ASSESSMENT OF CLIMATE CHANGE IMPACTS ON RIVER BASINS ORIGINATING IN THE WESTERN GHATS OF INDIA

Thesis
Submitted in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

by

AMOGH MUDBHATKAL

DEPARTMENT OF APPLIED MECHANICS AND HYDRAULICS
NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA
SURATHKAL, MANGALORE- 575 025

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DECLARATION

By the Ph.D. Research Scholar

I hereby *declare* that the Research Thesis entitled **"Assessment of climate change impacts on river basins originating in the Western Ghats of India",** which is being submitted to the National Institute of Technology Karnataka, Surathkal in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy in the Department of Applied Mechanics and Hydraulics is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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CERTIFICATE

This is to *certify* that the Research Thesis entitled **"Assessment of climate change impacts on river basins originating in the Western Ghats of India",** submitted by **Amogh Mudbhatkal** (Register Number: 148055 AM14F04) as the record of the research work carried out by him, is *accepted as the Research Thesis submission* in partial fulfilment of the requirements for the award of degree of Doctor of Philosophy.

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ABSTRACT

The Western Ghats of India are an environmental and climate-sensitive region of India. The Western Ghats are the mountainous forest range of tropical region which plays a major role in the distribution of Indian monsoon rains. The present study was focused on the assessment of climate change impacts on the hydrology of river basins originating in the Western Ghats of India. Nine river catchments across the Western Ghats were selected to represent the complete range of spatial, topographical and climate variability. The study was carried out with four objectives which include (i) Analysis of historical trends in rainfall, temperature, evapo-transpiration, and streamflow, (ii) Performance evaluation of bias correction methods for precipitation and temperature with regard to hydrological modeling, (iii) Simulation of catchment response under forecasted climate conditions by using the Soil and Water Assessment Tool (SWAT) hydrological model, and, (iv) Examination of dependence of streamflow on elevation and suitability of regional network of weather stations and river gauges for predicting hydrological impacts of climate change. The data used in the study were procured from India Meteorological Department (historical meteorological data), Rossby Centre Regional Climate Model - RCA4 (RCP 4.5 forecasted meteorological data), and India Water Resource Information System (river gauging data). The frequency analysis was also carried out on the river flow to obtain flow quantiles at 10% duration intervals in the range 10% - 90%. The High flow index (HFI) (Q10/Q50) and the Low flow index (LFI) (Q90/Q50) were derived from the flow quantiles. The HFI was used to characterize the relative magnitudes of peak flow (Q10) with reference to the median flow (Q50), while the LFI was used to characterize relative magnitudes of low flow (Q90) to the median flow.

The trend analysis was performed using the modified Mann-Kendall trend test and the magnitude of the trend was estimated using the Sen’s Slope Estimator. The analysis was carried out for scenarios: Scenario 1 (1951-2005; historical data) and Scenario 2 (2006-2060; forecasted data). The trend analysis of historical data revealed that the effect of climate change in the river basins of Western Ghats of India is quite heterogeneous and the central and southern portions of the Western Ghats are more vulnerable to the climate change. The annual rainfall was found to increase over central rivers (Malaprabha and Aghanashini) by 4% and 3.5% per decade, respectively. The annual rainfall over southern rivers, Netravathi and Vamanapuram decreased by 3% and 4.3% per decade. The southern rivers indicated a weakening of the Indian South-west monsoon as monsoon rainfall decreased at the rate of 3.2%, 2.3%, and 6.2% per decade over Netravathi, Chaliyar, and Vamanapuram river catchments, respectively. However, the post-monsoon and summer rainfall was found to be increasing. No improvement was noticed in the forecasted scenario.

The historical temperature was found to be increasing with average annual temperature rising to the extent from 0.02 °C to 0.12 °C per decade. The southern river catchments witnessed the highest increase in average annual temperature ($0.12^{\circ\mathrm{C}}$ per decade in Vamanapuram catchment) and it was found that the southern river catchments are warming more rapidly as compared to the northern river catchments. Upon analysis of the seasonal temperature, the increase during monsoon season was the highest followed by the summer season. The forecasted scenario indicates a higher rate of increase in annual and seasonal temperature. The monsoon and summer season could witness an increase at the rate of 0.14 °C per decade. The potential evapo-transpiration indicates an increasing trend over several catchments, as a consequence of rising temperature. The streamflow in the rivers was found to be decreasing by as much as 17.50% annually in the southern rivers followed by 12% and 4% decrease in central and northern rivers, respectively. The river Aghanashini in the central portion of the Western Ghats of India demonstrated better resilience to climate change.

The bias correction methods adopted and compared in this study were the Linear Scaling (LS), Delta Change Correction (DC), Local Intensity (LI) scaling, Power Transform (PT), Variance Scaling (VS), and the Distribution Mapping (DM) method. These six methods may be classified into five bias correction methods applied for precipitation (LS, DC, LI, PT, and DM) and four methods for temperature (LS, DC, VS, and DM). The results indicated that the raw-RCM simulated

precipitation is biased by 42% and the temperature is biased by 12% across the catchments investigated. Subsequently, a bias of 65% was found in the streamflow. This was attributed to underestimation of heavy precipitation and overestimation of light precipitation events and precipitation frequencies, by the RCM. The DC method significantly improved the rainfall and temperature time series for the catchments. The hydrologic modeling using the bias-corrected data forced on SWAT hydrological model showed the superiority of DC method. The performance of the delta change correction method was consistently better for precipitation (with NSE >0.75 for 5 catchments) and temperature (NSE = 1) compared to other methods. Good performance was observed between the observed and bias corrected streamflow (daily time scale) for the catchments Purna (NSE = 0.97), Ulhas (NSE = 0.64), Aghanashini (NSE = 0.82), Netravathi (NSE = 0.89), and Chaliyar (NSE = 0.90), low performance with NSE of 0.3 was observed for catchments Kajvi and Vamanapuram. The methods failed for Malaprabha and Tunga catchments. This work concludes that, the delta correction method is the most appropriate method of bias correction for the impact analysis of climate variables for the catchments of the Western Ghats.

The examination of dependence of rainfall and streamflow on elevation stratification revealed that the lag time between the rainfall event and resulting runoff was proportional to elevation stratification (10, 20, and 30 days in Zone 1, 2, and 3, respectively for river Aghanashini). Also, the maximum intensity of rainfall over the west-flowing rivers of the Western Ghats of India is at some distance from the crest on the windward side. In the east-flowing rivers, the maximum rainfall is at the crest and decreases on the leeward side from the Western Ghats. The impacts of climate change on the local response to streamflow pattern was found to be varying and the availability of water in the month of May was higher compared to previous decades. The number of rainy days (rainfall>2.5mm/day) was lesser in the northern catchments and higher in the central and southern catchments indicating that, the central and southern portions of the Western Ghats receive more events of rainfall, but the intensity of rainfall is decreasing over time.

The major contributing months for monsoon rainfall are June-July and the second half of monsoon (August and September) are witnessing a decrease in rainfall. Compared to conventional peak streamflow availability during July and August, the peak streamflow availability is higher during July as a response to such changing rainfall pattern. The variation in annual streamflow availability is less in the northern rivers and decreasing in the southern rivers. The frequency analysis suggests more Q10 flows in central rivers (Malaprabha, Aghanashini, and Tunga) and lesser Q10 and Q90 flow in the southern rivers (Netravathi, Chaliyar, and Vamanapuram). The High Flow Index (HFI) slightly increased in the northern rivers and magnitude of increase was higher in central rivers. The HFI decreased in the southern rivers and accordingly, the Low Flow Index (LFI) increased. The present work is an attempt to comprehensively study the climate change and its impact on rivers of the Western Ghats of India. The work is an effective tool in understanding the hydrological impacts of climate change and adopting strategies to counter the impacts of climate change.

Keywords: Bias Correction Methods; Climate change; Elevation Stratification; Mann–Kendall; Regional Climate Model (RCM); Representative Concentration Pathways (RCP); Sen's slope; Soil and Water Assessment Tool (SWAT); Trend analysis; Western Ghats of India.

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CHAPTER 1

INTRODUCTION

Water is intricately blended with life, but the availability of water at sustainable quality and quantity is threatened by many factors, of which climate change plays a leading role. The Intergovernmental Panel on Climate Change (IPCC) estimates an increase in global mean surface temperature by 0.6 °C ± 0.2 °C since 1861 and predicts an increase of 2 °C to 4 °C over the next 100 years. The three prominent signals of climate change are an increase in global mean temperature, the rise in sea levels, and change in precipitation patterns. These signals convert to regional-scale hydrologic changes such as floods and droughts, water availability, water quality, sea water intrusion in coastal aquifers, and groundwater recharge. The increase in atmospheric temperature is likely to have a direct impact on river streamflow and on the evaporative demands of crops and affects all the hydrologic processes. This chapter provides the background and a brief introduction to climate change, its impacts and the methods of assessment.

1.1 CAUSES OF CLIMATE CHANGE

Climate change is a global challenge and recent events have demonstrated the world's growing vulnerability to climate change. Climate change is about an increase in the concentration of carbon dioxide (CO_2) and greenhouse gasses (GHGs) globally due to the burning of fossil fuels. The increase of CO_2 and other GHGs in the atmosphere enhances the "Greenhouse Effect" and leads to rise in temperature. The forests act as "carbon sinks" which absorb GHGs and prevent its release into the atmosphere. The loss of forests releases the stored carbon back into the atmosphere leading to increase in atmospheric GHG concentration.

The phenomenon of global climate change is being studied by a number of scientific communities. Studies show that, increase in global temperature has been highest in this century with a more rapid warming trend over the past 50 years. The year 2016 was the warmest year on record since measurements began in the year 1880. The carbon dioxide concentration surpassed 400 ppm (parts per million) for the first time in the year 2016 and global average temperature in the year 2016 was 0.99 °C warmer than the 20th century average (WMO 2017).

1.2 THE IMPACTS OF CHANGING CLIMATE

1.2.1 Regional impacts of climate change in Asia

The Himalayan mountain glaciers are melting as a consequence of global warming. Generally, the rate of glacier melting is higher during the summer season and any further intensification could lead to disasters. The immediate impact of the melting glaciers could potentially result in landslides and flash floods during monsoon season in lower Himalayan regions such as northern India, Pakistan, Nepal, and Bangladesh. The long-term impact of a warming climate would lead to the disappearance of these Himalayan glaciers which feed the main rivers (by meltwater) in Asia. By the year 2050, as many as one billion people could be affected by land degradation and drought as a consequence of water shortage (Christensen et al. 2007; IPCC 2007). According to the Internal Displacement Monitoring Centre (IDMC), during the years 2008 to 2014, an average of 22.5 million people have been displaced annually due to climate-related disasters and 17.5 million people have been displaced during the year 2014 (IDMC, 2015).

The Western Ghats of India are the mountain ranges along the west coast of the Indian subcontinent. The ranges of the Western Ghat extend from 8° 30′N to 21° 0′N and 73°0′E to 77°30′E starting from Gujarat state in the north to Tamil Nadu in the south. These ranges pass through the states of Gujarat, Maharashtra, Goa, Karnataka, Kerala, and Tamil Nadu for a length of approximately 2300 km and are as wide as 100 km at some places. Studies report that, the vulnerability to climate chance is higher in developing countries (such as India) compared to developed countries. In a tropical climate like that of Western Ghats mountain range, the changes in spatio-temporal distribution of precipitation and temperature would increase the frequency and intensity extreme events (floods and drought). The rise in temperature would result in lesser crop yield and stunt productivity. The increased water demand and decreasing flow in the river could affect the aquatic ecosystem and lead to conflicts among water users and nations.

1.2.2 Impacts of climate change on water resources

The hydrologic system is an integral part of the global climate system and circulates water between oceans, air, and land. Climate change could lead to the disruption of the hydrological cycle leading to either intense rainfall events (causing floods and landslides) or intensified droughts leading to reduce in agricultural productivity. The increase in temperature increases the potential evapotranspiration and leads to decrease in the soil moisture and groundwater which ultimately impacts the availability of water in the form of river flow.

1.2.3 Local impacts of climate change in India and the Western Ghats

The climate change impacts on surface water resources are expected to be severe in India. The increasing population along with the associated developmental activity has a threatening role on freshwater sources. The National Commission for Integrated Water Resources Development (NCIWRD) has made an assessment of the total freshwater resources of the country (GoI 2007). The water resources in the Indian subcontinent are expected to be stressed in the light of climate change and as much as 45% of annual runoff drains into the sea. Several schemes are proposed and under construction to minimize the loss of available runoff. But, the accomplishment of these water resource development plans in the rivers and agro-climatic zones is only possible with knowledge of spatio-temporal variation of precipitation and temperature in light of climate change.

The irrigation requirements in the non-irrigated areas are solely met by rainfall. The variation in precipitation due to climate change could strain the cultivation in these areas. Additionally, the irrigated areas may face water shortage during summer leading to scarcity of food and risk to the agricultural sector. It may be interesting to note that, the Central Statistics Office, Govt. of India (GoI 2017) reported a 4.1% growth rate of Gross Value Addition (GVA) of agricultural and allied sector in 2016-17 as first advance estimate.

The Western Ghats mountain ranges are located in the south-western part of India. Several rivers (west and east flowing) originate in the Western Ghats region of peninsular India. The population of several states such as Gujarat, Maharashtra, Goa, Karnataka, Kerala and Tamil Nadu is critically dependent on the services (such as freshwater services, regulatory services, and cultural services) provided by rivers of the Western Ghats. The people in the region are facing various problems such as, rapid land use changes on one hand and climate change on the other. It has been reported in the popular media that, the places (in coastal Karnataka and Kerala) which have annual average rainfall more than 3000 mm are facing drinking water problems during the summer.

1.3 ADAPTATION TO CLIMATE CHANGE

Although the climate change cannot be mitigated completely, strategies to complement adaptation to climate change are imperative. An ideal adaptation is difficult to achieve and there have been several cases of maladaptation. The short-term adaptation strategies involve development in highly vulnerable/risk prone areas and the long term strategies are tedious, require high capital and manpower. Some of the key elements in adaption to climate change are factors like education, infrastructure, resource management capabilities, and wealth.

