CHAPTER 11

CLIMATE CHANGE IMPACTS ON DROUGHTS

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11.0 Introduction

Climate change is arguably one of the most complex global environmental challenges facing the world today and water is the primary medium through which its effects will be translated to other water dependent sectors including agriculture, forests, health, and urban. However, the root causes of the climate change are ingrained across almost all sectors and industries. Global climate change is one of the key factors affecting the hydrological cycle (IPCC 2007). Any change in temperature affects the atmospheric moisture, precipitation and circulation pattern of the atmosphere. The global warming has triggered many changes to the Earth's climate resulting in changes in the characteristics of the extreme weather and climate events. Research is increasingly confirming the intense relationships between the global warming and intense hydrological cycles (Gosling et al. 2016; Ricke et al. 2017; Drijfhout et al. 2015).

The heat waves have increased and all-time high temperature records have been broken in many countries, viz., United Kingdom – 38.1°C, Germany – 40.2°C, India 50°C, France, Italy, Spain etc. resulting in human fatalities. The rising temperature leads to the atmosphere's capacity to hold more water vapour, thereby allowing for both, greater rates of rainfall and runoff when air is saturated and drier (under-saturated) conditions otherwise. A warmer climate increases the risks of both drought – where it is not raining, and floods – where it is raining, but at different times and/or places. Although the impacts of the climate change on the floods and droughts are uncertain (Andersen and Shepherd 2013), the changes in the precipitation intensity and quantum can cause changes in the mean discharges of rivers.

The extreme hydrological events including floods and droughts invariably result in considerable loss to the economy of a region and brings alongwith it massive hardships for the people living in the affected areas. Even though the impacts of the drought are not visible initially as in the case of floods, but they have the potential to cause substantial changes to the ecosystem and society of a region. In recent decades, the extreme drought frequency has increased considerably in many countries (Hoerling et al. 2012; Nandintsetseg and Shinoda 2013; Zhang et al. 2011 and Spinoni et al. 2014). From 1998 to 2002, below-normal precipitation and higher temperatures resulted in droughts covering wide areas of North America, Southern Europe, and Southern and Central Asia. Drought continued in some regions through 2004, including the Western U.S. which endured the most severe drought in 80 years. The worldwide drought has been linked to unusually warm waters in the Indian Ocean and western Pacific, which has been caused by global warming.

Climate change is expected to increase the frequency of droughts and floods in future. The increase in the temperature, changes in the precipitation pattern, its distribution and variability as a consequence of climate change, may lead to changes in the drought characteristics including drought frequency and severity. An increase in the land surface temperature and surface air temperature has been reported by many researchers around the world in the recent decades (WMO 2006). The world's four warmest years on record are 2016, 2015, 2017 and 2018 with temperatures between 0.9°C and

1.2°C above pre-industrial levels (WMO 2019, C3S 2019). However, there may be associated uncertainties due to different interpolation methods and data gaps (Blunden and Arndt 2014). The global average temperature is expected to continue to increase throughout this century as a result of projected increases in greenhouse gas concentrations. IPCC Assessment Report 5 (AR5) climate projections suggests that global temperature relative to 1986-2005 will increase for the mid-century (2046-2065) by 0.4-1.6°C for Representative Concentration Pathway (RCP2.6); by 0.9-2.0°C for RCP4.5; by 0.8-1.8°C for RCP6.0 and by 1.4-2.6°C RCP8.5. The warming projections for the end of the century (2081-2100) are 0.3-1.7°C for RCP2.6, 1.1-2.6°C for RCP4.5, 1.4-3.1°C for RCP6.0 and 2.6-4.8°C for RCP8.5 (IPCC 2013). The higher temperature in future time horizons will lead to changes in the rainfall pattern, higher rainfall variability along with higher evaporation and evapotranspiration. The high variability in the rainfall is expected to result in water scarcity and meteorological droughts whereas an increase in evaporation as a result of higher temperatures may result in higher occurrences of hydrological and agricultural droughts. Climate change has the potential to increase drought disasters, by subjecting various regions across the globe to much higher levels of drought frequency and severity.

The intensification of the hydrological drought, meteorological drought and agricultural drought due to the climate change related impacts will substantially influence the ecosystems, water security, food security and the living conditions of humans living in the affected regions. Managing the water stress in an optimal way may be the key to the sustainable development in future. This chapter presents a comprehensive review of the climate change impacts on droughts along with possible adaptation mechanisms to address it.

11.1 Drought and Climate Change Concepts

Drought is one of the extreme events that can be caused by climate variability as well as external forcing. The ecosystems, agriculture, livelihoods and settlements of a region are much dependent on its climate. This natural disaster invariably affects the agriculture, water resources and society resulting in enormous economic losses. The recurrent droughts seriously threaten the livelihood of billions of people who depend on land for most of their needs. Droughts occur in virtually all climatic zones, and are mostly related to the reduction in the amount of precipitation received over an extended period of time and various factors including high temperatures, high winds, low relative humidity, rainfall distribution, onset and termination of monsoon, dry spells occurrences during crop growing seasons, intensity and duration of rainfall, all play a significant role in the occurrence of droughts (Mishra and Singh 2010). A drought is a temporary aberration whereas aridity is a permanent feature of the climate restricted to low rainfall areas (Wilhite 1992). Similarly, the time scale associated with a heat wave is on the order of a week, whereas a drought may persist for months or years. There are many drought definitions but consistency among various drought definitions is a key to remove any ambiguity in framing drought policies and making decisions (Mukherjee et al. 2018).

The rainfall pattern including its spatiotemporal variability and timing, along with the temperature are the two important variables that govern the drought characteristics. Droughts impact the surface water, groundwater and the soil moisture which is very crucial for agriculture in rainfed areas. From an agricultural point of view, a state of higher than normal temperature will lead to higher evapotranspiration and higher water demands whereas the lower precipitation will result in higher water deficits leading to crop stress, reduction in crop yields or crop failures. Even regions with very high rainfall face drought and understanding of the drought phenomenon is important. Therefore, the understanding of the drought phenomena and its characteristics are of great importance in the planning and management of water resources (Mishra and Singh 2010).

Since drought is a creeping phenomenon, it is quite difficult to anticipate its occurrence well before it actually occurs. As such, it is difficult to determine the onset of drought even though weather forecasts with longer lead-times are now available from multiple sources with relatively better prediction accuracies. The negative impacts of the drought become evident only after it has crept in, and also there are hardly any structural losses as is seen in the case of the other natural hazards like floods, hurricanes, earthquakes, etc. However, the regular/continuous drought events cause considerable hardships to the local residents by widely affecting their livelihoods leading to malnutrition and deaths. The continuous and regular droughts often result in land degradation and loss of soil cover and fertility in the longer term.

Droughts are initiated by the reduction in precipitation and its variability. These are generally accompanied by high temperatures and heat waves. Even though the moisture deficits that constitute a drought, occur invariably due to precipitation deficits (Dai 2010), but the higher temperatures can increase the evaporative demand considerably, thereby increasing the overall drought impact (Dai 2013; Dai et al. 2004). The impacts of soil moisture deficit and runoff deficit can be very severe, leading to risks of wildfire (Westerling et al. 2006), damage to habitat of endangered species (Palmer et al. 2009) and lower hydropower production (US Energy Information Administration 2014).

Droughts are generally classified into four types, viz., meteorological drought, hydrological drought, agricultural drought and socio-economic drought (Wilhite and Glantz 1985; Smakhtin and Schipper 2008; Mishra and Singh 2010; Hao and Singh 2015). The meteorological drought is defined in terms of the magnitude of shortfall from normal rainfall and duration of the shortfall event. Agricultural drought is linked to the meteorological drought and occurs when the shortage of soil moisture adversely affects the agricultural production due to higher evapotranspiration losses that have not been properly met (Mannochi et al. 2009). Water deficit even for a relatively shorter period during the critical crop growth stages, viz., flowering and fruit set, can cause irreversible damages to crop yields. Agricultural drought is more dominant in rainfed systems; as supplemental irrigation facilities are seldom available in such regions. The hydrological drought is again linked to meteorological droughts which impact the surface water and groundwater availability. The hydrological droughts lag the meteorological and agricultural droughts. The socioeconomic drought is associated with the supply and demand of some economic goods with elements of meteorological, agricultural and hydrological drought. The climate change does have an impact on all the various types of droughts and therefore it is necessary that the future climate change impacts on drought be evaluated for the formulation of appropriate mitigation and adaptation mechanisms.

Climate change and the resulting increase in the maximum and minimum temperature would mean higher consumptive use requirements for vegetation as a result of higher potential evapotranspiration rates. However, the changes in the actual evapotranspiration will depend on the actual water availability which may also get altered due to the changes in the rainfall pattern, its timing and distribution. The irrigated areas may be impacted to a lesser extent under these changes, but a future drier climate will significantly affect the rainfed areas leading to reduction in crop production thereby affecting the food security of the region.

11.2 Sectors Impacted by Climate Change Induced Droughts

The climate change impacts on the extreme events, particularly the droughts is expected to have its effect on multiple sectors including water resources, agriculture, forests, urban, and health. Climate change has the potential to possibly exacerbate the drought characteristics in future. The drought conditions may worsen when higher temperatures coincide with minimal precipitation (Diffenbaugh 2015). It is widely perceived that the water resources sector shall be impacted in many ways. It is expected that the changes in the rainfall pattern and its distribution shall have its impacts on the surface water, groundwater and water quality. The variability in the precipitation pattern and its distribution is expected to have a direct bearing on the stream flows in river systems, storages in lakes and reservoirs which in turn may affect the environment and biodiversity of the region. Similarly, the over dependence on the groundwater systems, particularly during periods of water scarcity and drought due to the climate change impacts is expected to further affect the groundwater systems with problems of depleting groundwater levels and dwindling of the baseflow contribution to the river systems. The water quality, both surface and groundwater is expected to be affected under the influence of greater soil erosion due to high intensity rainfall, reduction in dissolved oxygen due to higher temperature, and higher nutrient contribution to lakes and reservoirs. With higher average temperature and a warmer air, a pattern of lengthy dry spells interspersed with brief heavy precipitation and flooding might emerge. The changing patterns of water availability and precipitation will further increase the water stress and competition among various water users.

Drought is a major natural hazard affecting the agricultural sector in developing countries. The water stress due to the variability in precipitation patterns coupled with increasing maximum, minimum and mean temperature as a consequence of climate change, does not augur well for the agriculture sector, as it may lead to higher evaporative demands, lower soil moisture and variability in water availability. The agricultural productivity may be affected to a great extent with the anticipated increases in the drought frequency, drought severity and drought duration. This may be one of the most challenging aspects of climate change impacts, as to how to ensure the food security for a growing population (Ray et al. 2015; Beddington et al. 2012; Challinor et al. 2014). The changes in the onset of monsoon and increased length of dry spells are expected to considerably affect the agriculture operations, thereby affecting the quality of the agricultural produce and its yield. However, these impacts may differ from region to region and some crops in few regions may also benefit. IPCC 2007 projected with medium confidence, an increase in crop yields by as much as 20% in East and Southeast Asia whereas a decrease in crop yields by 30% is expected in Central and South Asia by the mid-21st century. However, yield of few crops like maize is projected to increase marginally whereas the yields of rice, soybean and wheat are projected to decrease due to warming and water stress. The biodiversity and the soil health shall also be impacted adversely under the impacts of climate change induced droughts.

