximum rate (0.36 °C/decade) is observed at Jeur, where the maximum temperature is observed to be crucial in determining changes

in AMT. In the case of Pune Station, due to the bimodal character of data, increasing (1951–1972) and decreasing (1972–2015) trends are observed (Fig. 2b). A significant decline and rise in AMXT by 0.5 and 0.6 °C are observed during these periods, respectively. The rate of increase (0.48 °C/decade) in maximum temperature at the Pune Station is augmented abruptly during 1988–2015.

As the AMT data series were derived by averaging the maximum and minimum temperature records, temporal patterns in AMNT and AMXT are well reflected in the AMT trends (Fig. 2c). The Pune and Chikhalthana Stations experienced phases of increasing and decreasing trends during the study period. Despite this, the study area has experienced a rise in AMT, as all the stations except Jeur, exhibit significantly increasing trends. Particularly, during the post-1973 period, region-wide warming with a decadal rate of 0.1 to 0.3 °C is registered (Fig. 2c). The results obtained by Ray et al. (2019) and Kothawale and Rupa Kumar (2005) corroborate this finding. Additionally, the

Fig. 3 Trends in **a** monsoon rainfall (MRF), **b** monsoon runoff (MRO), **c** post-monsoon groundwater level (POGW), and **d** potential evapotranspiration (PET) over the study area. The rainfall, runoff, and groundwater are the weighted average values for the entire study area. * denote statistically significant trend at a 0.05 level. b = slope of regression line (rate of change per year), t = time, TMC = thousand million cubic meters. Data of POGW (extreme droughts) and PET are excluded and not available, respectively where the graph lines are disconnected. Temperature stations and representative areas: Pune (Karha Basin), Chikhalthana and Solapur (Upper and lower Sina Basins, respectively), Sangli (Yerala, Agrani and Man Basins), Solapur (Man Basin)



observed magnitude of increase in AMT compares well with those of the study carried out by Dhorde et al. (2017). Moreover, the Sangli, Chikhalthana, and Solapur Stations registered a swift rise in AMT after 1990 (at the rate of 0.25, 0.57, and 0.37 °C/decade, respectively). A notable increase of 0.30 °C/decade is noticed at Pune during post-1985. Among all the selected stations, the AMT records at Pune show an anomalous significant decline between 1951 and 1973. The study undertaken by Gadgil and Dhorde (2005) observed a comparable temporal pattern in temperature. Although the AMXT at Jeur reveals a considerably increasing trend, perhaps due to the averaging effect, the AMT exhibits an insignificant trend. However, the coefficient of variability in AMT is observed to be increased (from 1.4 to 41%) notably after 1973.

Hydro-climatic trends

A generalized picture of hydro-climatic trends over the study basins is given in Fig. 3. As the station-wise analysis displays a combination of increasing and decreasing trends in monsoon rainfall, perhaps due to averaging effect, the regional average rainfall shows no significant trend during the last three decades (Fig. 3a). The district-level study undertaken by Guhathakurta and Saji (2013) provided a comparable picture. The monsoon runoff over the semi-arid region is declining (notably after 1999); however, due to averaging effect, the trend is not statistically significant (Fig. 3b). The previous studies (Kale et al. 2014; Biggs et al. 2007) have registered comparable observations in the upper Krishna Basin (including the present study area).

It suggests the role of anthropogenic interventions in the semi-arid river basins of Maharashtra. In the case of the POGW level, the study area reveals declining trend (rise in water table particularly during the post-1998 period) between 1981 and 2014, as about > 55% of the selected dug wells show decreasing trend (Fig. 3c). The average regional POGW table is rising at the rate of 40 cm/decade, albeit the rates vary basin-wise. It is interesting to note that although there is no considerable increase in monsoon rainfall, the POGW table is steadily rising. However, at the local level, a decreasing trend in the groundwater level (rise in water table) has connection with monsoon rainfall (Todmal et al. 2018). On the other hand, the yearly groundwater withdrawal (GWW) shows a significant increase during 1981–2015 (Fig. 3d). It suggests that the extraction of groundwater is higher than the recharged volume. The study area witnessed GWW at the rate of 70 cm/decade (Fig. 3d), which nullifies the groundwater development achieved through the harvesting of rainwater and surface water. Under the recent warming scenario, the semi-arid regions in India registered a notable increase in PET (Sahu et al. 2021). By considering the availability of continuous temperature records, monthly PET values for all the selected stations excluding the Jeur Station were estimated. As the temperature has a direct connection with PET, the area under investigation displayed a significant increase in PET by > 100 mm during the last three decades. The selected stations registered an increase in PET