The Asian region is plagued with constraints and the media highlights the adaptation of population at a local scale. To cope with climate change, the villagers on the banks of river Gumani in Bangladesh are creating floating vegetable gardens. These floating vegetable gardens provide the livelihood and food security to the population during the July to October. The agricultural land in the densely populated country is flooded annually by the monsoon and Himalayan snow melt.

In order to cope with drought and long dry spells, the villagers from Hambantota in Sri Lanka practice rain water harvesting along with efficient techniques of irrigation. Special underground tanks are constructed with capacities as high as 15,000 liters and have been successful in saving as much as 90% of water compared to conventional irrigation. A bottom-up, reverse approach is suggested for adaptation of climate change in India. The approach inverts the conventional cause-effect chain, which usually starts from climate change and subsequently calculates changes in hydrology, effects on water resources and eventually on water and food security and health (Bhave et al., 2014).

1.4 ASSESSMENT AND MODELING CLIMATE CHANGE IMPACTS

1.4.1 The General Circulation Models (GCMs) and climate forecasting

Climate change is the change in the state of the climate which perseveres for a long period of time, typically 30 years or more. The most advanced tools for prognosis of climate are the General Circulation Models (GCMs). These are three-dimensional numerical models based on the principles of radiative heat transfer, thermodynamics, and fluid dynamics. The physical processes in the land surface, ocean, atmosphere, and cryosphere are represented in the GCM and the response to increased greenhouse gas concentration by the global climate system is evaluated. The climate system in GCMs is represented using specific model for each climate system component. Atmospheric models are used for atmospheric properties, clouds, wind speed, and temperature. Ocean models are used for circulation of water and salt content. Separate models are used for ice cover on sea and land surface. Models specific to moisture and heat transfer from vegetation are also adopted. The GCMs are incapable of providing climate information on finer scales and high-resolution Regional Climate Models (RCMs) are used to transfer the GCM information to finer scales. However, pre-processing or bias correction of RCM outputs is essential for representing accurate climate information.

Long term emission scenarios are being developed by the Intergovernmental Panel on Climate Change (IPCC) since the year 1990. These have evolved from the IS92 scenario (Leggett et al. 1992) to the Special Report on Emission Scenarios (SRES) (Nakicenovic et al. 2000). The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) replaced the SRES with new scenarios called Representative Concentration Pathways (RCPs). The RCPs are four new pathways and form the basis for modeling experiments in the long-term and near-term. The pathways are developed up to the year 2100 with four radiative forcing (i.e., 2.6, 4.5, 6.0, and 8.0 W/m^2). The radiative forcing represents the net effect of anthropogenic greenhouse gases (GHGs) along with other forcing agents. For example, the RCP 4.5 scenario describes medium stabilization after the year 2100 without overshoot pathway to 4.5 W/m^2. The four RCPs are developed as a product of collaboration between climate, terrestrial ecosystem, integrated assessment, and emission inventory modelers. A comprehensive dataset with high spatio-temporal resolution is developed for the period for two time slices, 1951 to 2005 (historical/evaluation) and 2006-2100 (forecasted).

1.4.2 The rainfall-runoff models

The application of models in hydrological studies has become an indispensable tool for the understanding of the natural processes occurring at the watershed scale. A number of computer-based hydrologic models have been developed and are available for applications in hydrologic modeling and water resources study. They are increasingly being utilized to analyze the quantity and quality of streamflow, flood forecasting, reservoir system operations, groundwater development and protection, surface water and groundwater conjunctive use management, water distribution system, water use, climate and land use change impact study, ecology and a range of water management activities (Singh and Woolhiser 2002; Wurbs 1998).

The selection of models necessitates thorough knowledge of the model in terms of complexity and functionality. The analytical models solve the governing equations which describe the conservation of energy, mass, and momentum. The empirical models are simple relations developed on the basis of experimental data. The distributed models based on physicality represent the climatic (such as rainfall, temperature, and other water balance components) and spatial variability (such as the land use and land cover, soil, slope, and topography) of catchment processes to a fair degree of accuracy (Akbari & Singh, 2012; Grayson et al., 1992; Niehoff et al., 2002; Wijesekara et al., 2012). The hydrologic models represent the processes like Horton runoff flow (infiltration excess), subsurface runoff, infiltration, canopy interception, soil moisture storage, groundwater flow.

The Soil and Water Assessment Tool (SWAT) model is a catchment scale, continuous time model operating on a daily basis (Arnold and Fohrer 2005; Neitsch et al. 2009). The SWAT model has been extensively used in the past two decades for different hydro-climatic conditions and the model has been found to have a fair degree of accuracy. The applications of SWAT model include: potential impacts of climate change on hydrology and water resources (Van Liew and Garbrecht, 2001; Varanou et al. 2002; Jha et al. 2004; Gosain et al. 2006), impacts of land management on water resources (Srinivasan and Arnold, 1994), assessment of watershed response to land use/cover changes on the annual water balance and temporal runoff dynamics (Fohrer et al., 2001; Pikounis et al., 2003; Kepner et al., 2004; Fohrer et al., 2005), and, streamflow prediction for a variety of watersheds (Saleh et al., 2000; Santhi et al., 2001; Govender and Everson, 2005; Mao et al., 2009).

1.5 SCOPE OF THE WORK

The Western Ghats of India is anticipated to have a variation in rainfall, increase in temperature and extreme events (droughts and floods) (NATCOM 2) (MoEF 2012). In light of climate change, the Western Ghats might witness calamities such as lower moisture content in the ecosystem and increased fire incidences. The increased temperature and change in intensity and magnitude of precipitation are bound to bring about changes in the evapotranspiration rates and affect the runoff in the rivers (Hamlet and Lettenmaier 2007). According to the study by Gopalakrishnan et al. (2011), the forests in the northern and central parts of the Western Ghats of India are most vulnerable to climate change and the temperature is expected to increase disproportionately higher than rainfall. These observations made by the scientific community motivate the present study in the evaluation of regional scale warming, rainfall pattern and availability of water under changed climatic conditions.

Several studies are being carried out to assess the hydrologic impact of climate change in the Western Ghats region by using the outputs of RCM forced on hydrologic models. Precipitation is an integral part of the hydrological studies, and the simulation of precipitation by RCM is more difficult than temperature. The reliability of the studies, therefore, is critically dependent on the ability of the RCM to represent the southwestern monsoon precipitation and regional dependency in the performance of the bias correction methods. It is essential to study the regional variability of various bias correction methods in quantifying hydrologic impacts.

The agriculture and allied sectors of India are critically dependent on the timely availability of sufficient rainfall. The changes in pattern of long-term rainfall causes a disparity in the supply and demand for water. The trend of hydrological cycle components is essential for managing the water resources and related hydro-infrastructure which are designed on the assumption of stationarity in climate. The changes to the rainfall due to climate change are bound to influence the streamflow patterns and necessitate the review of management practices in hydrology. The trend analysis of hydro-meteorological variables helps in the estimation of availability of water resources in the context of future water management.

Keeping this in view, the present research is proposed to examine the link between climate change and hydrological response of river basins. The study is proposed to be undertaken on the rivers originating in the Western Ghats of India with different topographical, climatic and soil regimes and comprehensively quantify the impact of climate change on the river basins originating in the Western Ghats of India.

1.6 OBJECTIVES OF THE STUDY

1. To analyze historical trends in rainfall, temperature, evapotranspiration, and streamflow of rivers originating in the Western Ghats of India.
2. To evaluate the performance of bias correction methods for downscaled precipitation and temperature along the river catchments of Western Ghats of India with regard to hydrological modeling.
3. To simulate the catchment response under forecasted climate conditions by using the hydrological model SWAT and to compare their responses.

4. To examine the dependence of streamflow on elevation and suitability of regional network of weather stations and river gauges for predicting hydrological impacts of climate change.

1.7 ORGANIZATION OF THE THESIS

The thesis report comprises of seven chapters as listed below:

- Chapter 1 (Introduction) presents the overview of climate change and the basis for the research.
- Chapter 2 (Literature Review) deals with a critical review of current understanding of work related to climate change and its hydrological impacts.
- Chapter 3 (Study Area) presents the details of the study area and the rivers considered.
- Chapter 4 (Bias correction) deals with the bias correction of RCM simulated precipitation and temperature.
- Chapter 5 (Trend Analysis) deals with the trend analysis of rainfall, temperature, potential evapo-transpiration, and streamflow across the Western Ghats of India.
- Chapter 6 (Impacts of climate change on hydrology) describes the impact of climate change on the water availability in rivers originating from the Western Ghats of India.
- Chapter 7 (Summary and Conclusions) presents the summary and conclusions of the research.

CHAPTER 2

LITERATURE REVIEW

This chapter attempts to critically review the current understanding of pre-processing of regional climate model (RCM) simulations, the impacts of climate change on hydrology, and the climate in the Western Ghats of India. Further, the gaps identified from review of literature are described.

2.1 NEED FOR BIAS CORRECTION METHODS IN CLIMATE CHANGE STUDIES

The impacts of climate change on the hydrology of river catchments play an integral role in the field of water resources and hydropower (Bates et al. 2008). The assessment of hydrological impacts of climate change involves combining hydrological models with the precipitation and temperature outputs of General Circulation Models (GCMs) (Graham et al. 2007; Pechlivanidis et al. 2011). The GCMs incorporate the major complexities of the global system and exhibit substantial skill at the hemispheric and continental scales, but are inherently unable to represent the catchment scale features (Fowler et al. 2007). The hydrologic modeling of montane catchments requires climate information on a fine-scale and the GCMs do not represent the altitude-dependence of climatic variables (Seager and Vecchi 2010). The GCMs are not capable of providing reliable climate information on scales <200km (Maraun et al. 2010) and therefore, the output of GCMs is not combined directly with hydrological models for impact assessment of climate change on hydrology of rivers (Chen et al. 2011b; Feddersen and Andersen 2005; Hansen et al. 2006; Sharma et al. 2007).

The GCM information is transferred to finer scales by dynamic downscaling, which uses a high-resolution regional climate model (RCM) with the boundary conditions adopted from a driving GCM (Dickinson et al. 1989; Giorgi 1990; Yang et al. 2010). The topographical effects on precipitation and the mesoscale patterns of local precipitation are more reliably represented in the RCMs (Buonomo et al. 2007; Frei et al. 2003, 2006; IPCC 2007). The other method of obtaining fine scale data from GCMs is by statistical downscaling. Based on the statistical relationships between the coarse GCMs and fine observed data, statistical downscaling is a simpler way of obtaining high resolution climate projections (Wilby et al., 2004). The statistical downscaling is generally used for small-scale data on future climate (maps, data, etc.). The observed data is the key input to calibrate and validate the statistical models and GCM data for future climate to drive the models (Wilby et al., 1998).

The methods used for statistical downscaling are generally classified as prefect prognosis (PP), model output statistics (MOS) and weather generators. In PP, the statistical downscaling relationships are established by observations. In MOS, gridded RCM simulations and observations are used together to develop downscaling relationship. Using PP, MOS or both of them, weather generators are hybrid downscaling methods. With respect to types of statistical methods, downscaling can be categorical, continuous-valued or hybrid (Fowler et al., 2007; Wilby et al., 1997). In categorical downscaling, classifications and clustering are the common statistical techniques to relate data to different groups according to largescale circulation patterns and data attributes (Zorita and Storch, 1999). For continuous-valued downscaling, regression relationships are widely used to map large scale predictors onto local-scale predictands (Chandler and Wheater, 2002). When the GCM simulated variables are large in number, nonparametric stepwise predictor identification analysis may be performed based on partial mutual information (Mehrotra and Sharma, 2010). In hybrid downscaling, different statistical approaches are combined (Wilby et al., 2002) and they are sometimes referred to as weather generators, based on algorithms of conceptual processes (Chandler, 2002; Kilsby et al., 2007)

The RCMs transfer large-scale GCM information to the watershed/catchment/basin scale (spatial resolution of 10 to 50 km). But, the comparison of RCM outputs with reference period at similar scales exhibits biases in the spatial distribution and magnitude of precipitation and temperature (Foley 2010). The biases in RCMs are often attributed to the imperfect parameterization of climate processes in the model and by inappropriate boundary conditions of GCM or reanalysis data (i.e., climate data produced by combining models and observations) used to run the RCM (Ehret et al. 2012; Teutschbein and Seibert 2012). The convective rainfall is predominant in the tropical regions and owing to the sub-daily rainfall, the RCMs do not perform well in tropical climatic conditions (Lenderink and van Meijgaard 2008). Studies show the lesser accuracy of the RCMs in representing convective and summer precipitation than the winter precipitation (Maraun et al. 2010). The heavy precipitation is generally underestimated, whereas, the light precipitation events and precipitation frequencies are overestimated (Fowler et al. 2007; Murphy 1999). The accuracy of RCMs in representing climate is, therefore, dependent on the region and season (Kotlarski et al. 2005; Maraun et al. 2010).

In light of the bias, pre-processing of RCM outputs is a prerequisite step before forcing the data on hydrological models to assess hydrological impacts of climate change. The bias correction methods are model output statistics that reproduce RCM misrepresentation into historically observed statistics with a certain degree of acceptance (Teutschbein and Seibert 2012). Different approaches of bias correction are developed ranging from sophisticated distribution mapping to simpler methods such as linear scaling (Chen et al. 2011a, 2013a; Iizumi et al. 2011; Lafon et al. 2012; Mpelasoka and Chiew 2009; Piani et al. 2010; Ryu et al. 2009; Salvi et al. 2011; Sharma et al. 2007; Teutschbein and Seibert 2012). The simpler methods involve shifting of seasonal and/or long-term annual mean to match with observations and the sophisticated methods involve adjusting of the frequency distribution. Although these methods preserve the variability of climate data generated by RCM projections, the performance of the RCMs depends upon the governing atmospheric circulation of the region. Several studies explore the performance and evaluate the different bias correction methods across the world and report the ability of the methods to minimize the RCM output errors (Bennett et al. 2011; Terink et al. 2009; Themeßl et al. 2011). Although the standard deviation and the mean of precipitation datasets are robustly corrected in most cases, the kurtosis and skewness corrections are sensitive to the selection of the calibration period and the bias correction methods (Lafon et al. 2012).