Climate change and drought directly and indirectly affects the forest sector. The growth and productivity of complex forest ecosystems may be affected due to changes in temperature, rainfall, weather and other related factors. The elevated levels of carbon dioxide also have an impact on the plant growth. The warming temperatures generally may lead to an increase in length of growing season. Many vulnerable species may be also susceptible to extinction. Even though many of the trees are resilient to some degree of drought, the increase in temperature coupled with water scarcity could make future droughts more damaging from the ones experienced in the past. Climate change could alter the frequency and intensity of forest disturbances such as wildfires and storms as being witnessed in many countries across the globe. Wildfires occur due to heat waves and soil moisture scarcity in forests. In 2011, wildfires consumed more than 8 million acres of forest in the U.S. due to warm temperature and drought conditions during the early summer (USGCRP 2014). Climate change is projected to increase the extent, intensity, and frequency of wildfires. Warmer spring and summer temperature coupled with decreases in water availability, dry out woody materials in forests and increase the risk of wildfire. Fires in-turn release large amounts of carbon dioxide to the atmosphere thereby contributing to climate change (CCSP 2008). These disturbances can reduce forest productivity, change the distribution of tree species and even lead to large scale deforestation. The loss of forest cover which otherwise acts as a carbon sink and also intercepts rainfall and allows it to infiltrate into the soil, will cause erosion of the top soil and cause floods and droughts. Ironically, the lack of trees also exacerbates drought in dry years by making the soil dry more quickly.

The urban temperature is highly influenced by the urban heat island (UHI) effect, which is cause by urbanisation. The urban climate in itself is expected to increase the heat stress experienced by people during periods of high temperature, particularly during night when the UHI is the largest (Pascal et al. 2005). The urbanisation will lead to shift in the water use pattern, with more water required for domestic use for maintaining the higher water use lifestyle of cities. However, the variability in the precipitation with longer dry spells and droughts will lead to severe water scarcity in cities, most of which are already under water stress due to their fast expanding suburbs. Moreover, it is expected that droughts and floods will coexist during the same season as a consequence of climate change. The devastating Kerala floods of 2018 are an example where drought like situation prevailed just after the cessation of the floods in many parts of the State.

11.3 Climate Variables Relevant to Drought

The most important climate variables that are responsible for initiating drought conditions are temperature and precipitation. The temperature variables of interest are maximum temperature, minimum temperature, and mean temperature. The increase in the maximum temperature will have its impacts on the water supply-demand scenario. The water demands for the agriculture sector are expected to increase due to higher consumptive use needs whereas the water requirement for the domestic and industrial sectors are also expected to increase due to higher water demands for cooling systems. The higher temperature shall lead to faster melting of the ice and glaciers leading to variability in the stream flow in the shorter-term and lower water availability in the longer term. Also, the water stored in lakes and reservoirs are expected to deplete faster due to higher evaporation rates as a consequence of higher maximum temperature, thereby affecting the water supply, hydropower generation, ecosystem and biodiversity. The higher temperature will lead to further increase in the use of air conditioning systems releasing more heat into the atmosphere and need for higher energy requirement. Higher energy requirement will translate into higher power generation leading to additional water requirement for cooling systems of the thermal power stations. The higher temperature will also result in lower dissolved oxygen in surface water bodies and rivers including the deterioration of water quality. The impacts of the water scarcity and droughts shall be exacerbated under the regime of higher temperature and heat waves. The higher maximum temperature and its timing are expected to impact the crop growth, particularly during the flowering and seed development stages, which may adversely affect the crop yields.

The impacts of increased minimum temperature exhibit a larger impact on the grain yield than the vegetative growth. It is believed that the daily minimum temperature will increase more rapidly than daily maximum temperature leading to increase in the mean temperature, with detrimental effects on grain yield. The minimum air temperature affects the night-time plant respiration rates and can potentially reduce biomass accumulation and crop yield (Hatfield et al., 2011). The increase in both minimum temperature and maximum temperature coupled with erratic precipitation, aids in developing drought conditions. Precipitation is another important variable, the shortfall of which is responsible for the initiation of meteorological drought and its translation into agricultural and hydrological droughts. The variability in the rainfall is another equally responsible factor for the development of drought conditions and the changes in its onset, affects the agricultural operations and crop yields to a great extent. The erratic rainfall coupled with higher temperatures leads to soil moisture deficits and thereby affects the crop growth and crop yields, particularly in rainfed areas. Similarly, the reduction in the rainfall will lead to reduced stream flows thereby causing hydrological droughts and affecting the irrigation operations. In such a scenario, the surface water storage structures including lakes and reservoirs do not get filled upto their design capacity, thereby affecting the irrigation and hydropower operations.

Another important aspect of climate change is the reduction in the number of rainy days. The reduction in the number of rainy days indicates prolonged intervening periods of dry spell, which may affect the crop growth in rainfed areas. In such a scenario, supplemental irrigation needs to be planned for meeting the crop water requirements during the dry spell periods. High intensity rainfall is projected to increase in future under the impact of climate change. Besides causing floods, this factor is a major contributor of the land degradation process due to the erosion of the top fertile soil under the rain impact. Generally, the land degradation and drought are interlinked and may be the net result of drought and higher temperatures, which is anyhow projected to increase in the future time horizons. In many regions, the annual and seasonal precipitation is not expected to change much under the impacts of climate change, but the variability of rainfall is of much concern. The increased incidences of droughts are expected to have a bearing on the low flows in the river systems, which are very crucial for meeting the various water demands and survival of the biodiversity in the river systems.

11.4 Climate Change and Associated Impacts on Droughts

Goal 13 of the UN Sustainable Development Goals (SDGs) states that "Climate change is now affecting every country on every continent. It is disrupting national economies and affecting lives, costing people, communities and countries dearly today and even more tomorrow". People are experiencing the significant impacts of climate change, which include changing weather patterns, rising sea level, and more extreme weather events. The poorest and most vulnerable people are being affected the most. Climate change increases the odds of worsening drought in many parts of the world in the decades ahead. At the peak of the 2012 US drought, 81 percent of the contiguous United States was under abnormally dry conditions. Globally, drought struck several major breadbasket regions simultaneously in 2012, adding to food price instability.

The frequency and magnitude of droughts are expected to change in the coming decades due to climate change, but the regional evolution of future droughts remains highly uncertain (Collins et al. 2013). The investigation of the evolution of past and future droughts using climate models indicated more severe drought conditions in the future (Dai 2013; Cook et al. 2015; Sheffield and Wood 2008; Taylor et al. 2013; Zhao and Dai 2015; Swann et al. 2016; Orlowsky and Seneviratne 2012). The hydrological outputs from climate models are not analysed directly, but instead the meteorology from the climate models are used to force offline models to derive estimates of droughts and aridity (Prudhomme et al. 2011; Schewe et al. 2014). However, potential limitations with offline modelling is that it cannot represent important land-atmosphere feedbacks that can modify the drought characteristics, such as the coupling between soil moisture and air temperature (Seneviratne et al. 2010; Koster et al. 2006; Yin et al. 2014).

The selection of an appropriate baseline period is very important for the comparison of future drought under climate change with respect to historical droughts as the reference period (Sheffield et al. 2012). Considering a longer base period, the drought indices can be better calibrated and the future drought events can be compared with appropriate historical droughts. However, the improper choice of baseline period may lead to considerable bias in the drought assessment under climate change. Say, if 1950–2008 is selected as the baseline period, it may include the effects of recent anthropogenic climate change and may mask the climate change signal in the results obtained (Trenberth et al. 2014). The incorporation of soil moisture estimates into the drought indices may improve the drought evaluations and help in avoiding misleading signals into the future. However, the uncertainties associated with meteorological forcing in hydrological models can lead to unreliable soil moisture estimates under climate change scenarios. Most of the studies on dryness and drought based on drought indices do not incorporate the aridity and thereby fail to incorporate humidity and wind speed (Sherwood and Fu, 2014; Fu and Feng, 2014; Feng and Fu, 2013).

The spatiotemporal inhomogeneity of forcing data can trigger large uncertainties in the assessment of drought under climate change. The techniques used for downscaling the coarser resolution GCM/RCM climate data to higher resolution data at the basin scale, is also another source of uncertainty which naturally gets translated into the evaluation of drought characteristics. Therefore, drought indices derived from precipitation require effective downscaling techniques that can resolve discrepancies arising from scale issues, thereby helping the stakeholders to improve decision making (Fundel et al. 2013). Drought assessments using GCM outputs are limited owing to considerable high bias associated with the precipitation estimates (Trenberth et al. 2014; Dai 2011), in addition to substantial intrinsic uncertainties originating from the inter-model variability (Langousis et al. 2014; Langousis et al. 2018; Chen et al. 2011; Deidda et al. 2000).

Even though the impact of reduction in precipitation on drought severity is evident, the possible effects of atmospheric evaporative demand (AED), another major climate component, on the drought severity are unknown. Wang et al. 2012 suggested that the vapor pressure deficit is driving the evaporative demand of the atmosphere in semi-arid regions whereas other studies have argued that the effect of climate change on AED is minimal and solar radiation and wind speed are more important (Roderick and Farquhar 2002; McVicar et al. 2012). These strong uncertainties in current AED trends, and their driving factors and uncertainties, has therefore prevented from arriving at any consensus on the evolution of drought severity in the last decades under a scenario of climate change and global warming. Thus most of the reports on climate change impacts on extreme events indicate only low-to-medium confidence of drought trends at global scale (Seneviratne et al. 2012).

Some of the prominent climate change impacts are expanding deserts and increase in the magnitude of floods and droughts. Climate projections are being used widely for assessing drought conditions for the 21st century on global as well as regional scales (Strzepek et al., 2010; Orlowsky and Seneviratne, 2012; Dai, 2013; Xu et al., 2015; Wang and Chen, 2014; Masud et al., 2017;

Thilakarathne and Sridhar, 2017). Dai (2013) found that droughts are intensifying under the impacts of climate change whereas Sheffield et al. (2012) reported that the changes in drought climatology were insignificant in the recent years. Turner and Annamalai, 2012 suggested that these contrasting results may be attributed to the limitations of the climate models in capturing the regional rainfall patterns. By about 2030, several billion people across the world could face water stress (Arnell, 1999; IPCC, 2013; Duiker and Spielvogel, 2009).

Loukas et al. 2008 evaluated the impacts of climate change on drought severity in Thessaly, Greece using observed precipitation from 50 stations and future precipitation from Global Circulation Model CGCM2 for SRES A2 and B2 scenarios. They reported that the drought severity increased for the complete region with higher drought extremes in SRES A2 scenario. The Annual Weighted Cumulative Drought Severity-Timescale-Frequency curves indicated that large increase in drought severity is expected towards the end of the century. Pereira et al. 2017 assessed the long-term trends in the drought indices including SPI and Standardized Evapotranspiration Index (SPEI) in Brazil at the time scales of 1 to 12 month. They reported that the ET rates have intensified the regional drought conditions and the selection of the time scale had a great influence on the drought trend assessments. They concluded that these trends could have significant reduction in crop yields of sugarcane and citrus crops.