at the rate of 30 to 40 mm/decade. However, the amount of annual PET is notably augmented after the late 1990s.

Trends in agricultural cropped area

Figure 4 exhibits a synoptic view of trends in cropped area under rainfed and irrigated (cash) crops in the study area. Broadly, the areas under rainfed crops (crops below the dotted black line) are observed to be declining in all the selected talukas (administrative subdivision of district). On the contrary, the irrigated cropped area registered a notable increase. However, at the micro-level, some of the talukas registered anomalous trends as well.

Trends in rainfed crops

It is evident from Fig. 4 that the cropped areas under sorghum and pearl millet (which together cover 50 to 60% of agricultural area) significantly declined in the study area, as about 85% and 60% of the selected talukas show a decreasing trend, respectively. Interestingly, the majority of them registered a rapid decline after ~ 1995. About 3/4th of the selected talukas reveal a decrease in area under pulses and edible oil seeds (collectively cover about 10 to 20% of the agricultural area), the majority of them (60%) is statistically significant (Fig. 4). However, no systematic pattern in step-changes in the cropped area is observed. The results of the step-change analysis indicate that area under these two crops

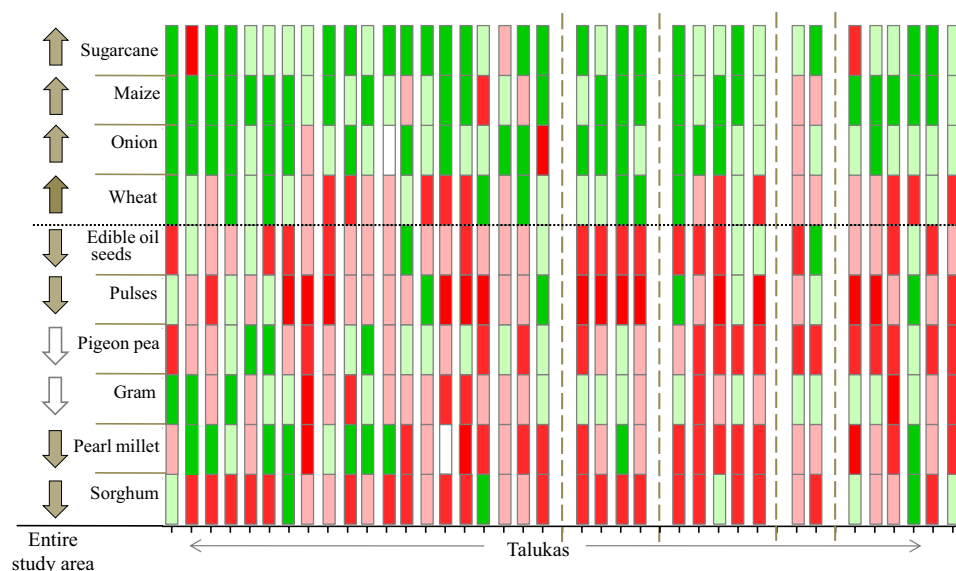


Fig. 4 Basin-wise and taluka-wise trends in the agricultural cropped area under selected crops. Red and green colors represent decreasing and increasing trends, respectively in cropped area, dark colors represent statistically significant change in the cropped area at a 0.05 level. White-colored box indicates data not available. Crops above and below the dotted black line are cash (irrigated) crops and rainfed