The runoff projections for Australian catchments (Mpelasoka and Chiew 2009) show the superiority of daily translation and daily scaling method over constant scaling in extreme runoff representation, as these two methods take extreme daily rainfall into consideration. The quantile mapping method improves the spatial correlation between RCM and observed output (Bennett et al. 2011). The comparison of raw RCM results with a set of seven statistical downscaling and error correction methods demonstrated good performance of the local intensity (LI) and the quantile mapping method for daily precipitation over the Alps region. The best performance in downscaling precipitation extremes is by the quantile mapping method (Themeßl et al. 2011). A great deal of uncertainty always creeps into the simulation of streamflow under changed climate conditions due to empirical downscaling methods (Chen et al. 2013a). The study was incomplete owing to the fact that, it was carried out on only two basins of North America. The completed study (Chen et al. 2013b) calibrated the hydrological models with direct RCM output and also evaluated six methods of bias correction across ten North American river basins. Minor improvement in the simulation of streamflow was reported from the investigation when the hydrological model was calibrated with direct RCM output and the comparison showed better performance of distribution-based methods than mean-based methods.

The selection of bias correction method plays a major role in the response of extreme hydrological events. Non-linear methods are quite effective in reducing errors whereas the gamma-based quantile mapping gives very good results when the precipitation datasets (observed and modeled) follow a gamma distribution (Lafon et al. 2012). The distribution mapping is established on the gamma distribution and has performed well even for heavy precipitation and drought index apart from daily precipitation over Europe (Piani et al. 2010). The most widely used distribution for fitting daily precipitation is the gamma distribution (Block et al. 2009; Ines and Hansen 2006; Katz 1999; Watterson and Dix 2003). The limitation of the gamma distribution is that it cannot adequately represent the extreme tail of precipitation's distribution at daily time step. To overcome such limitations, Vrac and Naveau (2007) used a mixed distribution involving Pareto distribution and gamma distribution. The delta change and the distribution mapping methods did not differ in projecting hydrological statistics for a catchment located on the west coast of Denmark (van Roosmalen et al. 2011).

The performance of the methods also depends on the size of the catchments owing to the spatial average of RCM outputs (large-scale, mesoscale and small-scale). One of the most comprehensive studies in terms of bias correction methods for hydrological impacts of climate change is carried out on five catchments in Sweden (Teutschbein and Seibert 2012). The study assessed three methods of bias correction for temperature and four methods of bias correction for precipitation. The distribution mapping method (quantile mapping based on a gamma distribution) is found to perform the best for hydrological impact quantification and climate projections. Although the study was thorough in terms of method and climatic conditions, the size of the catchments was small and ranged from 147 km^2 and 293 km^2. In order to summarize the understanding of the literature on bias correction methods, the brief description of the most commonly used methods is presented in Table 2.1.

Table 2.1. Brief descriptions of the bias correction methods

Sl No.	Bias Correction Method	Pros	Cons	Reference
1.	Linear Scaling **(LS)**	A mean monthly correction factor is used for the daily precipitation. It is the simplest bias correction method.	The daily precipitation sequence is the same as that of the RCM simulated data (usually, too many wet days are simulated). The frequency distribution of the precipitation is not accounted. The temporal structure of the precipitation is not adjusted.	Lenderink et al. (2008) and Teutschbein and Seibert (2012)
2.	Delta Change Correction **(DC)**	The RCM-simulated anomalies are superimposed over the observed time series. It is a stable method since it uses observed data as the basis and produces future time series with dynamics similar to current conditions.	It does not account for potential future changes in climate dynamics. Major events (e.g., heavy precipitation or hot days) will change by the same amount as all other events.	Teutschbein and Seibert (2012)
3.	Local Intensity Scaling **(LI)**	The frequency of wet days is corrected and a monthly correction is applied to the precipitation dataset.	The changes in the frequency distribution of precipitation are not accounted. No adjustment is made to the temporal	Schmidli et al. (2006)

Sl No.	Bias Correction Method	Pros	Cons	Reference
			structure of daily precipitation occurrence.	
4.	Power Transform **(PT)**	The mean and variance of data are adjusted, i.e., corrects percentiles and the coefficient of variation to some extent.	The probability of dry days and precipitation intensity is not corrected. The nonlinear transformation does not perform well when the bias in the frequency of wet days is large. Limited to precipitation due to power function	Leander and Buishand, (2007), Leander et al. (2008)
5.	Variance Scaling **(VS)**	The mean and the variance of temperature time series are corrected. The correction factors are assumed to remain the same for future conditions, but allow for changes in response to control and scenario run.	The nonlinear transformation does not perform well when the bias in the frequency of wet days is large.	Chen et al. (2011a, b)
6.	Distribution Mapping **(DM)**	The RCM-simulated precipitation is corrected based on a gamma distribution. The frequency of precipitation occurrence	The stationarity assumption that the same correction algorithm applies to both current and future climate	Ines and Hanson (2006), Piani et al. (2010), and Teutschbein

Sl No.	Bias Correction Method	Pros	Cons	Reference
		is corrected using the LI method.	conditions.	and Seibert (2012)
		It corrects most of the statistical characteristics and has the narrowest variability ranges, combined with the best fit of the ensemble mean.	The performance depends on whether the observed and RCM simulated precipitation follows the gamma distribution (or not).	

2.2 CLIMATE CHANGE STUDIES IN THE PAST

Over the recent years, there has been a growing global concern over the impacts of climate change on environmental dynamics, and their subsequent implication on societal activities such as drinking water, irrigation, food, energy requirement and hazard prevention. From shifting weather patterns to rising sea levels, the impacts of climate change are global in scope and are unprecedented in scale. Several investigations report the impacts of climate change on the fundamental drivers of the hydrological cycle (Zhang et al. 2016; Shashikanth et al. 2017; Anand et al. 2017). The hydrological cycle, as the key link between the atmosphere and the biosphere, is inevitably influenced by climate change. Pfahl et al. (2017) studied the regional pattern of extreme rainfall events by decomposing the extreme precipitation of GCM simulations into atmospheric dynamic and thermodynamic contributions. The study used maximum daily precipitation and temperature from 21 CMIP5 (Coupled Model Intercomparison Project Phase 5) models and demonstrated a robust increase in the Asian monsoon region by the dynamic contribution. It may be noted that dynamic contributions play a pivotal role in reducing the uncertainties of GCMs in future projection.

The increasing greenhouse gas emissions caused by anthropogenic activities exhibits significant impacts in the phase and amount of precipitation pattern, sea level rise and mean temperature globally (Christensen et al., 2004; Davidson and Janssens, 2006; Diabat et al., 2013; Safeeq and Fares, 2012; Tian et al., 2013). The rising trends of extreme events such as droughts and floods are attributed to rising temperature and the reports of Intergovernmental Panel on Climate Change (IPCC) highlight the increase in global mean temperature by magnitude of 0.74°C, during 1906 to 2005, with a rapid warming over the past 50 years (Abbaspour et al., 2009; Dobler et al., 2012; Eum and Simonovic, 2012; IPCC, 2007, 2012, 2014; Wang et al., 2011; Xu et al., 2012). Although the climate change assessments are on a global scale, there is a need for evaluating the local scale hydrological impacts. The impacts of climate change alter the frequency and magnitude of annual streamflow (Luce and Holden, 2009; Stewart, 2009; Stewart et al., 2005). The warming also leads to reduced and early flow in cold regions as the quantity of precipitation is higher in the form of rain than snow (Christensen and Lettenmaier, 2007; Elsner et al., 2010; Jin and Sridhar, 2012; Tang et al., 2012; Tang and Lettenmaier, 2012; Vano et al., 2012). Although there is no snow in the tropical regions, these changes alter the ecosystems and hold high potential in impacting water management practices due to increase in wildfires and droughts (Mote et al., 2003; Westerling et al., 2003).

The rivers in the montane regions have pronounced climatic regimes and are often characterized by narrow valleys, deep canyon confinements and broad floodplains (Church, 2015; Montgomery et al., 1996; Stanford and Ward, 1993). The channel slope generally sets the tone of confinement in the river flow and higher gradients have a lesser bottom width of the valley. The variations in the slope and channel confinement control the climate gradients and geomorphic processes in the region. The heterogeneous rainfall patterns along with physical habitats and vegetation are highly influenced by the varying topography in mountain systems (Beniston, 2006; Montgomery and Buffington, 1997; Niu and Yang, 2004; Poulos et al., 2012). The temperature and orographic effects of montane regions influence the magnitude of precipitation and studies report as much as five times more precipitation in the higher elevations (Katzfey, 1995a, 1995b; Lundquist and Cayan, 2007; Minder et al., 2010; Roe, 2005; Rolland, 2003; Sinclair, 1994). The streams and rivers originating in the montane regions alternate between the canyon and floodplain segments and the local elevation, topography and meteorological characteristics heavily influence the generation of streamflow (Hunsaker et al., 2012). Yet, few studies evaluate the structure and function of elevation in modifying streamflow patterns.

The evidence of a clear change of pattern in the annual streamflow is reported by the researchers globally. The regions at higher latitude are experiencing an increase in annual streamflow (Hyvärinen 2003; Tao et al. 2003a; b; Walter et al. 2004). Studies claim that 1°C rise in temperature in the 20th century will lead to an increase in global total streamflow by almost 4% (with regional variation) (Labat et al. 2004). It was reported that southern Latin America, southern Europe, and West African regions are experiencing decreased streamflow (Milly et al. 2005). However, these findings were challenged for the reason that, the non-climatic factors also influence the streamflow and there could be bias in the data due to lesser data points (Legates et al. 2005).

The streamflow records used in climate change studies for hydrologic model calibration and trend detection integrate the water from all the tributaries across spatial and temporal distribution of precipitation and large variation in elevation and vegetation (Barnett et al., 2004; Christensen and Lettenmaier, 2007; Fritze et al., 2011; Hamlet and Lettenmaier, 2007; Luce and Holden, 2009; Muttiah and Wurbs, 2002; Rauscher et al., 2008; Stewart, 2009; Stewart et al., 2005; Tang and Lettenmaier, 2012). The streamflow records are very useful in understanding their integrated response, there is little research work reported in evaluating the signals of combined effects of variation in elevation and climate change.

Several investigations are made on catchments/basins of diverse scales and report the effects of climate change on the streamflow in rivers across India (Gosain et al. 2006; Narsimlu et al. 2013; Giang et al. 2014; Pervez and Henebry 2015). The impact of climate change on India is significant due to its geographical complexity, varied climatic conditions, and growing anthropogenic activities. There are strong indications of change in the trend of climatic parameters at the regional level in line with the effect of global warming (Zhu and Houghton, 1996; IMD, 2013; IPCC, 2014). The climate of India is dominated by the southwest monsoon precipitation (June to September) which is widely distributed in space and time. India receives about 80% of its total rainfall during the southwest monsoon season and studies report the change in the trend of climatic variables at regional level due to global warming. As per the Central Water Commission’s report, the average annual precipitation in India has decreased from about 4000 billion cubic meters (BCM) (CWC 2005) to 3882 BCM (CWC 2009) over the period of 5 years signifying decreasing trend in the precipitation. According to (Gleick. et al. 2012), China and India use about 40% of global freshwater for irrigation.

2.3 IMPORTANCE OF CLIMATE STUDIES IN THE WESTERN GHATS

The study by Bhowmik and Durai (2008) demonstrated the underestimation of rainfall over the Western Ghats in four models used by the IMD (India Meteorological Department). The models considered were Limited Area Model (LAM) and Mesoscale Model Version 5 (MM5) operational at IMD New Delhi, and the MM5 and T-80 models operational at the National Centre for Medium Range Weather Forecasting (NCMRWF), Noida, India. The study pressed the need of incorporating the influence of orography in the proverbial south-western monsoon of India. The rainfall along the western coast of India is attributed to the Western Ghats and the spatial distribution of rainfall over the region is demonstrated in the study carried out by Sijikumar et al., (2013). The study uses rainfall obtained from the TRMM (Tropical Rainfall Measuring Mission) and the simulations of Advanced Research Weather Research and Forecasting (AR-WRF) model in demonstrating the spatial distribution. The numerical models of European Centre for Medium-Range Forecasts (ECMWF) with the improvised topographic definition are quite reasonable in predicting the heavy rainfall rates in the Western Ghats of India (Basu, 2005). Although the study evaluated the models of the NCMRWF (National Centre for Medium Range Weather Forecasting) and ECMWF (European Centre for Medium-Range Forecasts) and reported errors in the magnitude of heavy rainfall and rainfall forecast along ridgelines, the rate of rainfall was reasonably predicted.

The correlation of rain gauge station based rainfall and elevation is attempted in the study by Raj and Azeez (2010) which illustrated the intensification of rainfall due to valleys, elevations and topographical features in the Pallakad gap (Kerala state) of the Western Ghats. The study also observed decreasing rainfall owing to deforestation. The difficulty in relating topography with rainfall distribution and identification of homogeneous rainfall intensities in coastal districts of Karnataka and Kerala were reported by Simon and Mohankumar (2004) and Venkatesh and Jose (2007). The study by Simon and Mohankumar (2004) reported less than 75% rainfall from southwestern monsoon on the leeward side of apex regions. The lack of spatial coverage of rain gauges in the Western Ghats limits the study of rainfall in the rugged terrain and combination of satellite observations is attempted in the study of elevation dependence of rainfall (Bhowmik and Das, 2007; Tawde and Singh, 2015). The satellite-based rainfall products (such as TRMM) require regional scale calibration and are able to detect the distribution of rainfall spatially, but, the intensities of rainfall are found to be underestimated along the coastal region of Western Ghats (Mitra et al., 2009).

2.4 CLOSURE

From the review of past literature, it is evident that, the Western Ghats of India is one of the eight "hottest hotspots" of biological diversity in the world and are listed as the UNESCO World Heritage Site (UNESCO 2013). Many major rivers of peninsular India originate in the Western Ghats. The population in the seven states of India viz., Gujarat, Maharashtra, Goa, Karnataka, Kerala, Tamil Nadu, and Andhra Pradesh is critically dependent on the rivers originating in the Western Ghats. The region is facing problems related to extreme weather conditions such as prolonged drought. A great deal of research has been conducted on the changing climate of the Western Ghats of India, but few studies have been carried out on the prognosis of water availability. Most of these studies are being carried out using the outputs of RCM forced on hydrologic models. Precipitation is an integral part of the hydrological studies and the simulation of precipitation by RCM is more difficult than temperature. The reliability of the studies is, therefore, critically dependent on the ability of the RCM to represent the south-western monsoon precipitation and regional dependency in the performance of the bias correction methods. It is essential to study the regional variability of various bias correction methods in quantifying hydrologic impacts.