Ukkola et al. 2018 analysed the historical simulations (1950-2004) of 20 models from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) for deriving a variety of drought metrics and thresholds using a standardized drought index for Australia. The variation in the drought characteristics (severity and duration) for the various types of droughts characterized by precipitation, runoff and soil moisture was evaluated. Results indicated that on a global scale, most of the climate models agreed well on most precipitation drought metrics, but systematically underestimated precipitation drought intensity as compared to the observations. However, the runoff and soil moisture droughts varied significantly across models, particularly for intensity. They concluded that the CMIP5 models show large, metric-dependent discrepancies in precipitation, runoff and soil moisture droughts during the historical period and suggested the use of multiple models in drought impact studies to account for large model discrepancies.

Margaret et al. 2008 studied the impacts of climate change and the management options for the world's river basins. They reported that the major rivers worldwide have experienced dramatic changes in flow, reducing their natural ability to adjust to and absorb disturbances. Loss of native biodiversity and risks to ecosystems and humans from increased water shortages and floods is expected in the future. The river discharges were projected under different climate and water withdrawal scenarios alongwith the data on the impact of dams on large river basins, to assess the potential changes in discharge and water stress for dam-impacted and virgin basins. The projections indicate that every populated basin in the world will experience changes in river discharge and many will experience water stress. The magnitude of these impacts is used to identify basins likely and almost certain to require proactive or reactive management intervention. Wurl et al. 2018 quantified the hydrological resilience of a water-limited arid ecosystem under future extraction scenarios and changing climate conditions, through a model that included socially-sustainable management practices. In this study, the hydrogeological and socio-economic components were linked together to address the depletion in the Santo Domingo Valley. The concluded that the depletion of the groundwater resources may lead to groundwater drought and lead to further water stress during periods of droughts due to limited groundwater availability.

Summarizing all these above discussions, it can be concluded that still there are large uncertainties in the evolution of drought given the complexity of the drought phenomenon in itself, difficulties of drought quantification based on impacts, assessment of future climate variables and difficulties in drought prediction and forecasting and then translating it into policies. However, many of the regional studies carried across the globe and the evidences clearly indicate an increase in the drought impacts and an increase in the drought severity as a consequence of global warming. Reliance on historical climate conditions will no longer be tenable since climate change generates conditions well outside past parameters for current and future planning.

11.5 India Specific Climate Change Related Impacts on Droughts

Climate change is a great challenge to the water resources, food security, and social welfare of 1.2 billion people in the 21st century in India. India is one of the most drought-affected countries in the world (Mishra and Singh, 2011). South Asia and Southeast Asia are among most vulnerable globally to the impacts of climate change based on the risk index released at the annual climate summit at Katowice, Poland. Sri Lanka, Nepal, Bangladesh and India are ranked second, fourth, ninth and fourteenth respectively as the countries most affected by climate change in 2017, whereas Bangladesh and Pakistan are ranked eighth and ninth respectively as the countries most affected by climate change based on the 20-year data from 1998 to 2017 (Eckstein et al. 2019).

India has experienced several devastating climate extremes during recent decades. For instance, the drought of 2016 covered about 10 states and affected about 330 million people, causing an economic loss of $100 billion (ASSOCHAM Report 2016). Numerous studies have predicted an increasing trend in annual surface temperature (Rupa Kumar et al. 1994; Singh and Sontakke 2002; Subash and Sikka 2014) and a significant decreasing/increasing trend in rainfall at different regional and local scales in India (Chaudhary and Abhyankar 1979; Srivastava et al. 1998; Kumar et al. 2005; Kumar et al. 2010; Adarsh and Janga Reddy, 2015). Throughout the 21st century, it is projected that India and Southeast Asian countries will face more warming than the global mean and there will be greater variations in temperature, with higher warming rates in winter than in summer (Christensen et al. 2007). As a result of climate change, droughts have been occurring frequently due to higher rainfall variability which has led to reduced water availability and higher water demands in the last few decades (Mishra and Singh, 2010; Mishra and Singh, 2011). In India, the impact of climate change is expected to be significant in rainfed areas and coastal areas including Gujarat, Andhra Pradesh, Rajasthan, Maharashtra, Odisha, Tamil Nadu, West Bengal, Madhya Pradesh and Bihar. Many parts of the country located in these states were under drought during 2018.

The reduction in the rainfall quantum, reduction in the number of rainy days and the rise in maximum and minimum temperatures will lead to the intensification of droughts in India. Over the last five decades, very severe droughts hit India in the 1960s (1965), 1970s (1972 and 1979), in the late 1980s (1987), and late 2010s (2009), where more than 40% of the area was affected (Kaur 2009). A spatial shift is observed in the droughts in India towards coastal south India, Central Maharashtra and Indo-Gangetic plains (Mallya et al., 2016). A significant decrease in the number of wet days and prolonged dry spells have been observed during monsoon along the east coast (Sen Roy and Balling, 2004) and the Upper and middle Gangetic plains has seen significantly drying trends during summer

(Jha et al., 2013). Gossain et al. (2006) found that under the climate warming scenario, severity of droughts and intensity of floods may increase in many parts of the region.

A World Bank (2008) study for the drought prone arid regions of Andhra Pradesh indicated higher projected temperature (2.3°C–3.4°C) and an erratic increase in rainfall (4% to 8%) which may translate into deteriorating agro-climatic conditions leading to reduction in crop productivity of rice, groundnut and jowar, and substantial decrease in farm incomes. Similar study in the districts of Nashik and Ahmednagar districts of Maharashtra indicated higher projected temperature (2.4°C–3.8°C) and variable increase in rainfall (20% to 30%), which may lead to higher yields of several crops leading to increase in the farmer incomes. However, sugarcane yields are expected to decline substantially across Maharashtra as a result of heat stress caused by warmer climate. In north-western India, an increasing risk is expected because of drought, while an increase in wetness is projected in southern India (World Bank 2013).

The observed impacts of climate change on evapotranspiration (McVicar et al., 2008), soil moisture (Mishra et al., 2014), and stream flow, and climate extremes have increased during the recent decades and are likely to become more prominent under the projected climate change. Most of the studies based on general circulation model (GCMs) suggest that India will face warmer and wetter conditions under the projected future climate (Kumar et al., 2005; Mishra et al., 2014). Bhutiyani et al. 2008 studied the impact of global warming in 20th century on the stream flow pattern in Beas, Chenab, Ravi and Satluj rivers in north-western Himalayas. An episodic variation was noted in discharge in all three seasons on a longer timescale of about 82 years (1922–2004) whereas a statistically significant decrease in the average annual and monsoon discharge and insignificant increase in winter and spring discharge was reported for Satluj river. The decreasing discharge during winter and monsoon seasons in the post-1990 period, despite rising temperatures and average monsoon precipitation strongly indicated decreasing contribution of glaciers to the discharge and their gradual disappearance. On a shorter timescale of last four decades of the 20th century, the Beas River showed a significantly decreasing trend, whereas the other three rivers showed a statistically insignificant change in their average annual discharge (at 95% confidence level).

Based on the IPCC SRES A2 scenario using 17 GCMs, an increased drought frequency is projected in central, north-eastern, west central, and peninsular India in the second half of the 21st century (2050–2099) (Ojha et al. 2012). Monthly rainfall projections based on five GCMs and three emission scenarios (RCP2.6, RCP4.5, and RCP8.5) using kernel regression-based statistical downscaling shows an increase in the occurrences of extreme dry spells over central, southeast coastal, eastern, and some parts of north-eastern India for the 21st century (Salvi and Ghosh 2016).

Kumar et al. 2013 analysed the monsoon droughts over India and reported that the variability is influenced by the El Nino/Southern Oscillation (ENSO). The warming of the equatorial Indian Ocean is responsible for the observed increase in intensity of droughts during the recent decades. Kumar et al. 2017 studied the impact of climate change on water resources of upper Kharun catchment in Chhattisgarh, India. The evaluated the changes in the water balance components using SWAT and bias-corrected PRECIS projections and reported that the simulated annual discharge will decrease by 2.9% for 2020s and percolation decrease by 0.80% for 2020s. These relationships suggested for water stress in the basin in the near future and advocated studies to detect the hotspots.

Mishra and Lilhare (2016) evaluated the hydrological sensitivity of Indian sub-continental river basins to climate change using Soil and Water Assessment Tool (SWAT) and bias corrected downscaled future climate projects for RCP 4.5 and RCP 8.5. Even though they projected precipitation increase of 3-5°C in the post monsoon season, there is large inter-model uncertainty in the precipitation projections. The sensitivity analysis for Ganges and Godavari river basins showed that runoff is more sensitive to changes in precipitation and temperature rather than ET. ET is projected to increase by more than 10% for majority of the river basins. The results indicated that water availability in the sub-continental river basins is more sensitive towards changes in the monsoon season precipitation rather than air temperature and therefore the spatial and temporal (inter-annual) variability in the monsoon precipitation under the projected future climate may play a significant role.

The climate change impacts on the Upper Indus hydrology was studied by Lutz et al. 2016 using an ensemble of statistically downscaled CMIP5 GCM outputs for RCP4.5 and RCP8.5 to force a cryospheric-hydrological model for generation of transient hydrological projections for the 21st century. They concluded that the future of the Upper Indus basin's water availability is highly uncertain in the long run; mainly due to the large spread in the future precipitation projections. Despite large uncertainties in the future climate and long-term water availability, basin-wide patterns and trends of seasonal shifts in water availability are consistent across climate change scenarios. Most prominent is the attenuation of the annual hydrograph and shift from summer peak flow towards the other seasons for most ensemble members.

Reshmidevi et al. 2017 analysed the impact of climate change in Malaprabha river basin in Karnataka using the rainfall and hydro-meteorological variables simulated using Modified Markov Model-Kernel Density Estimation (MMMKDE) and k-nearest neighbour downscaling models. Climate projections from an ensemble of 5 GCMs (MPI-ECHAM5, BCCR-BCM2.0, CSIRO-mk3.5, IPSL-CM4, and MRI-CGCM2) and the hydrological model SWAT were used. A marginal reduction in runoff ratio, annual streamflow and groundwater recharge was projected towards the end of the century. An increase in the irrigation demand is expected towards the end of the century due to the projected increase in temperature and ET. It was also reported that the short and moderate wet spells are projected to decrease, whereas short and moderate dry spells are projected to increase in future. They concluded that the projected reduction in stream flow and groundwater recharge along with the increase in irrigation demand is likely to aggravate the water stress in the region in future.

Gupta and Jain, 2018 analysed the future climate data from Regional Climate Models (RCMs) for RCPs 4.5 and 8.5 for the drought characterisation using Standardized Precipitation Index (SPI), Standardized Precipitation-Evapotranspiration Index (SPEI) and Standardized effective Precipitation Evapo-Transpiration Index (SP*ETI). They reported that the future drought dynamics in most parts of India will depend on the projected increase in ET due to the increasing temperatures. They also concluded that except for few southern states, almost all regions of the country will face escalation in drought and North India is more vulnerable to increase in drought events in the near future.