crops, respectively. Vertical dashed lines separate basins. Upward and downward arrows denote increasing and decreasing trends, respectively. Solid gray arrows represent a statistically significant trend at a 0.05 level. Trends for pearl millet and wheat (entire study area) are significant by excluding the extreme cropped area values

is notably reduced after 1986–1994 period. At the same time, the decreasing trend in pigeon pea and gram is not statistically significant over the study, although about 70% and 54% of talukas, respectively reveal a reduction in the cropped area. May be due to the averaging effect, despite the considerable decline registered in some talukas, the regional averages not displayed a notable trend. Secondly, both of these crops have good market value as compared to other rainfed crops, which can be another reason for the marginal decline in cultivation. In nutshell, the area under investigation witnessed a decrease in area under rainfed crops during the last three decades.

Trends in irrigated/water-intensive crops

In the case of irrigated crops, the cropped area registered a notable increase over the study area during the last three decades. Particularly, the cultivation of maize is increased in about 86% of talukas. About 75% of them show a significant growth in hectares (Fig. 4). The obtained results also suggest that the expansion in area under maize was remarkably accelerated after 1990–1997 period. Onion is another short-duration high-water-requiring crop, which exhibits a notable increase in hectareage, as about 90% of the selected talukas reveal an increasing trend (Fig. 4). However, only half of them are statistically significant. Ironically, in spite of severe water scarcity in western Maharashtra, sugarcane is a leading cash crop (Todmal 2016). Therefore, about 90% of talukas show an increase in sugarcane cultivation. About 65% of them registered statistically significant growth in the cropped area. The World Bank (2008) has documented almost comparable findings. The study area experienced a rapid expansion of the sugarcane crop after the period 1992–1997. The contradictory results can be observed in the case of wheat, which is one of the high water-requiring (*rabi*) crops. The cropped area is, by and large, observed to be declining over the study area, as more than 55% of the talukas reveal decreasing trend (Fig. 4). However, by excluding the effect of droughts (in 2002–2003 and 2011–2012), the cropped area under wheat is increasing over the entire study area. Perhaps due to the lower market value (as compared to the other cash crops), the area under wheat is expanding at a slower pace.

Hydro-climatic connections with agriculture

As the rainwater and groundwater are the main sources of irrigation for about 80% of agricultural land in the semi-arid region of Maharashtra (Todmal 2022; GoM 2014), the agricultural cropped area and yield are linked with climatic as well as hydrological variables. The monsoon rainfall considerably determines the agricultural productivity of rainfed and irrigated crops as well (Table S2). The monsoon

rainfall over the study area has a significant connection with SOI (Todmal 2022). Therefore, it is not surprising that the SOI exhibits a significant connection with agricultural productivity in the study area. More than 50% of agriculture relies on groundwater resources (Udmale et al. 2014a). The present study confirms the same fact, as the POGW level strongly determines the productivity of rainfed and irrigated crops. Moreover, the annual GW withdrawal has a considerable role in determining the productivity of rainfed crops (Table S2). However, the yield of irrigated crops is marginally determined by the GW. The results also suggest that the monsoon runoff and IOD have no considerable link with agricultural productivity in the study area. On the other hand, the interlinkages between agricultural cropped areas and hydro-climatic variables reveal interesting facts. None of the hydro-climatic variables, except GW withdrawal, denotes considerable linkage with the area under rainfed crops (Table S2). It is pertinent to note that the GW withdrawal is negatively and positively associated with rainfed and irrigated crop hectares, respectively. As the availability of water is crucial for the cultivation of water-intense crops, the monsoon rainfall, POGW, and GW withdrawal exhibit significant relationships with the cropped area under irrigated crops.