Studies have been undertaken to correct the bias of RCM simulations for climate change impact studies. Most of these studies report reasonably good ability of the bias correction algorithms. It may, however, be noted that, the efficiency of the bias correction methods largely depends on several variables such as governing atmospheric circulation of the region and the size of the watershed. No extensive studies have evaluated the performance of bias correction methods on river catchments originating in the Western Ghats of India. Therefore, the bias correction methods need evaluation and comparison, especially for rivers in the Western Ghats. The major gap found in the review of the literature was that the climate change studies in the past are limited to certain regions of the Western Ghats and there are no studies which comprehensively profile the complete stretch of the Western Ghats of India for climate change.

CHAPTER 3

STUDY AREA

3.1 STUDY AREA

The Western Ghats of India are older than the Himalayas and their geomorphic landscapes are pivotal in the moderation of tropical climate in the region (UNESCO 2013). They extend for about 2300 km parallel to the entire west coast of India. It is a stable land mass of Archaean and Precambrian rock formations with an elevation exceeding 2500 m above MSL (mean sea level) at some places. The Indian monsoon is highly influenced by the Western Ghat mountains, its characteristic forest ecosystems, and is one of the best described tropical monsoon systems on Earth. The Indian monsoon rains approach the Indian sub-continent simultaneously from the Arabian Sea through the Western Ghats and from the Bay of Bengal through Gangetic West Bengal by the end of May or beginning of June and cover the entire country by the end of July.

The variation of topography and precipitation in the Western Ghats spawns a wide variety of vegetation varying from evergreen forests (west side) and dry deciduous (higher altitudes) to shrub vegetation on the east side. The strip of land between the Western Ghats and the sea coast (windward side) has a width ranging from 100 km to 200 km which receives an annual average rainfall of about 3000mm near the sea coast to about 6000mm near the Ghats. The maximum rainfall over the Western Ghats is about 7000 mm. The eastern part of the Western Ghats is a plateau region with a gentle slope towards the Bay of Bengal and an annual average rainfall of about 1500 mm which decreases towards east (Fig. 3.1). The average annual maximum and minimum temperatures range from 35°C to 41.5°C and 6°C to 12°C, respectively. The assessment of climate change impacts plays a major role in efficient planning and utilization of the stressed water resources in the region.

The study area extends from 8° 30’ N to 21° 0’ N latitude and 73° 0’ E to 77° 30’ E longitude and covers districts in four states of India: Gujarat, Maharashtra, Karnataka, and Kerala. The nine river catchments selected for this study represent the entire range of topography and climate of the Western Ghats of India such as westerly mountain area to flatter terrains. The catchment areas range between 287 km^2 to 3,351 km^2. The rivers represent five climate zones based on the revised Thornthwaite-type global climate classification (Feddema 2005). They are per-humid (A), humid (B3 and B4), dry sub-humid (C1), and moist sub-humid (C2). The Thornthwaite classification is based on the moisture index (I_m) derived from annual water budget components. According to this, the world is classified into moisture zones i.e., per-humid to arid. The dry climates have negative index values and humid climates have positive values. The per-humid (A) is one with I_m>100 and represents the wettest climate (generally found in rain forests of Western Ghats where southwest monsoon strikes against the Western Ghats). The humid climate (B3 and B4) with I_m between 20-100 and is characterized by forested area. The moist sub-humid (C2) and dry sub-humid (C1) have I_m ranging from 0 to 20 and 02 to -33, respectively. The C2 climate is characterized by grasslands and C1 is characterized by dry grasslands. The basic information of the nine river catchments is presented in Table 3.1.

Table 3.1. Basic information on the river catchments

State	River	Climate Zone	Catchment Area(km^2)	Avg.Annual Rainfall(mm)
Gujarat	Purna[a]	Dry sub-humid (C1)	1655	1600
Maharashtra	Ulhas[a]	Humid (B4)	886	3800
	Kajvi[a]	Humid (B4)	287	3600
Karnataka	Malaprabha[b]	Moist sub-humid (C2)	428	2800
	Aghanashini[a]	Per humid (A)	1295	3700
	Tunga[b]	Per humid (A)	2922	4700
	Netravathi[a]	Per humid (A)	3351	3700
Kerala	Chaliyar[a]	Dry sub-humid (C1)	1953	2700
	Vamanapuram[a]	Humid (B3)	541	1800

Note: [a] West flowing; [b] East flowing

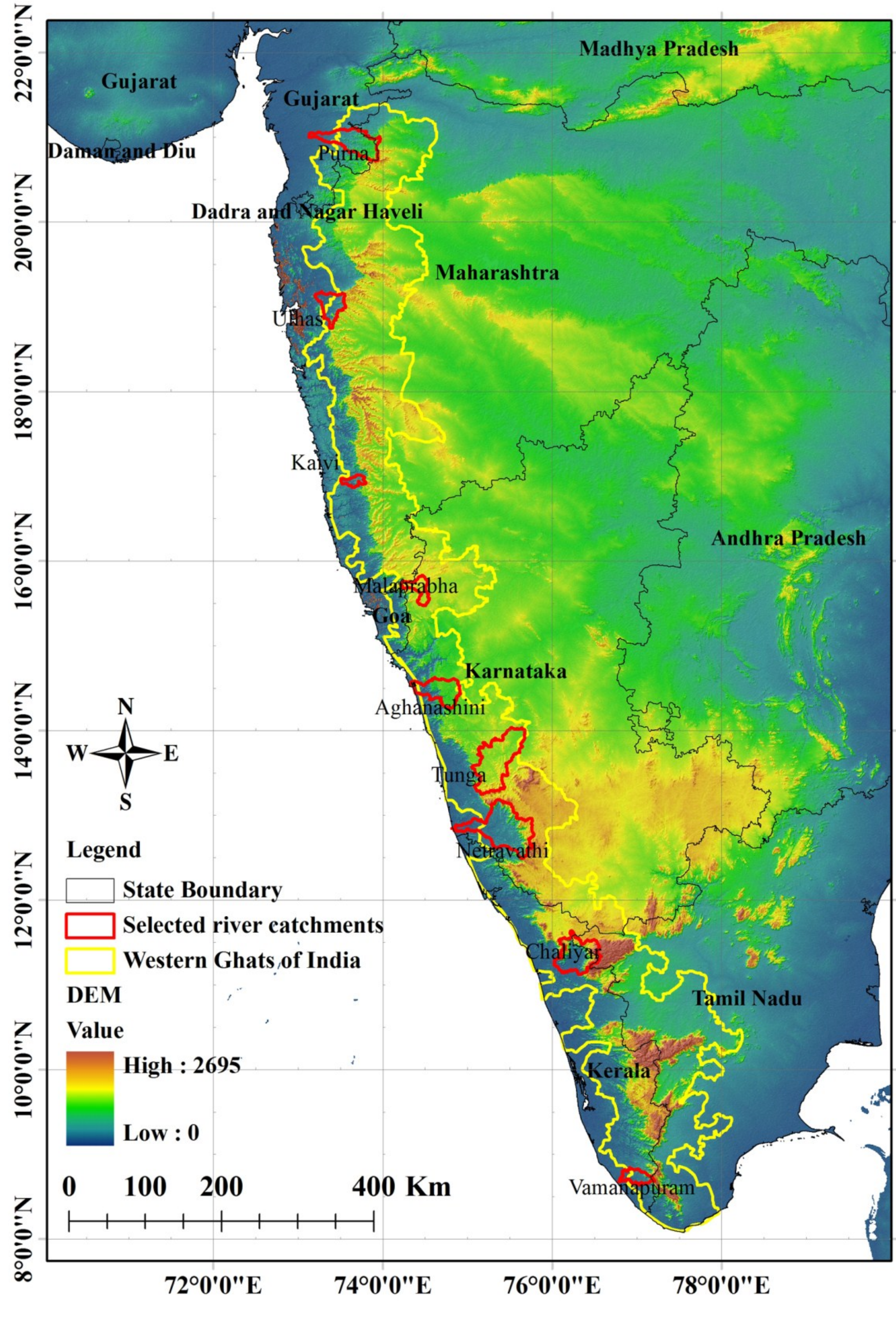

Fig. 3.1. Western Ghats of India showing the nine river catchments

3.2 TOPOGRAPHY

The topographic information was obtained in the form of topographical maps procured from the Survey of India (SoI) at 1:50,000 scale. The topographical maps were used to delineate the catchment boundaries. The Digital Elevation Model (DEM) at 90 m resolution from the Shuttle Radar Topography Mission (SRTM) was used to calculate basin parameters such as slope and slope length. The DEMs are presented in Fig. 3.2. The course of rivers in the Western Ghats are through thick forested gorges and valleys with intermittent structures of rock bed, deep stagnant pools and channeled flow with island formation. The river slope and the terrain of the river catchments are quite heterogeneous. The rivers Ulhas, Kajvi, Netravathi, Chaliyar, and Vamanapuram are very steep in the initials reaches and have long flat plains. The river Malaprabha is quite flat compared to the other rivers considered in this study (with the difference in elevation of about 400 m). The river Aghanashini has a fall of 116 m at Unchalli and the estuary portion at the river mouth is a flat expanse of water dotted with small islands and narrow creeks.

The drainage map of the rivers was created using the DEM and are given in Fig 3.3. The river Purna originates in the Western Ghats region of Maharashtra and flows through Maharashtra and Gujarat states of India to join the Arabian Sea. It is one of the northern most river of the Western Ghats of India. The river traverses through a length of 180 km spreading over 1655 km^2. The river Ulhas originates in the Sahayadri ranges of Western Ghats in Maharashtra and flows for about 122 km prior to joining the Arabian Sea. The river is used for the water supply of Badlapur, Navi Mumbai and Kalyan cities. The river Kajvi begins from Vishalghat region of Maharashtra and confluences with the Arabian Sea near the port of Ratnagiri. The Malaprabha river is an east flowing river originating at Kanakumbi in Karnataka and is one of the major tributary of the river Krishna. The river Aghanashini is an independent west flowing river originating from the Western Ghats of India in Karnataka.