Sharma et al. 2018 carried out a district-level assessment of the ecohydrological resilience to hydroclimatic disturbances and its controlling factors in India. Ecosystem water use efficiency (WUEe), defined as the ratio of net primary productivity (NPP) to ET, was used as an indicator of ecosystem functioning or its response to hydroclimatic disturbances. Higher ecosystem water use efficiency was found in lower Himalayan regions. The resilience was measured in terms of the ratio of the WUEe under the dry conditions and the mean WUEe, which indicates the ability to absorb hydroclimatic disturbance. Out of 634 districts only 241 districts were found to be resilient to dry conditions. The forest dominated districts were found to be more climate resilient. Also out of 30 states and union territories (UTs) studied, only 10 states had more than 50% resilient area. The results of this study highlighted the need for better ecosystem management policies in the country.

Jha et al. 2019 carried out a probabilistic evaluation of the vegetation drought likelihood under changing scenarios of temperature, precipitation and soil moisture content and its implications to resilience across India. They also studied the resilience of vegetation cover to disturbances induced by a dry condition. From the investigation, it is observed that at least half the area of 16 out of 24 major river basins is facing high chances of vegetation droughts due to lowered soil moisture levels. The croplands are most likely to be affected by drought, which is of paramount concern for country's food security. It was also found that at least one-third area of 18 river basins is non-resilient to vegetation droughts. Moreover, more than fifty percent of each vegetation type is non-resilient, which points out the fragility of country's terrestrial ecosystems. This study facilitates the understanding of vegetation drought hotspot regions, factors risking the terrestrial ecosystem and their ability to withstand such conditions. The analysis pertaining to evaluation of drought characteristics and detection of climate change signals have been carried out for various basins in India and the results from few case studies are discussed.

The climate variables viz., daily rainfall and daily temperature have been analysed for the Narmada basin for the identification of climate change signals. The variation in the 1-day maximum temperature over Narmada basin is given in Figure 11.1 whereas the variation in the 1-day minimum temperature is given in Figure 11.2. It has been observed that increasing trends at 5% significance level have been observed for both maximum temperature and minimum temperature. However, the increase in the minimum temperature is at a much higher rate than the increase in the maximum temperature (Thomas et al. 2013). A significant increasing trend at 5% significance level has been observed in the 1-day maximum rainfall during 1951-2008 and is given in Figure 11.3. The Mann-Kendal test results for the changes in the heavy rainfall (rainfall > 100 mm/day), very heavy rainfall (rainfall > 150 mm/day) and extreme rainfall (rainfall > 200 mm/day) is given in Table 11.1. It can be observed that these extreme rainfall events have been significantly increasing in the Narmada basin (Thomas et al. 2015). Similarly, the daily maximum and minimum temperature have been analysed for the Chambal basin and the temporal variation in the 1-day maximum temperature and 1-day minimum temperature is given in Figure 11.4 & 11.5 respectively. An increasing trend at 5% significance level has been observed in the maximum temperature whereas no significant trend has been observed in the minimum temperature.

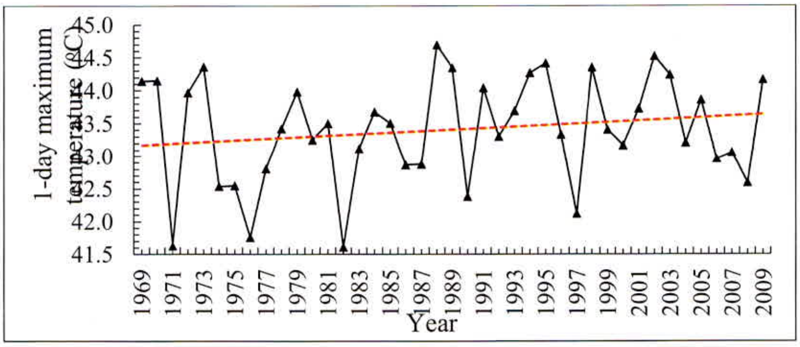

Figure 11.1: *1-day maximum temperature in Narmada basin*

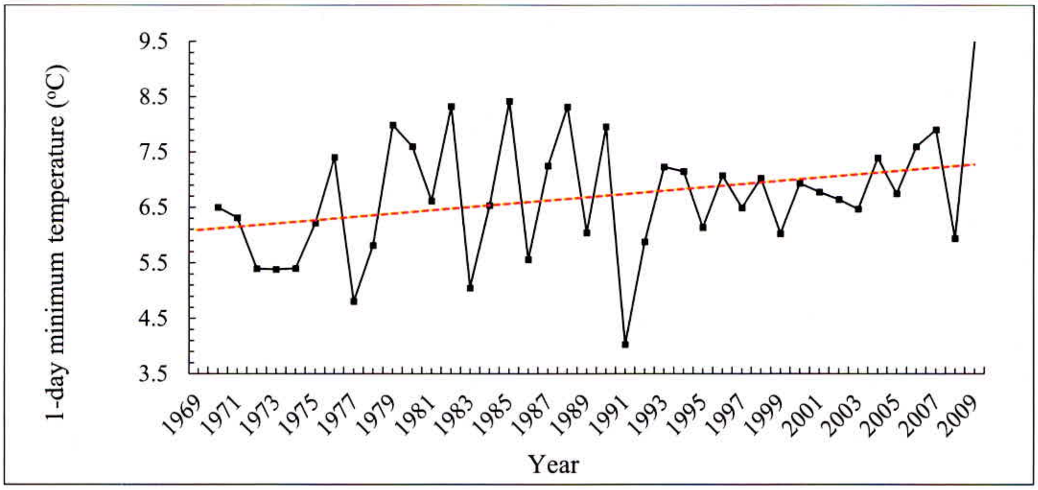

***Figure 11.2:** 1-day minimum temperature in Narmada basin*

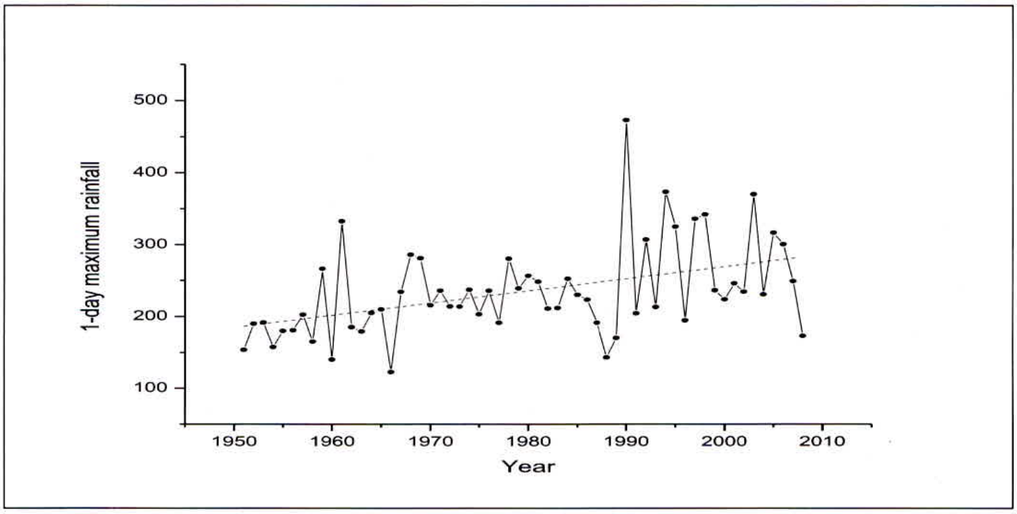

***Figure 11.3:** 1-day maximum rainfall in Narmada basin*

Table 11.1: Mann-Kendal test statistic for extreme rainfall events in Narmada basin

S. No.	Mann Kendal results	Heavy rainfall	Very heavy rainfall	Extreme rainfall
1.	Test statistic (z)	+2.321	+3.351	+3.704
2.	Inference	Significantly increasing	Significantly increasing	Significantly increasing

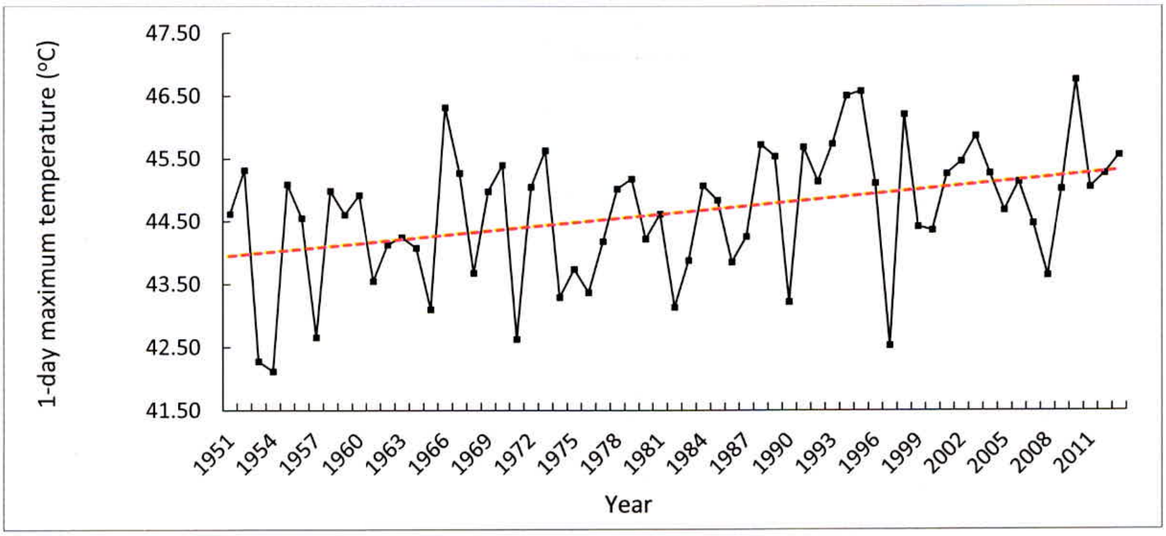

Figure 11.4: 1-day maximum temperature in Chambal basin in M.P.