Trends in plant heat stress (PHS) days

The crop-wise trends in PHS days are given in Table 2. The rate of increase in crop-wise PHS days above 34 °C is notably lower (0 to 5 days/decade) as compared to > 30 °C (3 to 9 days/decade) and > 32 °C (3 to 9 days/decade) thresholds. The results of Student's *t* test confirmed this observation. The crop-wise increasing rates of PHS days > 34 °C for the rainfed crops are almost negligible (except sorghum), as the trend is not statistically significant (Table 2). Although for sorghum, the obtained results show a considerable increase in PHS days at all the selected threshold temperatures, the threshold crossing days are mostly observed in the month of February (the harvesting period of sorghum). Therefore, it has very minor or no effect on growth or productivity. On the other hand, during the cash/irrigated crop cultivation periods a significant increase in PHS days (> 34 °C) by 2 to 5 days per decade is registered. The decadal increments (by 5–9 days) in heat stress days > 30 °C and > 32 °C are almost comparable for the rainfed and irrigated crops. Exceptionally, the cultivation periods of pearl millet and onion³ were observed with a marginal increase (< 4 days/decade). However, the effect of extreme temperature varies crop-wise. Therefore, the maximum temperature values (temperature tolerance) given in Table 2 suggest that sorghum, pearl millet, pigeon pea, and pulse (rainfed crops) have comparatively higher temperature tolerance. Due to

Table 2 Crop-wise decadal rate of increase in PHS days during 1971–2015

Crops (crop duration)	Maximum temperature	PHS days with > 30 °C	PHS days with > 32 °C	PHS days with > 34 °C
Rainfed crops				
Sorghum (October–February)	32–34 °C (Swami et al. 2021; Murari et al. 2018; IMD 2003)	7*	7*	3*
Pearl millet (June–October)	30–34 °C (Swami et al. 2021; Ong and Monteith 1985)	3* #	1	1
Pigeon pea (June–October)	30–35 °C (Murari et al. 2018)	8*	9*#	1
Pulses (October–February)	31 °C (Luo 2011)	6*	6*	1
Irrigated/cash crops				
Wheat (November–March)	26 °C (Wahid et al. 2007)	6*	5*	2*
Maize (June–February)	30–35 °C (Luo 2011; Commuri and Jones 2001)	9*	8*	3*
Sugarcane (July–July)	32 °C (Swami et al. 2021)	9*	8*	5*#
Onion ¹ (July–October)	25 °C (Lee and Suh 2009)	8*	7*	4*
Onion ² (October–February)		8*#	9*	4*
Onion ³ (December–April)		0	4*#	3*

* represents a statistically significant increase (trend) at a 0.05 level. # denotes the trend between 1981 and 2015. The crop durations taken from the crop calendar published by D.D.G.M., IMD (Agrimet) (2003), and Manivasagam and Nagarajan (2018) are given in bracket. Maize crop is taken during *kharif* (June to October) as well as *rabi* (October to February) seasons. Sorghum cultivated in *rabi* season is considered. IMD (2003) = Agrimet. IMD (2003)

lower heat stress tolerance (< 30–32 °C), onion, wheat, and maize are the more vulnerable crops. Particularly, the rising temperature during the *rabi* season (winter) resulted in increasing PHS days for wheat, onion, and maize crops. The higher number of days for onion² supports this observation.

Future climatic changes

The near-term future (up to 2050) trends in monsoon rainfall and annual mean temperature over the study basins (obtained from CORDEX RCA 4 model) are exhibited in Figure S2. The linear regression model shows no trend in the monsoon rainfall between 2015 and 2050. It signifies that the water availability (through rainfall) in the study basins will be more or less the same. The previous studies (Sandeep et al. 2017; Todmal 2021) corroborate this result. Although the TERI (2014) has estimated a marginal increase in annual rainfall over the study area, it is not statistically significant. It can be observed that the selected climate projection model estimate a higher frequency of years with low rainfall between 2030 and 2040. On the other hand, the study area is very likely to experience a rise of 0.3 °C/decade in AMT during the next three decades (Fig. S2). In other words, the study area may register AMT rise of 1.05 °C up to 2050. The findings that emerged from the study undertaken by TERI (2014) and Todmal (2021) are in good agreement of these results. The results of step-change analysis indicate that the semi-arid region of Maharashtra is very likely to experience warming at a notably rapid rate after 2034, which can adversely affect the rainfed as well as irrigated crops.