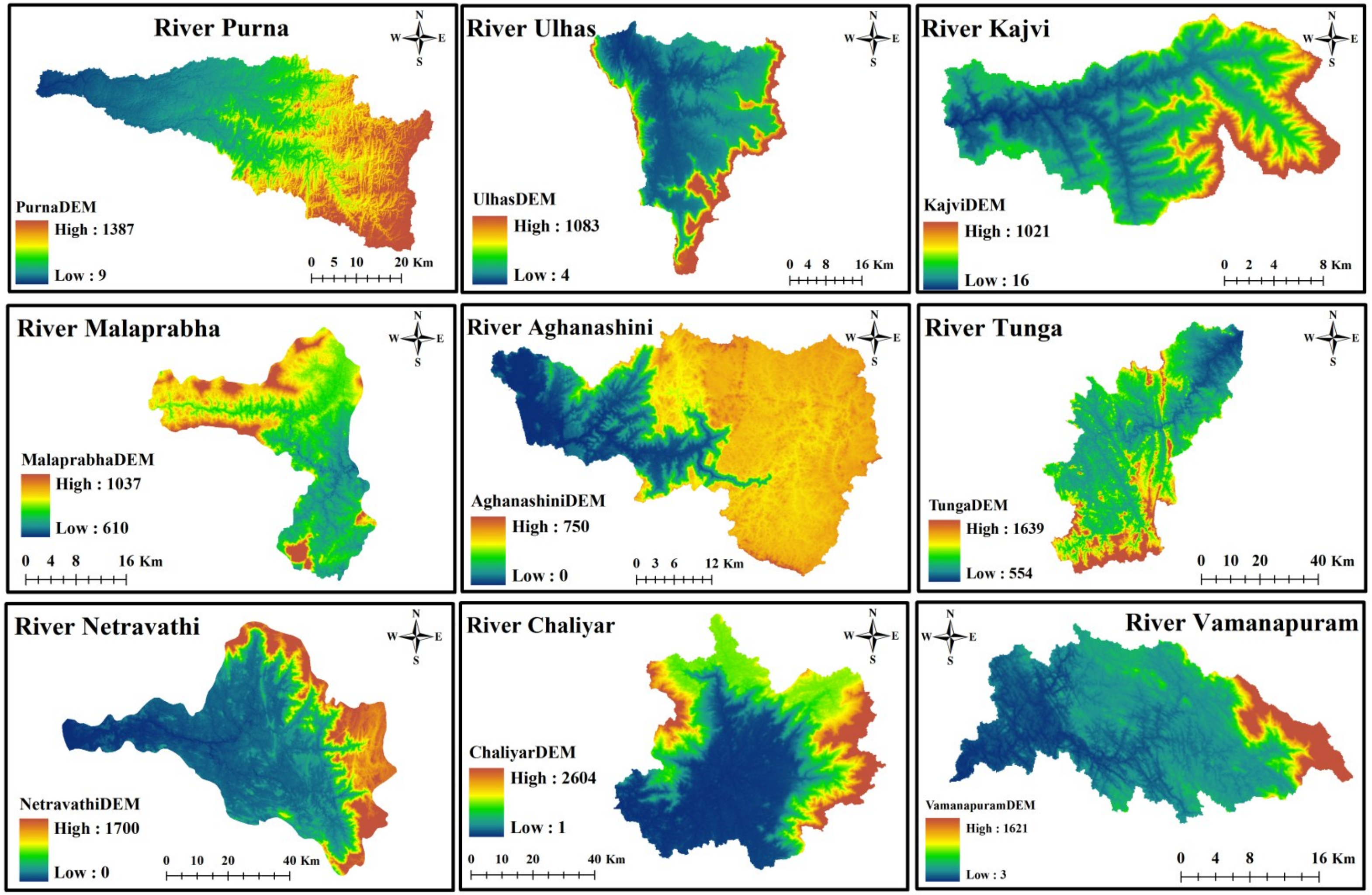

Fig. 3.2. Digital Elevation Model (DEM) of the selected river catchments

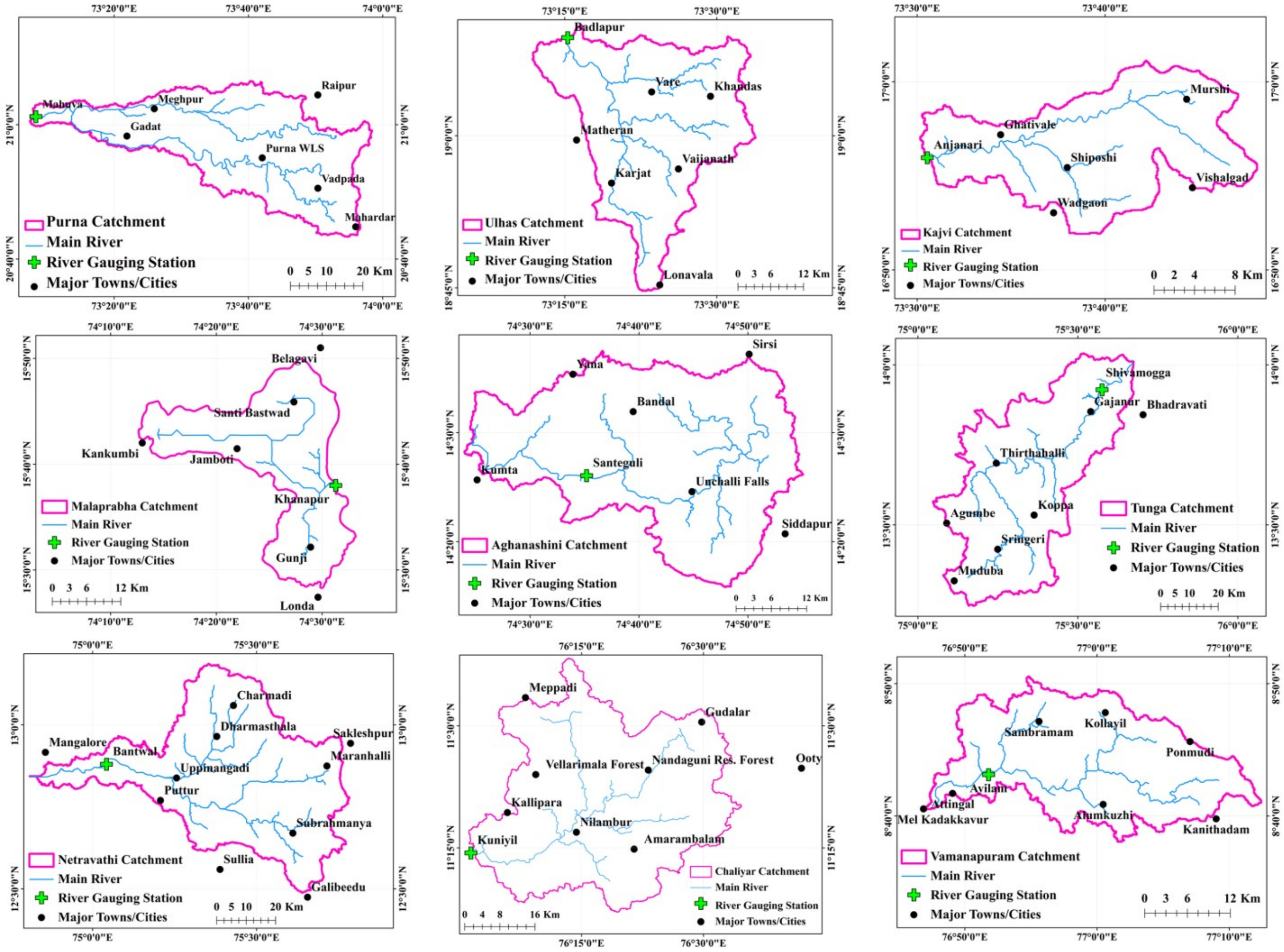

Fig. 3.3. Drainage map of the selected river catchments

The mainstream Aghanashini is one of the longest free-flowing and most pristine west flowing river along the west coast of India. The river Tunga is a tributary of the Tungabhadra River in the Krishna basin. Tunga is an east flowing river originating in the Western Ghats at Chikmagalur district of Karnataka. The river flows for 150 km before it merges with another tributary of Krishna river i.e., Bhadra River. The Netravathi River is a west flowing river in the southern part of the Karnataka state. The river flows for about 125 km before joining the Arabian Sea and has a catchment area of 3351 km^2. The river Chaliyar is a major river of Kerala state. It originates originates in the Elambalari hills of Wayanad plateau and about 13% of its catchment area lies in Tamil Nadu. The Vamanapuram River is the southern-most river basin considered in this study. It is also the southern-most west flowing river of the Kerala state with catchment area of 541 km^2. The river joins the Kadinamkulam Lake after flowing for 90 km.

3.3 LAND USE AND LAND COVER

The Western Ghats of India are characterized by the rain forests, evergreen forests and luxurious growth of vegetation owing to the heavy rainfall. The land use and land cover (LULC) data used in the present study was of 100-m spatial resolution at decadal intervals for 1985, 1995 and 2005. The data contained 19 classes which were merged to obtain the first level classification (forest, water bodies, urban settlements, agriculture, grassland, barren land). A second level classification was carried out to the forest class (evergreen broadleaf forest, deciduous broadleaf forest, mixed forest and forest plantation) owing to the large number of pixels in the forest class. In the northern portion of the Western Ghats (River Purna, Ulhas, and Kajvi), deciduous broadleaf forests and agriculture were observed to be the dominant land use (Fig. 3.4). In the central portion (River Malaprabha, Aghanashini, and Tunga), the dominant land use was found to be agriculture and evergreen broadleaf forests followed by deciduous broadleaf forests (Fig. 3.5). The southern portion was found to be dominated by forest plantations followed by evergreen and deciduous broadleaf forests, respectively (Fig. 3.6).

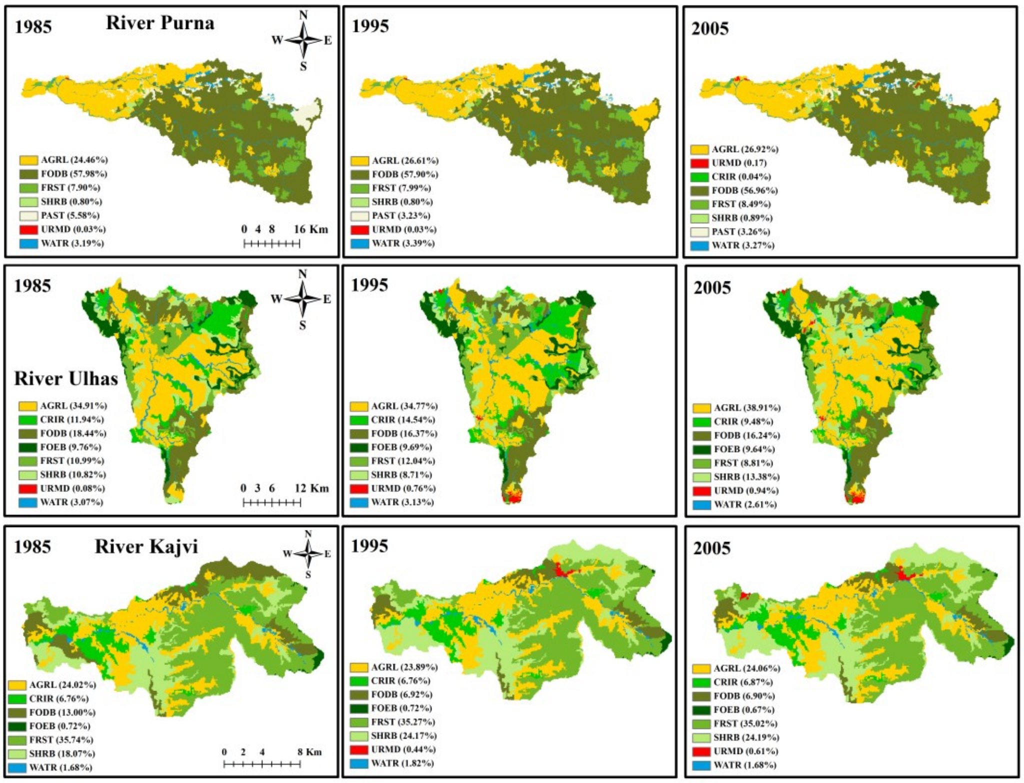

Fig. 3.4. Land use land cover map for the northern portion of the Western Ghats

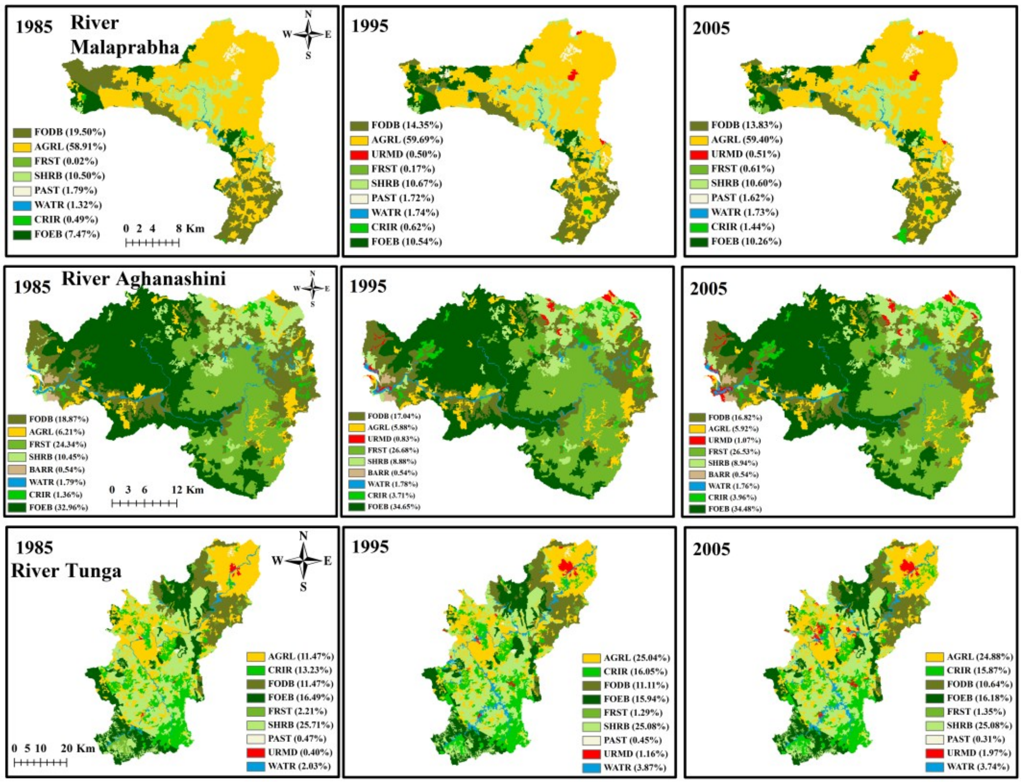

Fig. 3.5. Land use land cover map for the central portion of the Western Ghats

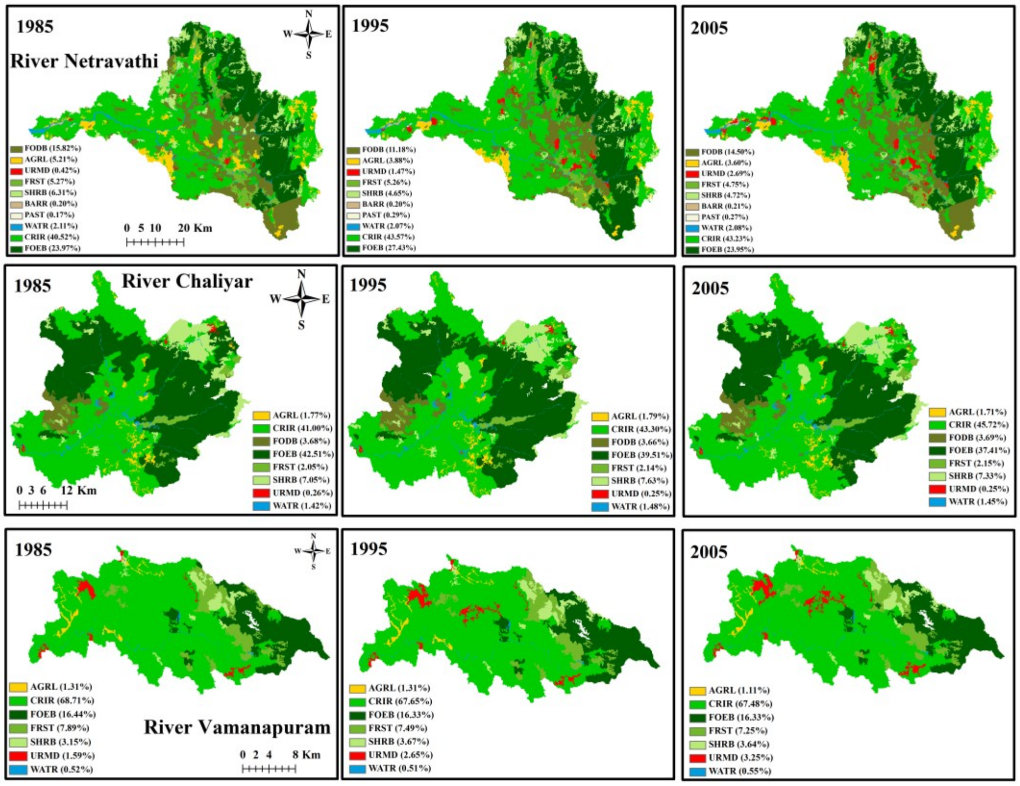

Fig. 3.6. Land use land cover map for the southern portion of the Western Ghats

3.4 SOIL

The soil map used in the study was obtained from the Food and Agriculture Organization of the United Nations. The dataset is based on the FAO-UNESCO (United Nations Educational, Scientific and Cultural Organization) Soil Map of the World. The Digitized Soil Map of the World, at 1:5,000,000 scale, is in the Geographic projection (latitude - longitude) intersected with a template containing water related features (coastlines, lakes, double-lined rivers). The major soil types in the catchments are sandy clayey loam, sandy loam, clayey loam and loam. The soil map for the selected catchments of the Western Ghats of India is shown in Fig 3.7.