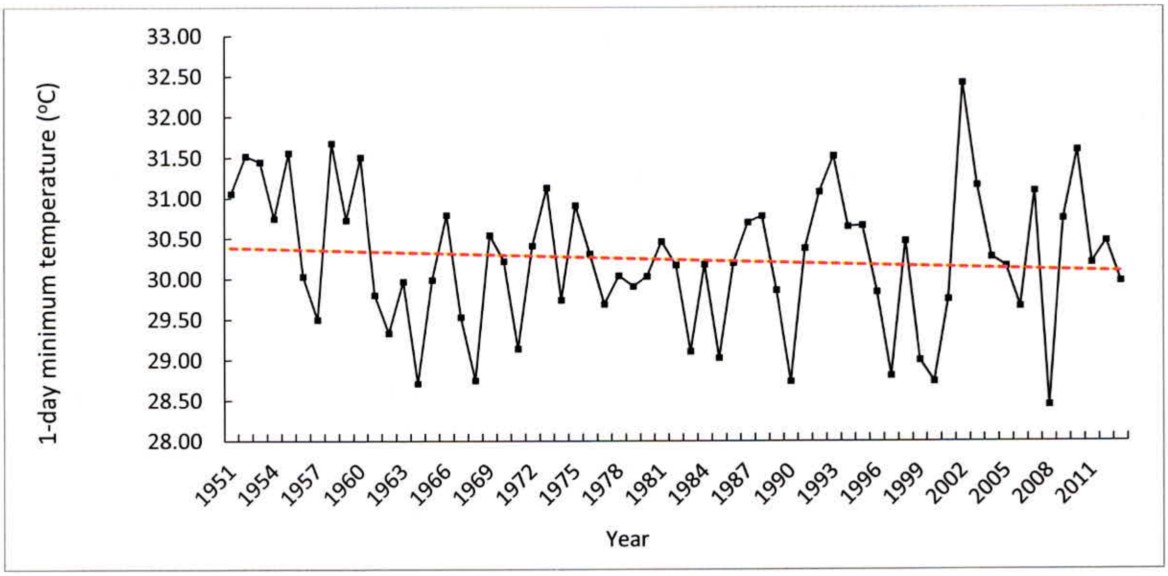

Figure 11.5: 1-day minimum temperature in Chambal basin in M.P.

In several other major river basins of the country, the number of rainy days has decreased while the number of intense events has increased (Jain et al. 2017). The decrease in the annual number of rainy days for Chambal basin in Madhya Pradesh is given in Figure 11.6. Similarly, a warming trend has been observed across India, with 2016 being the warmest year on record since nationwide records commenced in 1901 (IMD 2016). A warming trend of 0.57°C per hundred years across India has been observed during 1881–1997 (Pant and Kumar 1997) and significant increases in the maximum winter temperature and the minimum post-monsoon temperature were noted during 1901–2000 (Sonali et al. 2017). An increase of 2-4.8°C in average temperature across India is expected based on the projections from 18 CMIP5 models from 1880s to 2080s (Chaturvedi et al. 2012).

The number of clod nights (Minimum Temperature < 10°C) has been evaluated for Chambal basin falling in M. P. and is given in Figure 11.7. It can be observed that the number of cold nights is decreasing in the basin whereas the number of very hot days (Maximum Temperature > 40°C) is increasing steadily in the basin as shown in Figure 11. 8.

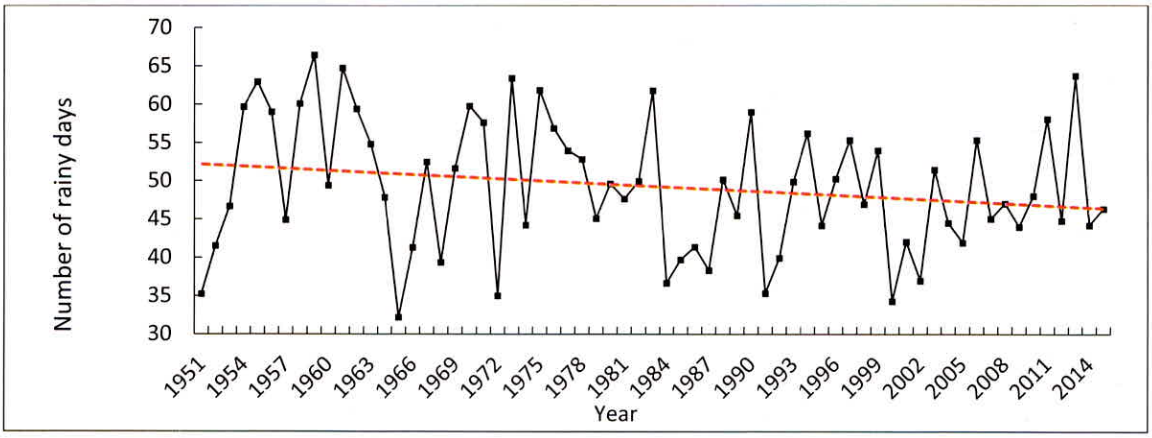

Figure 11.6: *Number of rainy days in Chambal basin in M.P*

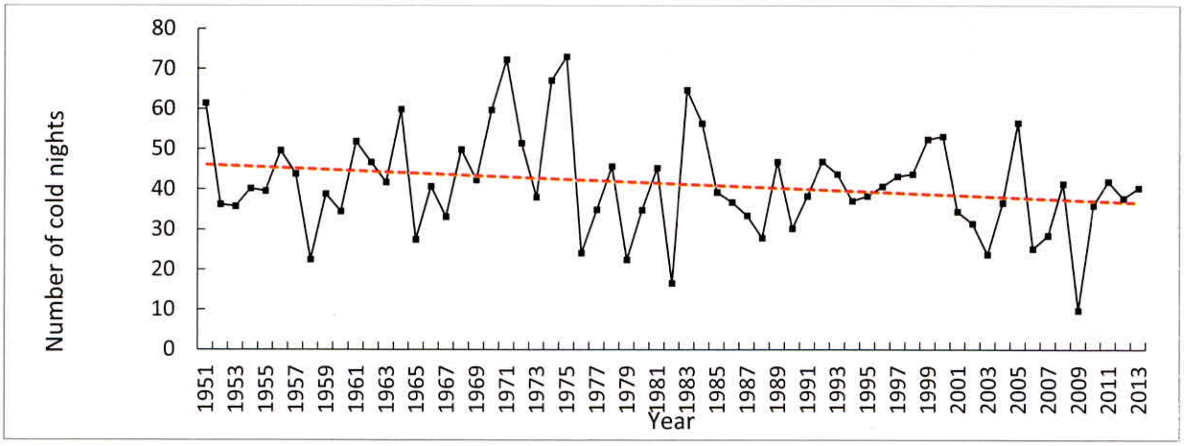

Figure 11.7: *Number of cold nights in Chambal basin in M.P*

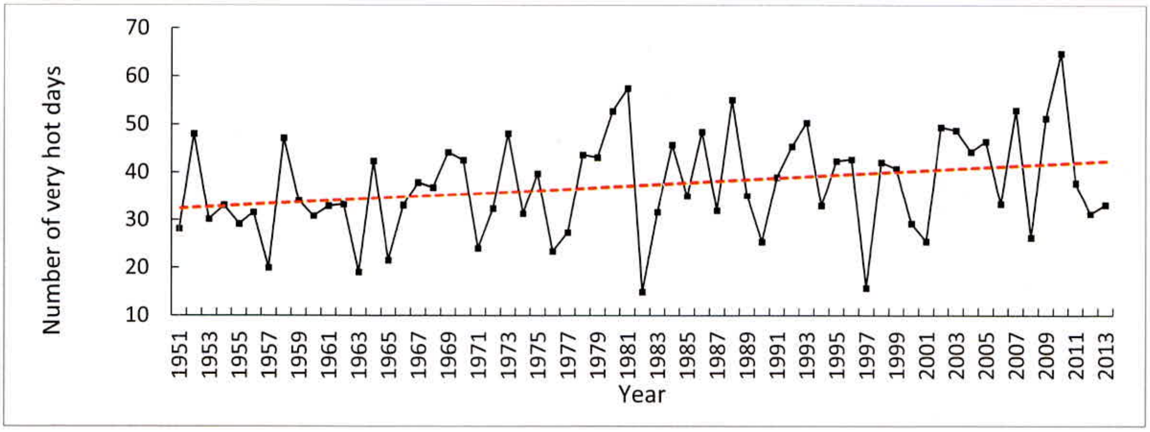

Figure 11.8: *Number of very hot days in Chambal basin in M.P*

The identification of the drought years and the drought severity is generally identified based on the departure of annual/seasonal rainfall from its normal values. The analysis carried out for Bundelkhand region in Central India for the identification of drought years along with the drought severity for the various blocks of Panna district is given in Table 11.2. It can be observed that the drought frequency varies between 1 in 3 years at Ajaygarh, Pawai, Gunera and Shahgarh to 1 in 4 years at Panna.

The identification of drought prone blocks is generally carried out based on the probability analysis of the annual rainfall. A block is considered as drought prone when the probability of the 75% mean annual rainfall is less than 80%. Table 11.3 gives the drought prone blocks identified for Chambal basin in M.P. and are given in. It can be seen that 26 blocks out of the 53 selected blocks are drought prone for Chambal basin in M. P.

Thomas et al. 2015 analysed the meteorological droughts over Bundelkhand region in Central India comprising of six districts in Madhya Pradesh and seven districts in Uttar Pradesh and reported decreasing trends in the annual rainfall and number of rainy days in few blocks in Bundelkhand, even though no clear climate change signals could be detected in the historical climate datasets. They analysed the spatiotemporal variability of drought characteristics using SPI and reported an increase in the drought frequency in Bundelkhand varying between 1 in 3 years to 1 in 5 years.

Table 11.2: Frequency and severity of droughts in Panna district

Data range/ Frequency	Drought years	Departure (%)	Drought severity	Data range/ Frequency	Drought years	Departure (%)	Drought severity
Ajaygarh				Panna			
1964-2010 (1 in 3 yr)	1965-66	-30.30	Moderate	1964-2010 (1 in 4 yr)	1965-66	-41.12	Moderate
	1966-67	-23.12	Mild		1968-69	-34.55	Moderate
	1979-80	-39.29	Moderate		1970-71	-34.17	Moderate
	1981-82	-22.47	Mild		1973-74	-30.78	Moderate
	1983-84	-28.81	Moderate		1979-80	-47.17	Moderate
	1984-85	-48.72	Moderate		1994-95	-26.41	Moderate
	1986-87	-52.13	Severe		1998-99	-23.29	Mild
	1987-88	-28.65	Moderate		2000-01	-32.83	Moderate
	1988-89	-31.69	Moderate		2002-03	-26.36	Moderate
	1989-90	-54.55	Severe		2006-07	-30.95	Moderate
	1991-92	-29.11	Moderate		2007-08	-56.42	Severe

	1992-93	-30.55	Moderate
	1994-95	-48.83	Moderate
	1995-96	-62.90	Severe
	1998-99	-21.14	Mild
	2006-07	-53.83	Severe
	2007-08	-81.24	Severe
	2008-09	-50.88	Severe
Pawai			
1964-2010 (1 in 3 yr)	1965-66	-56.88	Severe
	1966-67	-47.61	Moderate
	1968-69	-45.75	Moderate
	1973-74	-33.66	Moderate
	1974-75	-29.20	Moderate
	1979-80	-60.32	Severe
	1981-82	-30.50	Moderate
	1986-87	-27.86	Moderate
	1987-88	-39.32	Moderate
	1989-90	-26.95	Moderate
	1995-96	-34.40	Moderate
	1998-99	-51.13	Severe
	2006-07	-35.85	Moderate
	2007-08	-30.92	Moderate
	2009-10	-28.66	Moderate
Gunera			
1984-2010 (1 in 3 yr)	1986-87	-29.44	Moderate
	1989-90	-27.05	Moderate
	1995-96	-25.43	Moderate
	2002-03	-24.72	Mild
	2006-07	-47.68	Moderate
	2007-08	-31.70	Moderate
	2009-10	-23.65	Mild
Shahnagar			
1982-2010 (1 in 3 yr)	1985-86	-21.89	Mild
	1995-96	-21.52	Mild
	1996-97	-34.51	Moderate
	1998-99	-32.47	Moderate
	2000-01	-31.39	Moderate
	2006-07	-23.00	Mild
	2007-08	-46.57	Moderate
	2008-09	-23.77	Mild
	2009-10	-23.05	Mild

Table 11.3: Drought prone blocks for Chambal basin in M. P.