Discussion

The results given in the preceding section highlight changes in rainfall, runoff, groundwater, temperature, PET, and agricultural cropping pattern in the semi-arid region of Maharashtra. Although there is station-wise variation in rainfall trends, it is interesting to note that the changes (increase and decrease) are notable after ~2000. Considering the entire study area, there is no change in monsoon rainfall over the study basins during the last three decades. However, the decline in rainfall over the low-crop potential zone (LCPZ) is a major concern from the agricultural viewpoint. On the other hand, the western part of the study area (Yerala and Karha Basins) shows an increase in monsoon rainfall along with an increase in heavy rainfall events (Fig. 2). It denotes that the basins in the vicinity of Western Ghats received an additional amount of rainfall through the heavy rainfall events, which have increased seasonality in monsoon rainfall. The rainfall over semi-arid region of Maharashtra (including the study area) is observed to be more seasonal (Rai and Dimri 2020; Guhathakurta and Saji 2013), which adversely affect the productivity of pearl millet, gram, pigeon pea, maize, and pulses crops (cultivated during monsoon period). Apart from this, an increase in heavy rainfall (1-day maximum rainfall) events may augment the frequency of flood in the study area. The catastrophic floods experienced in Konkan and the southern part of Madhya Maharashtra subdivision (Kolhapur, Satara, and Sangli Districts) resulted from the heavy rainfall events in August 2019 and July 2021 (Todmal 2021; Hindustan Times 2021) could be the trailer. The previous studies (Todmal 2021; TERI 2014) have estimated a notable increase in rainfall over the

Western Ghats (the western part of the present study area). However, the additional rainfall in the form of heavy rainfall events can adversely affect the regional agro-economy.

The present investigation also confirmed trends in regional water resources including surface runoff and groundwater. The surface runoff volume over the Upper Bhima Basin has notably declined due to the increased number of surface impoundment structures during the recent decades (Biggs et al. 2007; Samal and Gedam 2012). Being a part of Bhima Basin, the present study area shows almost comparable results, as the monsoon runoff registered a declining trend (Fig. 4). It is important to mention that the study area has 135-weirs, 159-small projects, and 19-medium projects/dams (Todmal 2016; GoM 1999) majority of which were constructed during the last three decades. The small and medium dams irrigate up to 2000 and 2000 to 10,000 ha, respectively. Therefore, very likely due to a considerable increase in harvesting of surface water, the monsoon runoff volume over the study area is declined. Apart from this, a substantial increase in PET during the same period (Fig. 3e) could be another reason to decrease surface runoff through the augmentation of regional hydrological losses. On the other hand, due to the considerable harvesting of surface water during the study period, the PMGW level registered a significant decrease (increase in water table). However, the study also highlighted that the rate of GWW is higher than the recharged groundwater volume. This investigation verified that the GWW has a direct positive and negative connection with increase and decrease in area under cash/irrigated and rainfed crops, respectively (Table S2). The growing population and agricultural water demand may have led to additional groundwater extraction, which is increasing by 7 cm/year. Therefore, the study carried out by Surinaidu et al. (2013) has estimated a decline in the groundwater level in the Upper Bhima Basin (including

the present study area) by 6 m in foreseeable future. It suggests that the present efforts and initiatives taken by the government and non-government organizations are not sufficient to achieve the goal of sustainable development of groundwater resources.