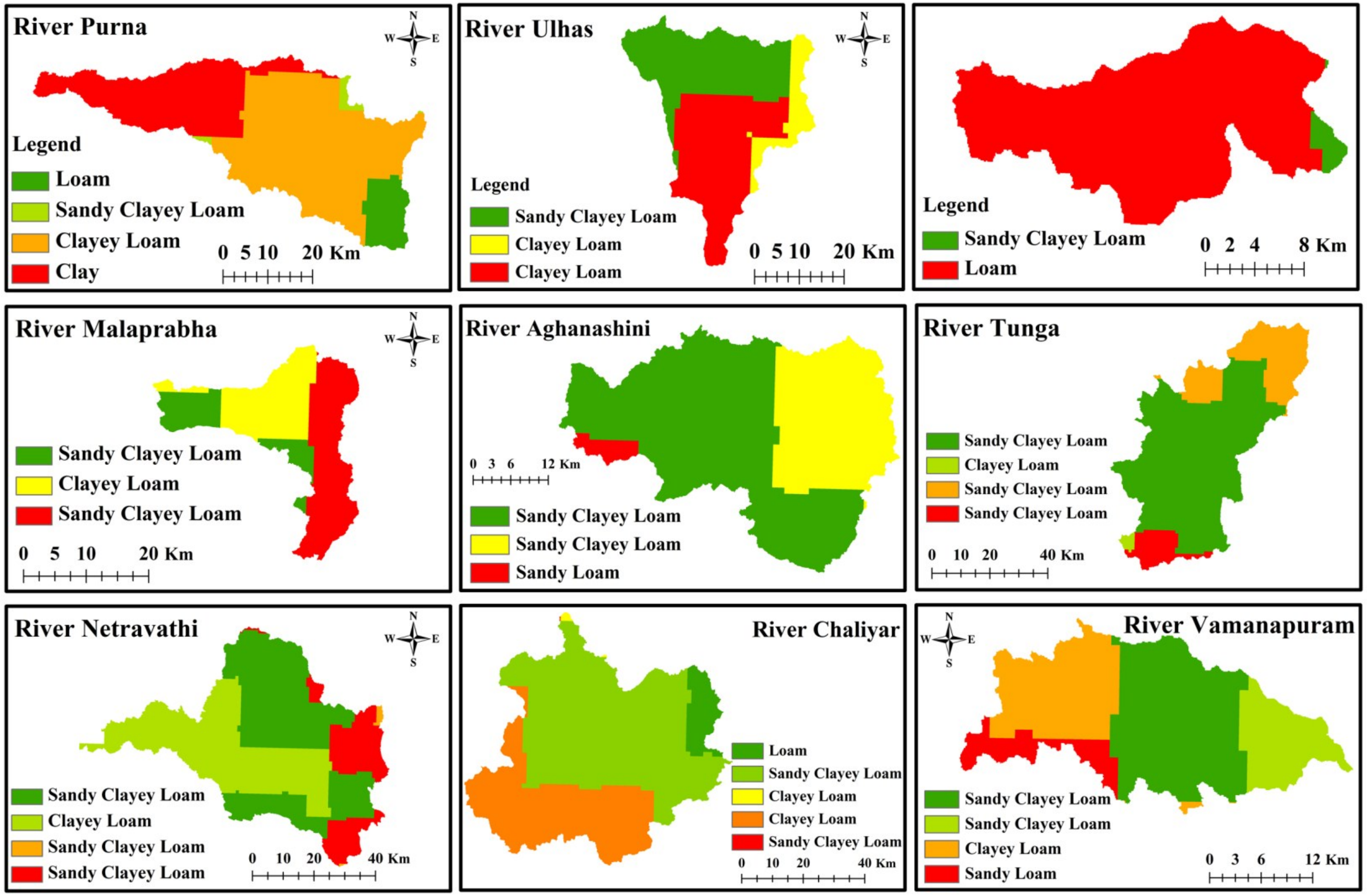

Fig. 3.7. Soil map of the selected river catchments

3.5 DATA USED

The rain gauge station data from Water Resources Development Organization (WRDO), Government of Karnataka and Indian Meteorological Department (IMD) were procured. Also, the gridded data on precipitation (0.25° x 0.25°) and temperature (1° x 1°) were procured from India Meteorological Department (IMD). The processing of the gridded data may be found in Pai et al. (2004). The discharge data was obtained from India Water Resource Information System (https://www.india-wris.nrsc.gov.in/wris.html) and from the Water Resources Development Organization (WRDO), Govt. of Karnataka, India. The RCM-simulated precipitation and temperature were obtained from the COordinated Regional climate Downscaling EXperiment (CORDEX) (http://www.cordex.org/). The South-Asian domain (WAS-44) of the CORDEX experiment has 11 suites which constitute a combination of various RCMs driven using the initial and boundary conditions of different GCMs. Although four suites provide bias-corrected data, they employ distribution based correction method. The RCP 4.5 scenario describing the medium stabilization after the year 2100 without overshoot pathway to 4.5 W/m^2 was used in this study. The RCP 4.5 assumes a significant role of renewable energy (such as nuclear, hydropower and solar) in the future. The natural vegetation in terms of forest is assumed to increase while the cropping (grassland) is expected to decrease. The greenhouse gas concentration continues to trend at about 650 ppm (parts per million) of CO_2 equivalent with a temperature anomaly of about 2.4°C.

The Rossby Centre Regional Climate Model - RCA4 developed at the Rossby Centre and downscaled to a subset of Global Climate Model (GCM) simulations from the CMIP5 (Coupled Model Intercomparison Project Phase 5) was used in this study. The data was available at a horizontal spatial resolution 0.44° x 0.44° (~50 km) and daily temporal resolution. Out of the 11 experiment suites of CORDEX, the RCA4 simulations were selected for the present study because it has demonstrated good performance (close proximity to observed data) in the complex mountainous topography of India (Ghimire et al. 2015). For catchments smaller than one RCM grid box, precipitation and temperature were basin-averaged. The averaging of grid points is a requisite for watersheds of smaller size and helps in elimination of the grid-point numerical effect of computational schemes in climate models. The averaging concept is also used in studies carried out by Teutschbein and Seibert (2012).

CHAPTER 4

BIAS CORRECTION FOR PRECIPITATION AND TEMPERATURE

This chapter deals with the bias correction of Regional Climate Model (RCM) outputs. The bias correction methods adopted and compared in this study are the linear scaling (LS), delta change correction (DC), local intensity scaling (LI), power transform (PT), variance scaling (VS), and the distribution mapping (DM) method. Out of the above, five bias correction methods were applied to precipitation (LS, DC, LI, PT, and DM) and four methods were applied to temperature (LS, DC, VS, and DM). The bias corrections were carried out on daily basis. A brief description of the bias correction methods is already presented (Chapter 2) and this chapter presents the methodology for bias correction, results and discussion.

4.1 METHODOLOGY

The bias correction methods were evaluated by split-sampling and cross-validation approach (Bennett et al. 2011). The calibration was carried out using: (1) Separation of the observed and RCM-simulated meteorological variables (precipitation and temperature) into 40 years period (1951-1990) and 15 years period (1991-2005). (2) Calibration using 40 years data and validation using 15 years data. (3) In an opposite sense, 15 years (1951-1965) were used to calibrate and 40 years (1966-2005) were used to validate. The split-sampling and cross-validation approach is a common practice in hydrological studies. It helps in reducing the risk of over-fitting the model to a period and the effects of inter-annual variation of the climate system.

The bias-corrected precipitation and temperature were compared with the observed values. After correcting for bias, the precipitation and temperature data were used to drive the Soil and Water Assessment Tool (2009) model and then simulate daily streamflow for 55 years (1951-2005). The precipitation and temperature output of the raw-RCM (without bias correction) was used to run the hydrological model. The streamflow simulated using bias-corrected variables and raw-RCM was compared with the observed streamflow. The performance of the bias correction was evaluated during the four principal seasons of India: Monsoon (June to September), post-monsoon or north-east monsoon (October to November), winter (December to February), and summer (March to May).

4.2 HYDROLOGICAL MODEL - SWAT

The Soil and Water Assessment Tool (SWAT) is a catchment scale, continuous time model operating on a daily basis (Arnold et al. 2005; Neitsch et al., 2009). For the development of the models, the required spatial database has been projected to the Universal Transverse Mercator (UTM) and WGS 1984 datum, using ArcGIS 9.3. The ASTER GDEM 2 has been used to delineate the watershed and to analyze the drainage patterns of the land surface terrain. The SCS curve number procedure was used in this study to estimate the streamflow in the SWAT model, and Hargreaves method (Hargreaves and Samani 1985) was employed to calculate the potential evapotranspiration. The Hargreaves method is a temperature based method for computing potential evapotranspiration and gives reasonable results with global validity (Allen et al. 1998). Although the Penman-Monteith method is widely used for agriculture studies (Shukla et al. 2014), it requires an extensive database, which was not available for this study. Hence, Hargreaves method was used for computing potential evapotranspiration due to its limited data requirement.

The SWAT model is adopted owing to the following reasons: (i) The work on climate change requires the model to simulate continuous processes rather than single-event and the SWAT model has demonstrated the ability to predict the variables required by the work (such as long-term sequence of flow). Other models such as Variable Infiltration Capacity (VIC), Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS), MIKE-SHE (System Hydrologique European) are more suitable for event-based studies, (ii) the SWAT model is a command line tool that uses text input and output files. The source code and executables are readily available for customization. Also, the model is available for free of cost and can be used with existing software (such as ArcGIS and MATLAB), and, (iii) adequate literature is available to understand the governing equations and parameters of the model.

The SWAT hydrological model was calibrated and validated using the observed streamflow data. The models were calibrated on a daily time step to achieve robust calibration and to avoid averaging of data errors over monthly calibration. The split-sampling approach was adopted with the available data. The guidelines on optimal Nash-Sutcliffe Efficiency (NSE) and Coefficient of determination (R^2) and their ranges for the hydrologic modeling are given by Moriasi et al. (2007). The SUFI-2 (Sequential Uncertainty Fitness version 2) algorithm was employed and the SWAT model was subjected to uncertainty analysis. The R-factor (Abbaspour 2013) was used to ascertain the degree of uncertainty and strength of calibration. The SUFI-2 algorithm was specifically selected for the present study since parameter uncertainty would account for all sources of uncertainties including uncertainty in conceptual model, measured data, driving variables (e.g., rainfall) and parameters (Abbaspour 2013).

The details of calibration and validation of the SWAT hydrological model are presented in Table 4.1. The calibration and validation are carried out using daily average flow. Fig. 4.1 compares the annual cycle of streamflow for the observed (Qobs) and simulated (Qsim) during the validation period. The minor deviations observed in the hydrographs might be introduced by the hydrological model. The NSE values across all the 9 basins ranged between 0.71 and 0.87 for the calibration period and between 0.67 and 0.87 for the validation period (Table 4.1). The NSE values indicate a good fit of the model as the calibration was done on a daily scale and represents the good quality of meteorological inputs. The R-factor for the nine catchments ranged from 0.05 to 0.37 indicating a good strength of calibration.

Table 4.1. Performance of SWAT hydrological model during calibration and validation (daily streamflow)

State	Catchment Name	Calibration Period	NSE (Calibration)	Validation Period	NSE (Validation)	R-factor
Gujarat	Purna	1971-1990	0.79	1991-2000	0.70	0.36
Maharashtra	Ulhas	1982-2000	0.73	2001-2011	0.67	0.17
	Kajvi	1992-2001	0.74	2002-2010	0.78	0.10
Karnataka	Malaprabha	1977-1990	0.87	1991-1996	0.77	0.05
	Aghanashini	1989-1996	0.84	1997-2002	0.85	0.04
	Tunga	1973-1992	0.87	1993-2000	0.87	0.07
	Netravathi	1980-1995	0.85	1991-1995	0.87	0.37
Kerala	Chaliyar	1981-1995	0.78	1996-2000	0.79	0.18
	Vamanapuram	1990-2005	0.71	2006-2011	0.83	0.05