S. No.	Station name	Normal rainfall	Probability of 75% mean rainfall	Inference
1	Sanwar	930.11	79.20	Drought prone

2	Dewas	979.45	75.28	Drought prone
3	Tonkkalan	979.65	77.86	Drought prone
4	Piploda	894.06	77.30	Drought prone
5	Ujjain	915.23	74.51	Drought prone
6	Sailana	858.54	75.66	Drought prone
7	Khachrod	858.50	75.42	Drought prone
8	Mahidpur	871.39	73.93	Drought prone
9	Ghatia	911.50	78.33	Drought prone
10	Shajapur	963.41	76.42	Drought prone
11	Jaora	809.06	76.38	Drought prone
12	Alot	876.16	74.13	Drought prone
13	Barod	920.14	74.21	Drought prone
14	Agar	921.04	77.32	Drought prone
15	Mandsour	789.21	78.85	Drought prone
16	Sitamau	839.16	74.14	Drought prone
17	Susner	902.21	76.55	Drought prone
18	Garoth	887.63	76.89	Drought prone
19	Bamhori/Chachora	1040.75	77.34	Drought prone
20	Nimach/Jawad	836.35	78.71	Drought prone
21	Bhanpura	870.20	77.07	Drought prone
22	Raghogarh	1037.97	77.04	Drought prone
23	Guna	1032.63	78.01	Drought prone
24	Ratlam	611.18	77.73	Drought prone
25	Sarangpur	720.53	79.12	Drought prone
26	Bagli	737.3	79.69	Drought prone

The temporal variation of the 3m-SPI, an indicator of the meteorological drought is given in Figure 11.9 which indicates continuous droughts in the last decade. Similarly, the 3m-SPI for the Begumganj block in Bina basin is given in Figure 11.10.

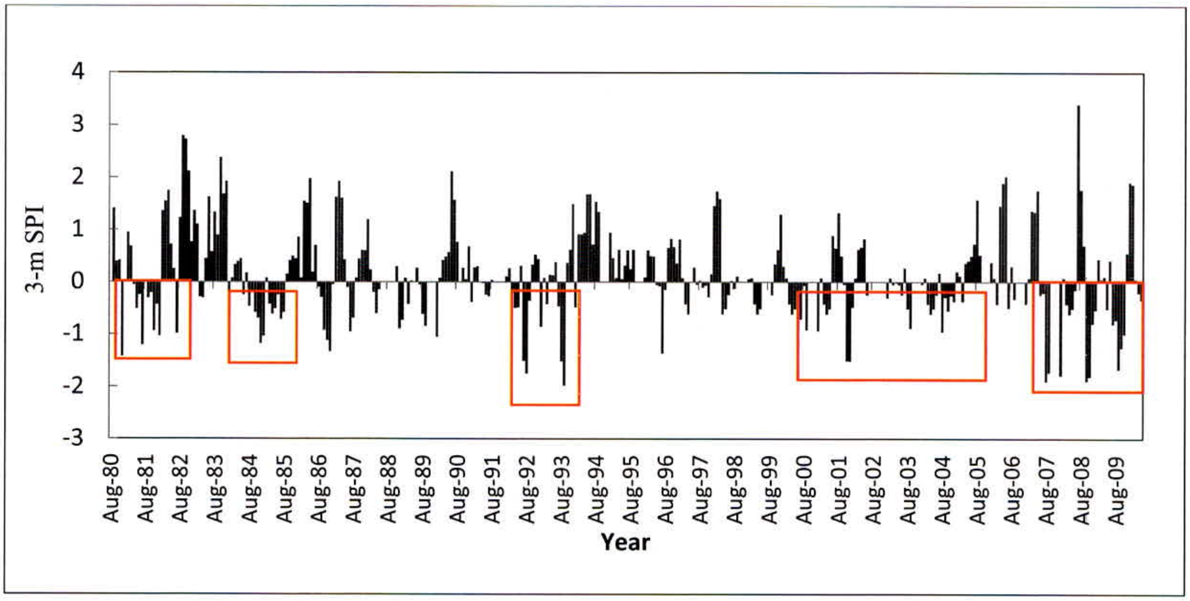

Figure 11.9: *3m-SPI at Lalitpur block in Lalitpur district in Bundelkhand*

The trend in the time series of the 3m-SPI was evaluated using the non-parametric Mann-Kendall test. Only few blocks depicted a falling trend in the 3m-SPI time series indicating the intensification of meteorological droughts in these blocks.

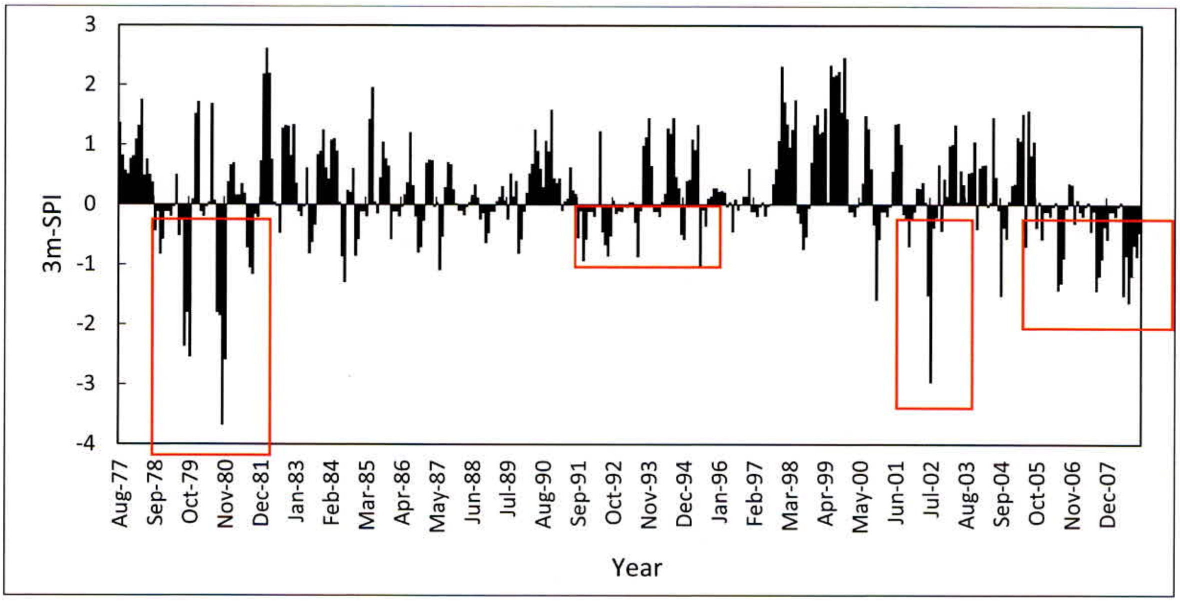

Figure 11.10: *3m-SPI at Begumganj block Bina basin*

Similarly, the surface water drought characteristics have been evaluated using the Surface Water Drought Index (SDI) and the 3m-SDI and 6m-SDI at Rahatgarh gauging site on Bina river and is given in Figure 11.11. It can be observed that there has been a continuous surface water deficit at

Rahatgarh gauging site in Bina river during 2003-04 to 2008-09. This is the period during which the Bundelkhand region faced continuous droughts.

The groundwater droughts have also been evaluated using the Groundwater Drought Index (GDI). The temporal variation of GDI at Rahatgarh in Bina basin is given in Figure 11.12. The spatiotemporal variation of groundwater drought in Bina basin during the monsoon months of 2007-08 is given in Figure 11.13. Five classes have been defined based on the severity of drought as described by GDI, viz., normal, mild drought, moderate drought, severe drought and extreme drought. The progression and withdrawal of the groundwater drought can be understood from Figure 11.13. It can be seen that the northern parts of the basin was under extreme and