The majority of districts in Maharashtra is experiencing changes in agricultural cropping patterns (Kalamkar 2011). The present study area is not an exception for this. The area under irrigated crops is observed to be increasing, whereas the cultivation of the rainfed crop is significantly declined during the last three decades (Fig. S3). By considering the entire study area as one unit, the cropped area under sorghum, pearl millet, and edible oilseeds is significantly decreased during 1980–2010 at the rate of 0.5 to 1.2% per year (Table 3). Perhaps due to the lower market value, farmers' preference to cultivate rainfed crops is declined during the post-1990 period (as compared to the 1980s period). On the contrary, the area under irrigated/cash crops in the study region is observed to be increasing by 3.3% per year. This investigation also highlighted that the sugarcane, onion, and maize hectares registered a growth of > 40% during 1990s and 2000s. Notably, the expansion of these crops at a notable pace is observed after ~ 1995 (Table 3). The results indicate that the irrigated crops are replacing the area under rainfed crops in the study area. This shift in a cropping pattern is mainly due to the farmer's growing commercial perspective toward agriculture. The availability of a perennial source of irrigation is another factor, which promotes the cultivation of irrigated/cash crops. Therefore, the construction of a large number of small and medium surface water structures in the study area during the post-1990 period (Todmal 2016) could be another reason for the observed change in cropping pattern. As sugarcane is a high water-requiring and long-duration crop, it cannot be cultivated in areas where no perennial source of irrigation is available. In this situation,

Table 3 Change in cropped area over the study area

	Rainfed crops		Irrigated crops		
	Year	% Change	Year	% Change	
Pearl millet (– 1997)	1980–2010	–0.5%	Sugarcane (+ 1994)	1980–2010	+ 3.5%
	1990–2010	–7%		1990–2010	+ 48%
Sorghum (– 1996)	1980–2010	–1.1%	Onion (+ 1992)	1980–2010	+ 2.6%
	1990–2010	–15%		1990–2010	+ 40%
Edible oil seeds (– 1997)	1980–2010	–1.2%	Maize (+ 1997)	1980–2010	+ 3.3%
	1990–2010	–11%		1990–2010	+ 49%
Total rainfed cropped area (– 1997)	1980–2010	–1.1%	Total irrigated cropped area (+ 1995)	1980–2010	+ 3.3%
	1990–2010	–14%		1990–2010	+ 47%

Results of % change in cropped area are based on linear trends. – and + signs represent a decrease and increase in the cropped area. Bold values denote % change in the average cropped area during 1990–2010 with reference to the average between 1980 and 1990. Change during 1980–2010 is the annual rate of increase or decrease in a cropped area with reference to the long-term mean. Total cropped area = aggregate area under crops considered in this table. Years in bracket are the year of step-change and years with + and – signs denote increase and decrease after this year, respectively. All the % changes, trends and years of step-change in the cropped area are statistically significant at a 0.05 level

to increase the profitability of agriculture, farmers prefer to cultivate short-duration cash crops such as maize and onion.

The present study region experienced a higher frequency of drought events after 2000, which adversely affected agricultural productivity (Todmal 2019). The present investigation confirmed that the monsoon rainfall neither changed during the recent past (1980–2014) nor it is expected to increase in the near-term future (up to 2050) (Fig. S3). It denotes no change in the availability of regional water resources. Under such circumstances, hysterically increasing areas under irrigated crops (Fig. S3 and Table 3) may intensify the water scarcity problem, as it increases agricultural water demand. The groundwater resource irrigates > 50% of agriculture in the semi-arid region of Maharashtra (GoM 2014). Therefore, increase in cultivation of water-intense crops can accelerate the rate of groundwater extraction, particularly in the areas where no surface irrigation facility is available. Due to this reason, groundwater is observed to be depleted in about 55% of districts in Maharashtra (Udmal et al. 2014a; GoI 2003), the majority of which falls in the drought-prone region (GSDA 2014). Furthermore, in the case of Maharashtra, depletion of the groundwater level has a connection with farmer suicides (Chinnasamy et al. 2019). Therefore, it can be stated that the observed changes in agricultural cropping patterns can exacerbate agrarian distress. Apart from this, the production of cereals and food grains is reduced (due to a decrease in the cultivation of rainfed crops) during the last few years, which is resulted in food inflation in Maharashtra (Joshi and Tupe 2014), including the study area.