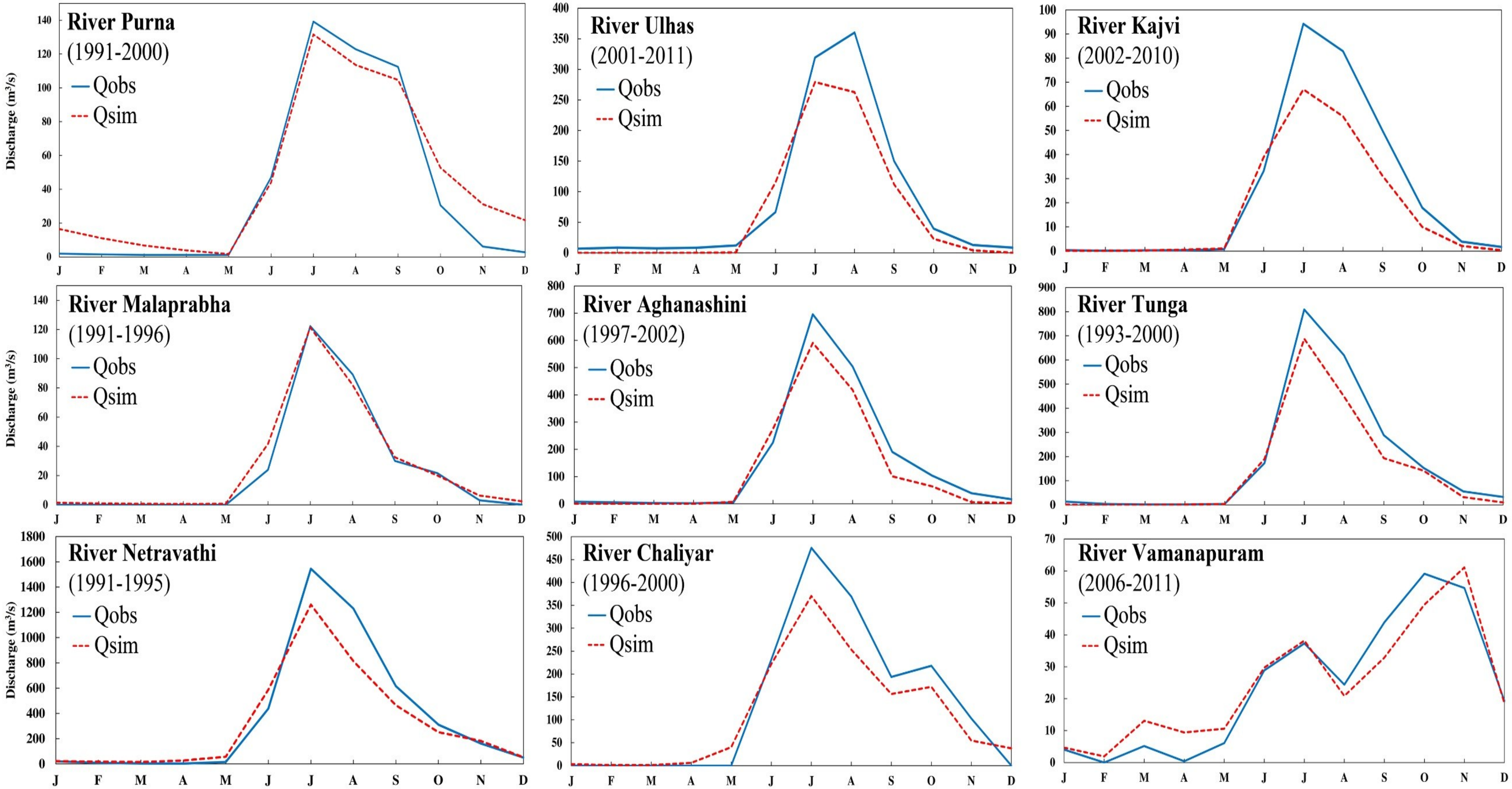

Fig. 4.1. Performance of SWAT model during validation period

4.3 RESULTS AND DISCUSSION

4.3.1 Climate Simulation

The rainfall affects the overall hydrology of the catchment and successful simulation of wet and dry days is very important in the impact studies. The factors affecting the performance could possibly be the location, topography and catchment area of the rivers. The elevation of Western Ghats of India varies and is about 2695 m above mean sea level (MSL) and the Ghats are close to the sea coast at certain locations. The bias in precipitation of the RCM was calculated for all the months and the results of monsoon months (June to September) are presented in Fig. 4.2. The results obtained across the river catchments indicate the inability of the raw-RCM in the representation of Indian southwest monsoon. The raw-RCM tends to underestimate the heavy rainfall events leading to negative values. The over-estimation in the river Vamanapuram may be because, it is one of the southernmost rivers of India and is influenced by both the south-west as well as north-east monsoons. It may be, therefore, noted that, the hydrology of a catchment is very sensitive to precipitation and a small bias could lead to large deviation in the hydrological components.

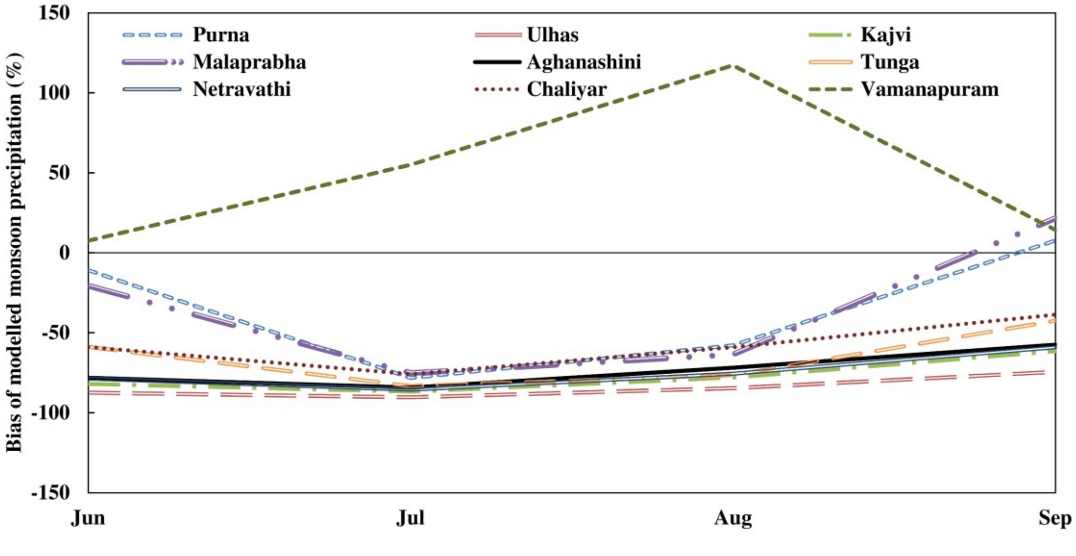

Fig. 4.2. Bias of raw-RCM precipitation during monsoon season

The absolute relative error (ARE) for precipitation is defined as |(Psim-Pobs)x100/Pobs)| of mean wet-day precipitation (precipitation intensity >2.5 mm/day). Fig. 4.3 (a) presents the boxplot of the ARE for mean wet-day precipitation (annual precipitation). The results clearly show the bias of raw-RCM precipitation upon comparison with the observed precipitation. The LS, LI, PT and DM methods did not improve the statistic of mean wet-day precipitation. The LS and LI methods apply corrections to monthly mean precipitation and tend to overestimate the wet days. The DC method corrects the frequency of wet days since the anomalies between the scenario runs are superimposed over the observed time series. The DC method improves the mean precipitation of wet days significantly. The ARE for the LS, LI, PT and DM methods were 24.78%, 24.81%, 28.30% and 28.74%, respectively. The DC method tends to perform better than other methods consistently.

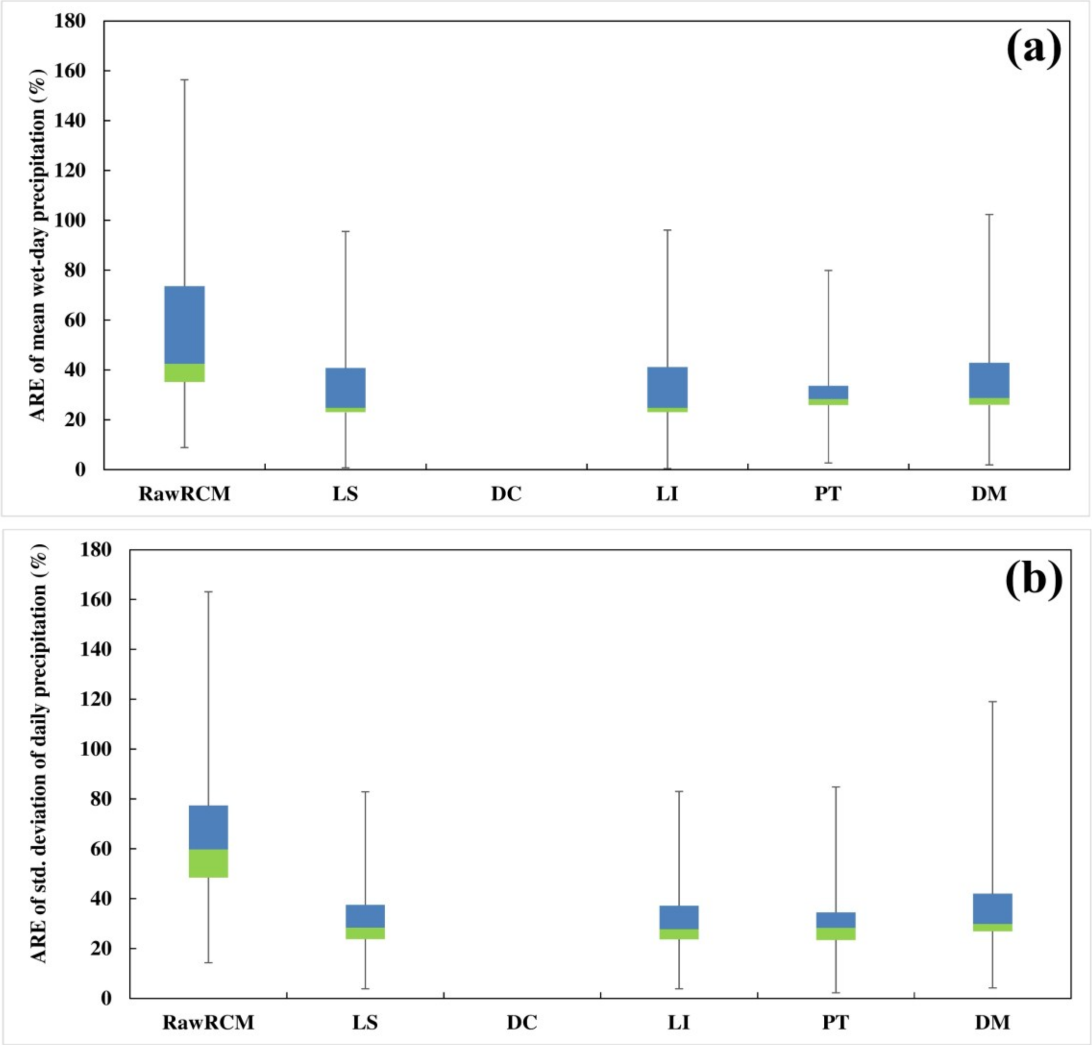

Fig. 4.3. Boxplot of the absolute relative error (ARE) for (a) mean wet-day precipitation (annual precipitation); (b) standard deviation of daily precipitation

The aim of the bias correction methods is not to correct the variance of precipitation (on a daily basis). However, the variance does get affected when mean precipitation is corrected. The ARE for the standard deviation of daily precipitation are calculated and are presented in Fig. 4.3 (b). The standard deviation of the raw-RCM was found to be biased similar to the mean precipitation. The bias correction methods corrected the standard deviation of precipitation to a certain degree. The LS, LI, PT and DM methods performed equally in the correction of standard deviation. The DC method performed the best in improving the ARE of standard deviation.

The performance evaluation metrics for observed and bias corrected daily precipitation time series are presented in Table 4.2. The DC method performed well with NSE >0.75 for Purna, Ulhas, Kajvi, Aghanashini, Netravathi, and Chaliyar catchments. The performance of the methods was poor for the remaining three catchments with NSE <0.50. This indicates that the bias correction methods which use raw-RCM anomalies for correcting the observed data perform better in the correction of standard deviation rather than the direct use of RCM simulations for future conditions. The extremes in daily precipitation are not specifically considered in the LS and LI methods. The precipitation during the monsoon (accounts for about 80% of annual precipitation) and post-monsoon (10-15% of annual precipitation) are corrected with same factors calculated for winter and summer (light precipitation). It is, therefore, observed that, heavy precipitation is not satisfactorily corrected for bias.

Table 4.2. Performance of bias correction methods in correcting daily precipitation time series

Catchment	**Raw RCM**		**LS**		**DC**		**LI**		**PT**		**DM**	
	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2
Purna	-0.09	0.01	-0.79	0.04	***0.96***	***0.98***	-0.81	0.04	-0.92	0.03	-1.03	0.02
Ulhas	0.00	0.05	-0.14	0.14	***0.95***	***0.96***	-0.15	0.13	-0.59	0.08	-0.44	0.08
Kajvi	0.01	0.08	-0.48	0.16	***0.75***	***0.92***	-0.48	0.16	-0.87	0.12	-0.56	0.13
Malaprabha	-0.27	0.02	-0.47	0.15	0.43	***0.86***	-0.52	0.14	-1.61	0.07	-2.08	0.06
Aghanashini	0.01	0.06	-0.19	0.17	***0.76***	***0.82***	-0.21	0.17	-0.51	0.13	-0.56	0.10
Tunga	-0.15	0.01	-0.64	0.16	0.44	***0.83***	-0.67	0.16	-	-	-1.75	0.09
Netravathi	-0.04	0.03	-0.07	0.21	***0.92***	***0.94***	-0.10	0.20	-0.48	0.14	-0.72	0.11
Chaliyar	-0.41	0.01	-0.27	0.13	***0.73***	***0.91***	-0.33	0.13	-1.14	0.07	-1.64	0.06
Vamanapuram	-0.96	0.00	-0.38	0.01	0.41	0.54	-0.50	0.01	-1.15	0.00	-1.67	0.00

Note: ***Bold italicized*** typeset indicates good performance

The PT method uses power function and the degree of correction depends on scaling parameter which is a function of the exponent. The exponent was estimated to be large for most of the months in this study, indicating underestimation of the coefficient of variation (CV) of observed precipitation on daily time step. The DC method performed better although, the bias in heavy precipitation is dependent on RCM. The DC method reduced the bias to a good degree and indicated the robust performance in correcting bias of daily precipitation along the Western Ghats of India.

It is interesting to figure out the reason behind the satisfactory and poor performance of bias correction methods. The precipitation in the plateau region on the leeward side is difficult to model than the precipitation on the windward side of the mountain. The rivers such as, Purna (1387 m above MSL to 9 m above MSL), Ulhas (1083 m to 4 m), Aghanashini (797 m to 0 m), Netravathi (1700 m to 0 m) and Chaliyar (2600 m to 1 m) which flow across larger elevation difference on the windward side of the Western Ghats show good performance (NSE > 0.64; $R^2 > 0.84$). Also, the catchment areas of all these rivers are greater than 850 km^2. The Malaprabha and Tunga rivers originate on the leeward side of the Western Ghats and flow in the eastern direction to join river Krishna. Although, the sizes of the Malaprabha and Tunga are 428 km^2 and 2922 km^2 respectively, the performance of the bias correction method was not satisfactory for these catchments. This may be because the RCMs are forced to work from a lower elevation to a higher elevation. Hence, the model is more appropriate to simulate orographic precipitation than the precipitation in the plateau regions (leeward side of Western Ghats).