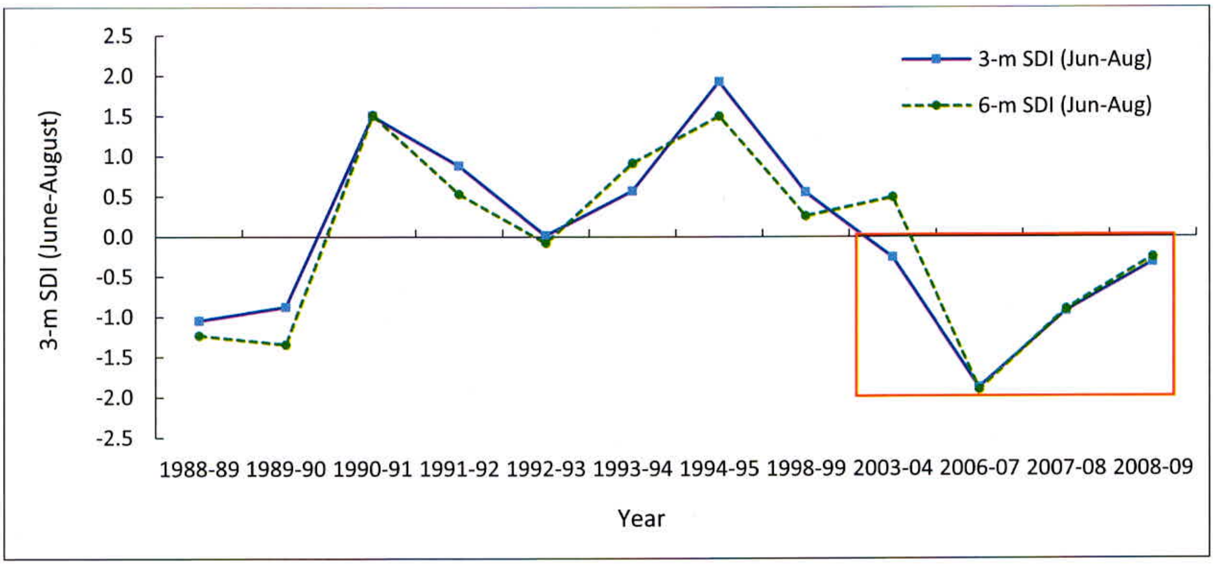

Figure 11.11: *3m-SDIand 6m-SDI at Rahatgarh gauging site on Bina river*

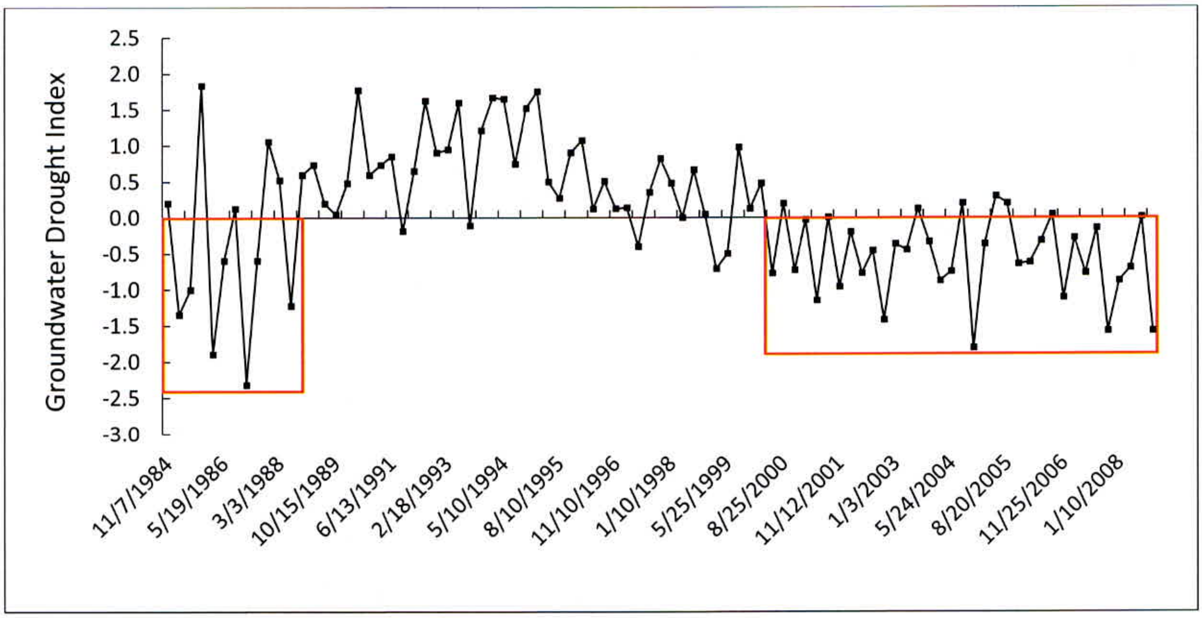

Figure 11.12: *Temporal variation of GDI at Rahatgarh in Bina basin*

severe drought conditions during June 2007. However due to the recharge of groundwater from the monsoon rainfall during the subsequent months, the groundwater conditions improved in the basin and the drought severity in the northern parts of the basin was limited to mild drought only.

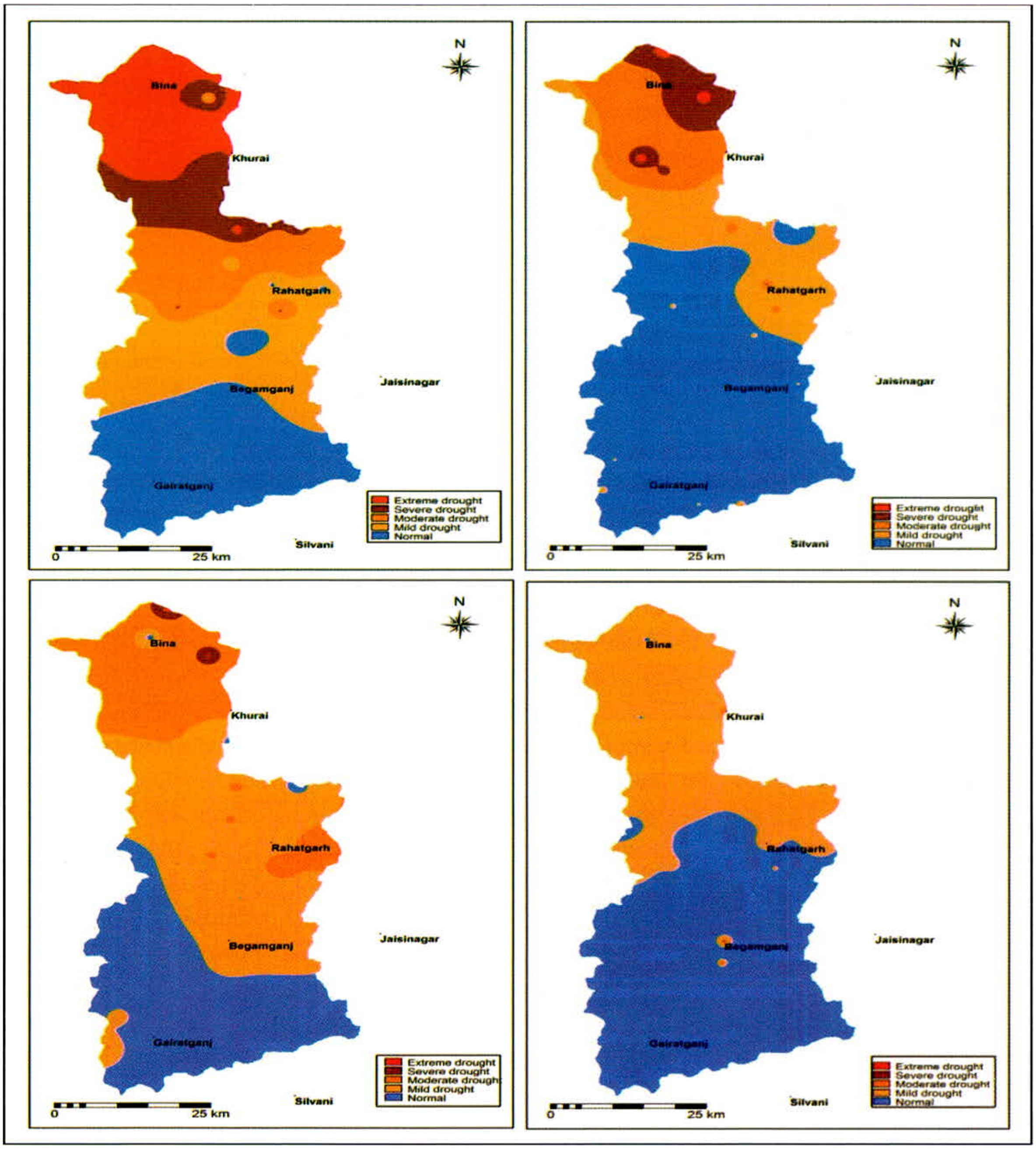

Figure 11.13: *Spatiotemporal variation of groundwater drought in Bina basin*

The changes in the drought characteristics during the future time horizons can be evaluated based on the future climate data available from Global Climate Models (GCMs) or Regional Climate Models (RCMs). An attempt was made to evaluate the meteorological and surface water drought characteristics for future time horizons. The COrdinated Regional climate Downscaling Experiment (CORDEX) datasets for South-Asia have been used for the analysis. The RCM datasets used for the analysis has been based on the Commonwealth Scientific and Industrial Research Organisation

(CSIRO), Conformal Cubic Atmospheric Model (CCAM; McGregor and Dix, 2001) experiments driven by the GCM's viz., ACCESS 1.0, CNRM-CM5, CCSM4, GFDL-CM3, MPI-ESM-LR, and NorESM-M available at 0.5° resolutions for four time horizons, viz., 1970-05 (historical), 2006-70 (near-term), 2041-70 (mid-term) and 2071-99 (end-term) for two scenarios viz., RCP4.5 (low emission scenario) and RCP8.5 (high emission scenario).

The quantile mapping technique has been used for the bias correction of the temperature and precipitation obtained from these RCMs. These climate variables have been bias corrected using the cumulative density function (CDF), which maps the CDF of the RCM variable in the historical period (1970-2005) to the observed CDF based on IMD data during the same period and then applies the same mapping to the CDF of the future RCM variables. The bias correction has been performed separately for each month. This can be considered as an enhanced non-linear technique for removing systematic biases from the RCM future climate data sets based on the CDF's of the observed and RCM climate data during the historical period.

The cumulative drought duration and cumulative drought magnitude based on 3m-SPI (summed over the particular time horizon) has been evaluated during 2006-40, 2041-70 and 2071-99 and is given in Figure 11.14. The drought characteristics have been evaluated using the bias corrected precipitation data from all the six RCMs. Similarly, the hydrological drought characteristics have been evaluated at the various gauging sites located on Narmada river upto Barmanghat gauging site. To obtain the future stream flows, the Soil and Water Assessment Tool (SWAT) was setup, calibrated and validated with the historical precipitation, maximum and minimum temperature and other climate variables. The tested SWAT setup was thereafter forced with the future bias corrected climate variables to obtain the future stream flows for the purpose of evaluating hydrological drought using SDI. The future hydrological drought scenario for Narmada at Barmanghat is given in Figure 11.15.

11.6 Non-Stationary Climate and Drought

The appropriate selection of probability distribution plays an important role in deriving robust drought indices under climate change, especially considering stationary (historical) vs. nonstationary (future scenarios) patterns of climate variables. SPI is based on either Gamma distribution or Pearson type III distribution, whereas SPEI is based on a Log-Log distribution, and these distributions perform considerably well in fitting the time series of the hydroclimatic variables over a wide range of climatic region. However, the selection of a single probability distribution is challenging (Vicente-Serrano et al. 2012). Vicente-Serrano et al. 2012 investigated the best probability distributions for Standardized Streamflow Index (SSI), and reported that log-normal, Pearson type III, log-logistic, general extreme value, generalized Pareto, and Weibull distributions provided good fits to stream flow data for flow frequency analysis. However, none of the six probability distributions were able to adequately fit the stream flow series based on the L-moment diagram. Therefore, the selection of the appropriate distribution in developing a drought index is crucial and, and can generate large uncertainties, if not chosen properly.

Stationarity, which implies physical constancy of mechanisms involved in the hydrologic processes, may not be that much applicable now, due to the substantial anthropogenic changes in the present climate. The assumption of stationarity of a time series implies that it has a probability distribution function (pdf) which is invariant with time.