The study also deciphered the interconnections between hydro-climatic and agricultural variables. On account of marginal surface irrigation facility (< 20% area), the agricultural productivity heavily depends on rainfall and groundwater resources. Although the SOI-rainfall relationship at the All India-level is weakening recently, the meteorological subdivisions in Maharashtra show a considerable interconnection (Todmal et al. 2022). As the SOI considerably explains variations in crop productivity, these statistical relationships can be considered while designing the probabilistic model to estimate future trends in regional agricultural water demand and production. The positive connection of rainfall, POGW, and GWW with an expansion of area under irrigated crops indicates that the decision to expand the area under onion, maize, wheat, and sugarcane (cultivated during the late monsoon or post-monsoon period) is strongly influenced by the amount of rainfall received and groundwater availability in the respective year. No considerable linkage between GWW and agricultural productivity supports this fact. It should also be noted that the Agriculture Department of Maharashtra State collects yearly crop area records at the time of sowing. Therefore, the cropped area may remain unchanged, even during the low or high rainfall

year. Therefore, none of the hydro-climatic variables could explain year-to-year variations in the area under rainfed crops.

The Indian sub-continent has registered a significant increase in annual mean temperature by 0.51–0.80 °C during the last century (Kothawale et al. 2010; Dash et al. 2007), which is intensified after 1970 (Jain and Kumar 2012; Dash and Hunt 2007; Subash and Sikka 2014). During this period (post-1970), a notable rise in temperature by 0.3 °C per decade is recorded over western India (including the present study area) (Nayak and Mandal 2012). This study observed a comparable rise in temperature over the selected semi-arid region of Maharashtra. Based on the obtained results, it is clear that the study area experienced a rise of 1.02 °C, 0.50 °C, and 0.82 °C in AMNT, AMXT, and AMT, respectively during the last 30 years. These findings signify that as compared to AMXT, the rise in AMNT has considerably contributed to the increase in regional AMT. It can also be stated that the study region is experiencing warmer nights. It is obvious to observe an increase in PET along with a rise in AMT (Fig. 3e and Fig. S3), which could be partially responsible to intensify the hydrological and agricultural droughts in the study area, particularly after 2000 (Todmal 2019). The warming during the post-1970 period has reduced agricultural productivity in India (Bapuji Rao et al. 2014). Additionally, scientific studies have confirmed that the temperature rise can adversely affects the growth and productivity of rainfed as well as irrigated crops (TERI 2014; Kumar and Sharma 2014; Hebbar et al. 2013; Boomiraj et al. 2011; Singh et al. 2009; World Bank 2003; Kumar and Parikh 2001). The agricultural crops have an optimum temperature range, which is supportive for plant growth and reproduction (Ashraf and Hafeez 2004). The temperature higher than the optimum range adversely affects the growth, yield, and survival of crops (Luo 2011). The present investigation observed that the decadal increase in PHS days (> 30 °C and > 32 °C) for rainfed and irrigated crops is comparable. However, due to low heat tolerance, the irrigated crops (particularly, onion, maize, and wheat) are more susceptible to adverse effects of warming. The studies undertaken by Wahid et al. (2007) and Ashraf and Hafeez (2004) support this finding. The higher heat tolerance characteristic of rainfed crops (sorghum, pearl millet pulses, and pigeon pea) and a negligible increase in PHS days during these crops (Table 2) suggest a marginal effect (negative) of heat stress. Therefore, from the agro-meteorological viewpoint, under the scenario of climate change, the traditional rainfed crops are more sustainable and suitable for the study area. On the other hand, rapidly increasing PHS days during the cash crops (sugarcane, wheat, maize, and onion) cultivation period may have negatively affected crop growth and yield. Particularly, the increasing PHS days may reduce the duration of wheat (Mall et al. 2006). The temperature rise from

27 to 30 °C reduces ~7.5% of mature individual wheat kernel mass (Stone et al. 1995). The temperature > 30 °C negatively affects the maize kernels and thus reduces yield (Commuri and Jones 2001). The onion crop matures early due to a sudden increase in temperature (Ratnarajah and Gnanachelvam 2021). Moreover, the temperature above 25 °C reduces onion bulb wet (Lee and Suh 2009). Therefore, heat stress could be another threat for the rapidly expanding cultivation of irrigated/cash crops and the semi-arid agrarian economy.