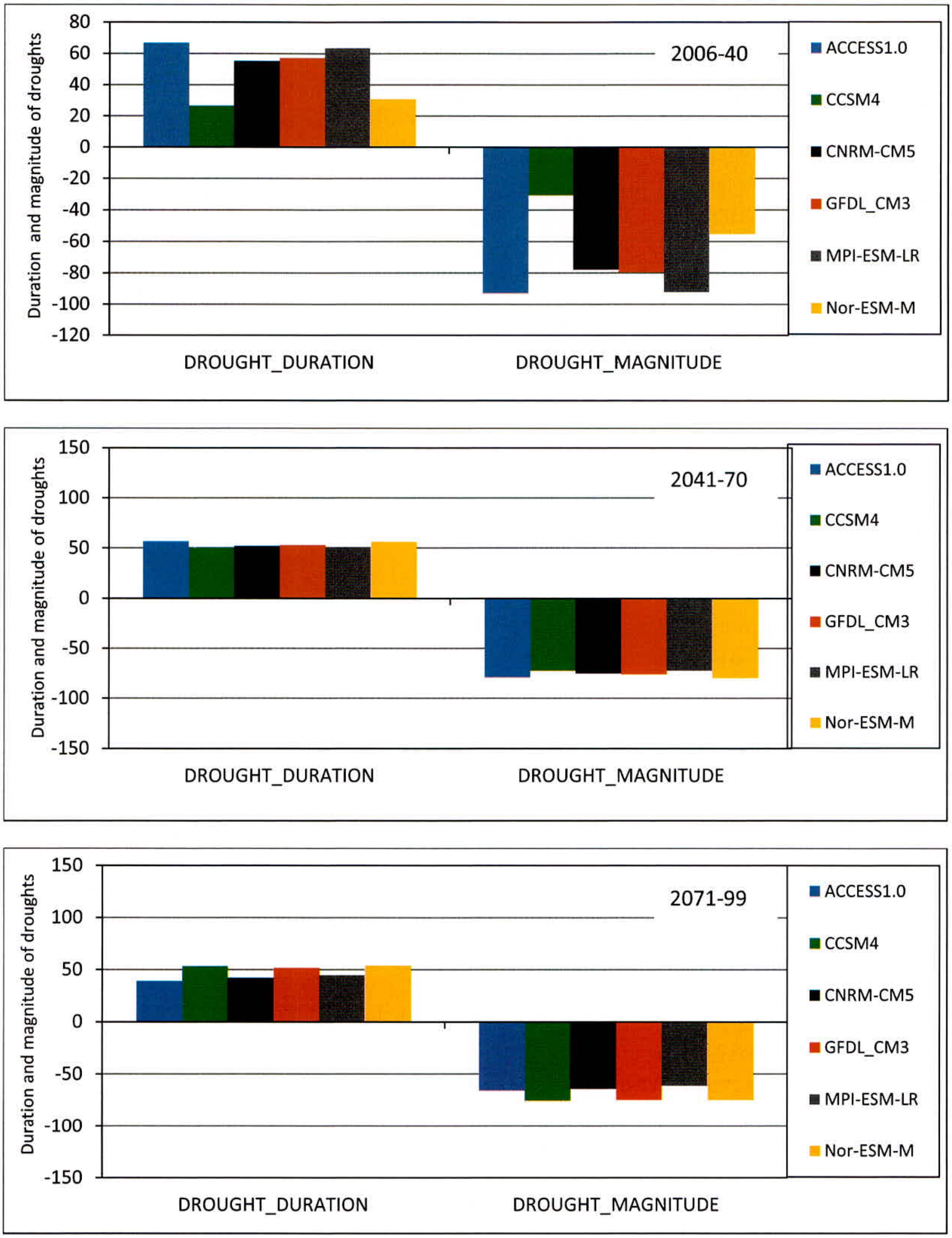

Figure 11.14: *3m-SPI based characteristics of droughts and wet days under RCP8.5 for Narmada basin upto Barmanghat.*

However, this assumption cannot be guaranteed and therefore the nonstationary models capable of producing linear and non-linear variation with time of the parameters of the selected pdfs should be used (Milly et al. 2008; Villarini et al. 2010). Drought characteristics may also be non-stationary and therefore, non-stationary statistics that are deterministic functions of time should be implemented in reliable assessment of drought characteristics in a changing climate (Milly et al. 2008). The probability distribution parameters of precipitation will change over time due to the non-stationary nature of climate variables under future climate scenarios. Therefore, it is important to consider non-stationarity by changing the probability distribution parameters over different timescales to improve drought assessment under climate change. Considering the strong association between precipitation and soil moisture, a similar assumption will also hold for soil moisture.

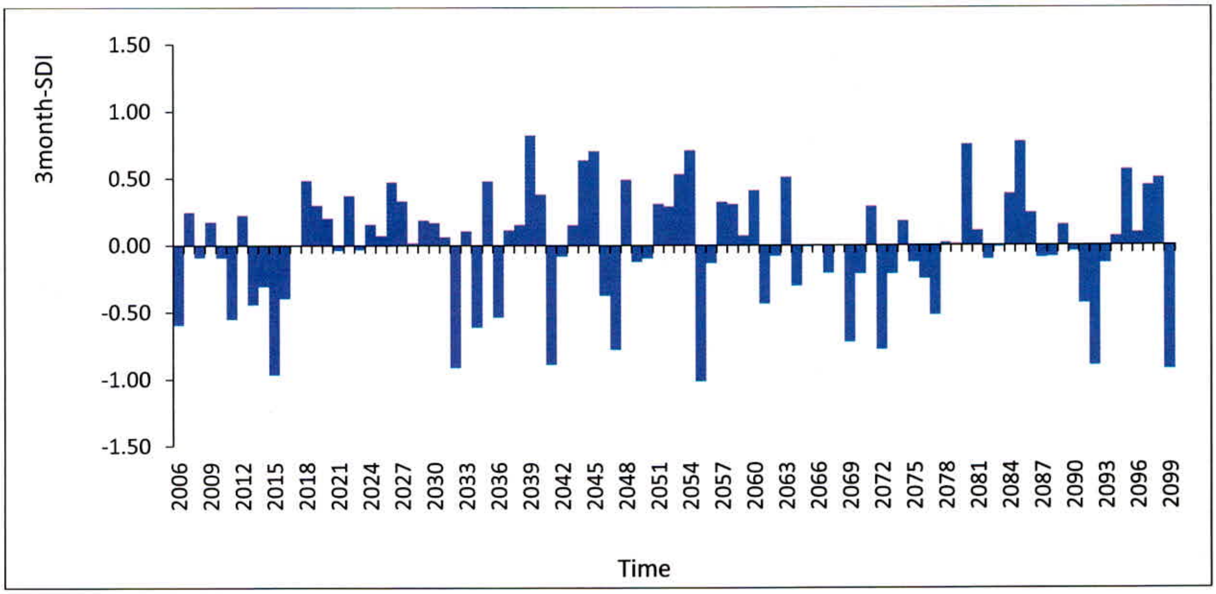

Figure 11.15: *Hydrological drought scenario for Narmada at Barmanghat*

Danielle et al. 2010 quantified the drought risk in a non-stationary climate, wherein the frequency and severity of droughts are analyzed for a range of climate states viz., different phases of the Pacific, Indian, and/or Southern Oceans, to demonstrate the marked variation of drought risk over inter-annual through to multi-decadal time scales. They highlighted the fact that drought risk is not stationary in Australia, rather it varies on a range of time scales viz., seasonal, annual, inter-decadal, multi-decadal, and the palaeo scale and is strongly influenced by the underlying climate state. It was therefore advocated that the drought management strategies based on the 'stationary climate assumption, are likely to fail, even if potential impacts of climate change are factored in. The projections of future drought risk, on either the short (seasonal up to 5 years) or long (more than 10 years into the future) term, currently have limited practical usefulness for water resource managers and government policy makers.

Osorio and Galiano, 2012 carried out the non-stationary analysis of dry spells in monsoon season of Senegal river basin using data from RCMs provided by European ENSEMBLES project for West Africa, together with the observed data. A non-stationary behaviour in the annual series of maximum length of dry spells (AMDSL) was reflected in the temporal changes in the mean and variance. They used the modelling tool GAMLSS (Generalised Additive Models for Location, Scale and Shape) to develop regional pdfs fitted to AMDSL series for the monsoon season. Since divergent trends were observed in the value ranges for parameters of the probability distribution functions (pdfs), regional pdfs were constructed using bootstrapping distributions based on probabilistic models. The results of the study indicated an increase in the length of dry spells associated with low probability occurrence in monsoon season.

11.7 Adaptation Measures to Address Climate Change Impacts on Drought

Azhoni et al. 2017 suggested some adaptation strategies which can be broadly classified into four aspects namely, i) behavioral, cultural or attitudinal change - which includes community's role in water management, (ii) institutional and structural change which includes an integrated framework for water management (iii) operational and technological change which includes increasing water use efficiency, increasing water storage capacity, promoting artificial recharge, rainwater harvesting, new and low-cost technologies for irrigation, efficient technologies for water conservation and inclusion of climate change aspects in hydrological designs and water resources management and (iv) development and dissemination of knowledge.

Climate change being a risk multiplier for water scarcity and given India's immense geographic diversity, exact policies and interventions will need to be tailored to local conditions. The reduction in the number of rainy days, which implies an increase in dry spells calls for creating new infrastructure for surface water storages. The high intensity rainfall events will lead to faster runoff from the catchment providing less time for the rainwater to percolate and join the groundwater aquifer. Therefore, the necessary infrastructure needs to be created for increasing the groundwater storage. The artificial recharge measures can be promoted towards achieving this goal and the necessary infrastructure could include percolation tanks, injection wells and recharge shafts.

In order to tide over the water stress during droughts as a consequence of climate change, a better option is to diversify the sources of water supply including conjunctive use of surface water and groundwater to reduce the risks. The waste water reuse can be a big step in this direction and the desalination of saline water in coastal regions can provide the alternate sources of water during periods of climate change induced droughts. Another important adaptation tool could be the implementation of the watershed management measures, which focuses on preserving and restoring vegetated land cover, manage runoff and reduce erosion of the fertile top soil. Promoting climate-resilient agricultural practices and cropping patterns is another area to develop resilience against climate change impacts in the agricultural sector. The development of drought-resistant crops, crop diversification, efficient water use, and improved soil management practices can help reduce some of the negative impacts. Diversification into agro-forestry which is more resilient, as well as livestock production can reduce the sole dependence on agriculture and provide the necessary cushion to tide over the adverse situations during crop failures. A paradigm shift to smart subsidies to encourage a shift to dryland cropping that are more suited to local conditions might be a good adaption measure. The efficient use of groundwater resources will need to be incentivized.

The modification of the water demand by supporting practices that reduce water use by thermal/nuclear power plants by promoting the use of reclaimed water instead of fresh water for cooling power plants and use of closed-loop water circulation systems can help in substantial reduction of use of fresh water. Creation of monitoring networks for measurement of discharge, snowmelt, reservoir levels, river levels, in-stream temperature, and water quality is necessary to have a better understanding of the surface water and groundwater conditions and climate change impacts. The development of real time drought monitoring systems is a much desired step towards adaptation. Drought early warning systems needs to be developed and followed by early actions based on reliability and transparency. The development of Decision Support Systems (DSS) for providing information based on alternate scenarios of climate change and droughts along with the necessary actions to be taken may also help to provide the necessary solutions to address the issues related to climate change and drought. Achieving these suggestions should enable adaptation to be recognized as an opportunity for creative solutions to support continued sustainable development in India.

11.8 Concluding Remarks

Climate change is a real challenge to the world today and it is a well-established fact that the occurrences of extreme events are ought to increase in the future due to the changes in the rainfall pattern and its distribution. It has already been observed that the incidences of droughts have increased manifold in the last two decades in the country. The projected high variability of rainfall both in space and time will aggravate the precarious situation to a much wider extent. Already many regions and cities in the country are bearing the brunt of the drought and its impacts. Therefore, it is necessary to anticipate this natural hazard well in advance so that appropriate policy frameworks can be devised to address this. However, at present there seems to be large uncertainties in the future climate data and these uncertainties are ought to translate in the evaluation of future droughts. The adoption of spatial decision support systems and real time drought forecasting models might be appropriate tools for the policy makers, whose decisions can then be realistically based on multiple scenarios and real time data.

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