It is estimated that about 80% of districts in Maharashtra (including the study area) are expected to experience notable warming in the near-term future (Todmal 2021). The present investigation confirmed that an increase in temperature over the semi-arid region of Maharashtra is inevitable. The climate projection model suggests a significant rise of 1.05 °C in AMT with no considerable change in monsoon rainfall up to 2050 (Fig. S2 and Fig. S3). Sugarcane is a major cash crop with rapidly increasing cropped area in the study region. However, the estimated warming is very likely to reduce the productivity of sugarcane by ~20% (World Bank 2003; Kumar and Sharma 2014), as it is a very sensitive crop to climatic changes (Srivastava and Rai 2012). Similarly, the growth and yield of wheat are heavily dependent on cold weather conditions. Therefore, the observed rapid increment in AMNT and the projected future warming may adversely affect wheat productivity (Todmal 2021). Furthermore, the expected increase in AMT over the study area has potential to reduce the productivity of sorghum by up to 18% (Boomiraj et al. 2011; Kumar et al. 2011). It may cause a considerable decline in the production of food grains, as it covers about 50% of the cultivated area. Briefly, the predicted warming over the semi-arid region can adversely affect the irrigated and rainfed crops as well.

Limitations of the study

Although this investigation has attempted to highlight the hydrological, climatic, and agricultural changes during the last few decades, it has some limitations as given in Appendix III.

Conclusion

As the agriculture and water resources in the semi-arid region are more vulnerable to adverse climatic changes, the present investigation has highlighted changes in climatic, hydrological, and agricultural variables in the drought-prone region of Maharashtra. The observed significant rise in temperature and increasing extreme rainfall events (in the vicinity of Western Ghats) could be a part of climate change over the study area. The observed interconnections between hydro-climatic and agricultural variables

can be useful to manage agricultural expansion and water resources. Already, the rising temperature has registered negative effects on agricultural productivity in India. The warming condition increases heat stress on agricultural crops (particularly, the irrigated crops) in the study area, which negatively affects crop productivity. Moreover, the region is very likely to experience a rise of 1 °C in AMT during the near-term future, which may further exacerbate the agricultural distress. As it is a serious concern from the agro-economic viewpoint, the agricultural scientist and agronomist should take an initiative to introduce crop varieties, which can sustain and perform well in comparatively warmer conditions.

Unfortunately, the availability of water resources (through rainfall) in the study area was and will be almost unchanged, which may not complete the future water demand. Under such circumstances, a rise in temperature is very likely to amplify the regional water scarcity and further add to the already difficult water management challenge. Therefore, the harvesting of rainwater, which drains out from the study basins can be one of the measures to accomplish the increasing agricultural water demand. However, the water resources managers have to take sufficient care that the intensive surface water harvesting should not cause a disparity in the allocation of water resources within a river basin (upstream and downstream reaches). During the recent period, it is obvious to have a commercial perspective toward agriculture, which resulted in a remarkable increase and decrease in area under irrigated/cash and rainfed crops, respectively in the study area. However, this change in cropping pattern is very likely to increase the agricultural water demand and pressurizes the available water resources. Due to the traditional flood method of irrigation, sugarcane alone consumes about 60% of irrigation water. Therefore, it is necessary to obligate the farmers to adopt modern water-saving techniques such as drip irrigation and sprinkler for high water-requiring crops. Apart from this, the zones should be demarcated based on the available water resources, irrigation facilities, and cropped area under irrigated crops. With the consideration of these zones, the agriculture department can design policies to limit or promote the cultivation of a particular crop (irrigated or rainfed). Moreover, the efforts to increase the level of water literacy in society can also help to cope with the upcoming water and food crisis under the scenario of climate change.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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