The temperature simulated by the raw-RCM was biased compared to the observed temperature. The extent of overestimation was found to vary from 1% to 12% across the catchments investigated. In the Netravathi catchment, the RCM underestimated the temperature by 6%. The LS, DC, VS, and DM methods were used to correct the bias in the temperature datasets. The mean monthly variation of temperature and the performance of the bias correction methods across the nine catchments are presented in Fig. 4.4. It may be observed that, all the bias correction methods performed well in correcting the temporal agreement of temperature on a monthly time step. The daily temperature was evaluated and the DC method was found to be very accurate (NSE = 1) across all the nine catchments (Table 4.3). The VS and DM method performed satisfactorily for the Purna catchment and the remaining methods did not perform well. It was found that the mean monthly time series tends to conceal the bias and hence the performance of the bias correction methods on monthly time step is good. The evaluation of daily time series provides a clear picture.

Table 4.3. Performance of bias correction methods in correcting daily temperature time series

Catchment	**Raw RCM**		**LS**		**DC**		**VS**		**DM**	
	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2
Purna	0.03	0.56	0.38	0.53	***1.00***	***1.00***	***0.62***	***0.65***	***0.62***	***0.66***
Ulhas	-1.53	0.47	0.31	0.48	***1.00***	***1.00***	0.57	***0.61***	0.57	***0.61***
Kajvi	-0.60	0.33	0.09	0.37	***1.00***	***1.00***	0.41	0.49	0.42	0.49
Malaprabha	-2.41	0.36	0.16	0.39	***1.00***	***1.00***	0.44	0.51	0.44	0.51
Aghanashini	0.16	0.33	0.27	0.44	***1.00***	***1.00***	0.44	0.51	0.44	0.51
Tunga	-2.58	0.24	0.29	0.46	***1.00***	***1.00***	0.54	0.58	0.54	0.58
Netravathi	-0.56	0.35	0.31	0.46	***1.00***	***1.00***	0.42	0.51	0.42	0.50
Chaliyar	-2.40	0.26	0.32	0.48	***1.00***	***1.00***	0.57	***0.60***	0.56	***0.60***
Vamanapuram	-0.59	0.22	0.03	0.31	***1.00***	***1.00***	0.22	0.36	0.21	0.36

Bold italicized typeset indicates good performance

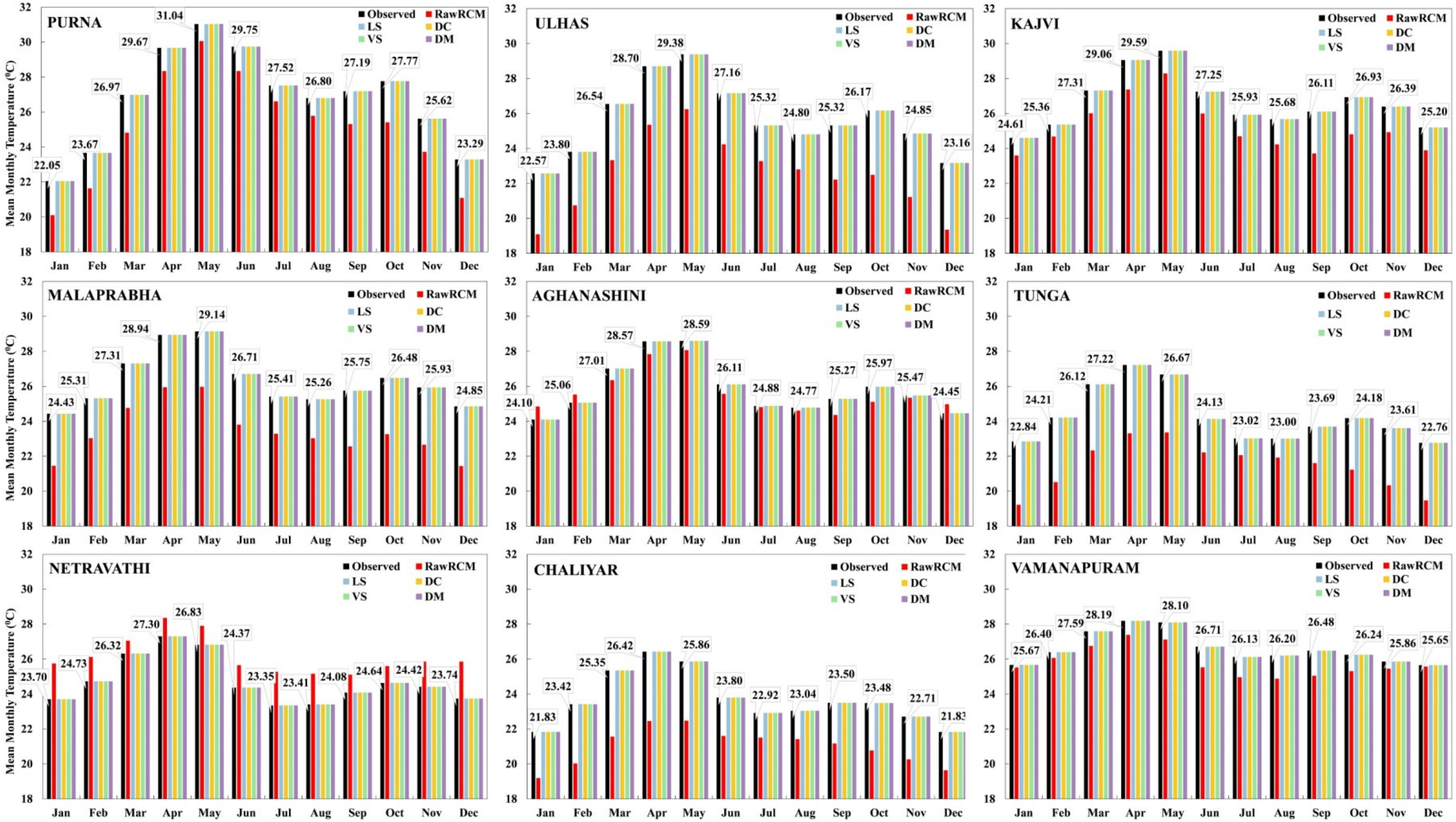

Fig. 4.4. Mean monthly temperature for the river catchments

4.3.2 Efficacy of bias correction methods in representing streamflow

The annual hydrographs for the river catchments under investigation are presented in Fig. 4.5. It may be observed that, the streamflow simulated using the raw-RCM does not accurately match with the reference streamflow of river catchments of the Western Ghats of India. Chen et al. (2013b) also reported that, the streamflow generation by raw-RCM is generally better in snow-dominated basins than in basins which have no snowfall. Particularly, the RCM could not represent the south-western monsoon (June to September) in this study. As the south-western monsoon contributes to about 80% of the total rainfall over the Western Ghats of India, it plays an important role in the hydrological impact studies. The peak discharge was underestimated significantly in all the catchments except for Chaliyar and Vamanapuram. The temporal agreement of streamflow was improved by all the bias correction methods across the Western Ghats. Reasonably good match with the reference streamflow may be seen with the use of bias-corrected climate variables. The evaluation metrics and hydrological statistics serve as better tools in assessing the differences and are described in the following sections.

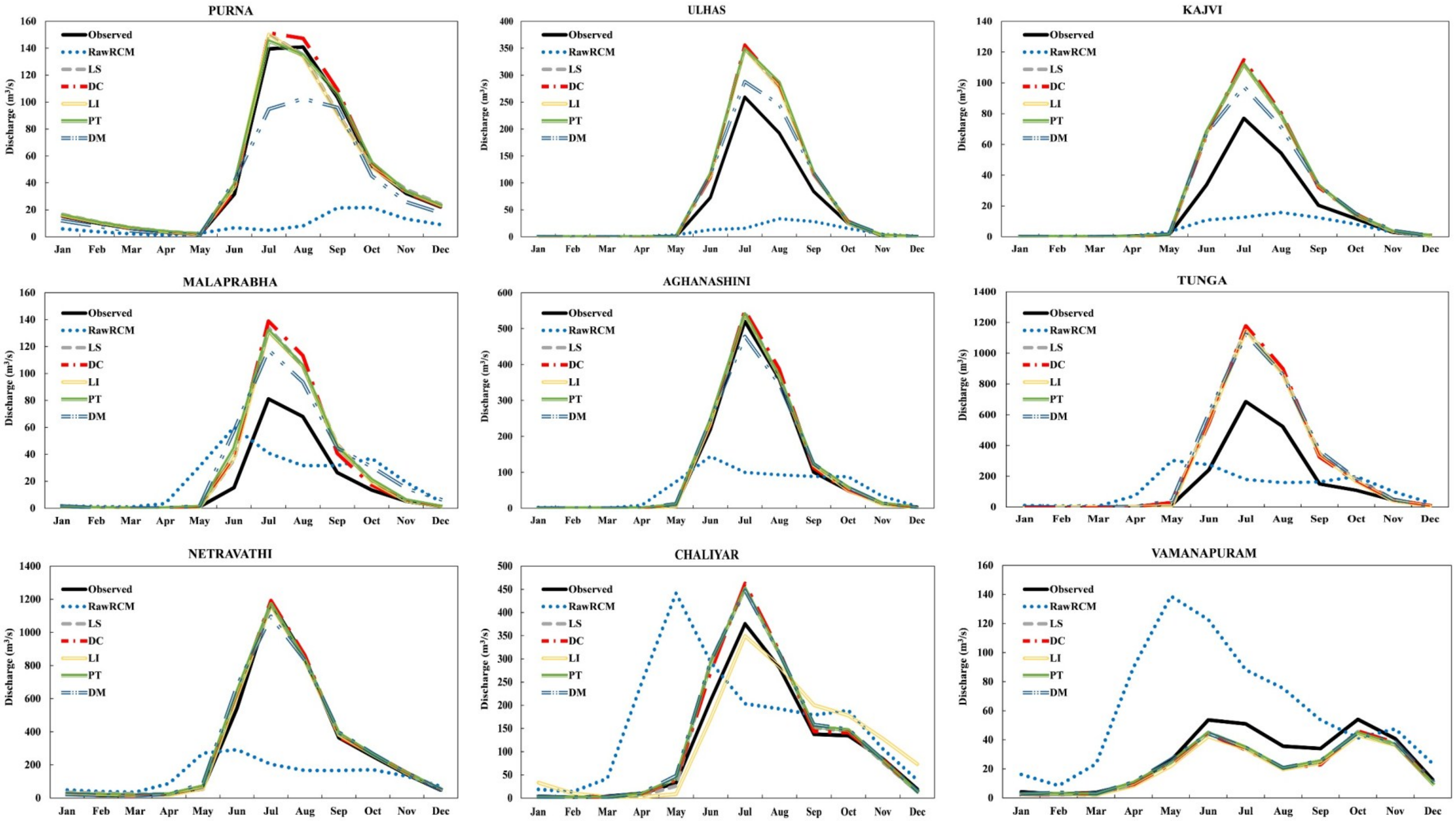

Fig. 4.5. Annual hydrographs for the river catchments

The AREs for the mean daily discharge were calculated for the simulations with and without correction of bias and are shown in Fig. 4.6. As expected, the mean discharge without bias correction (raw-RCM) is very biased with ARE of 65%. The mean discharge was improved to a small degree by all the methods. The ARE for LS and LI method was 57%, 52% for PT method, and 52% for DM method. The DC method with ARE of 44% performed better than the remaining methods. Although all the methods of bias correction differ in the way they deal with data, there is no obvious difference in the bias correction of LS, LI, PT and DM methods. The presence of outliers (especially in the DC method) is quite interesting to note and their mere presence indicates that the method may not have performed well on at least one basin.

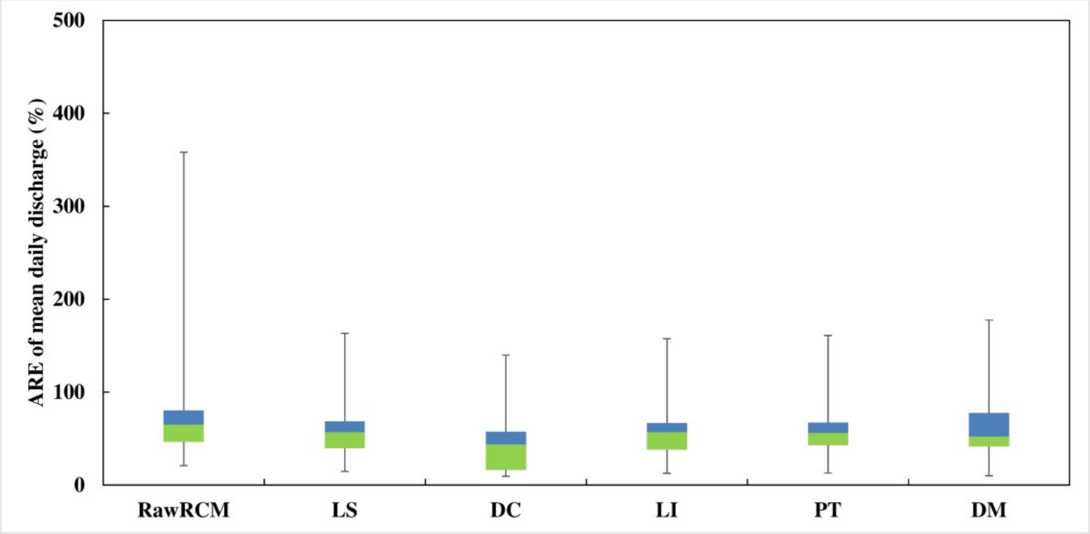

Fig. 4.6. Boxplot of the ARE of the mean daily discharge

The AREs for high flow and low flow season are presented in Fig. 4.7. During the high flow seasons (monsoon and post-monsoon), the ARE was found to be very high for the raw-RCM. The ARE was calculated to be 71% and 91% during high flow season [Fig. 4.7 (a)]. The ARE during monsoon season for LS and LI method was 68% and that for PT and DM method was 61%. The DC method significantly improved the ARE during monsoon (45%) and post-monsoon (35%). The DC method was unable to perform better during monsoon and post-monsoon seasons because of the inherent property of RCMs to underestimate Indian southwest monsoon rainfall. Fig. 4.7 (b) presents the ARE during low flow (lean season flow), i.e., winter and summer. It may be observed that, the ARE during the lean season is very large and the bias correction methods marginally reduce the error. The ARE for DC method was found to be 29% and 17% during winter and summer, respectively. The variability across river catchments is small and indicates that all the bias correction methods improve the representation of low flows. Although all the methods performed equally well, the DC method was the best compared to others.

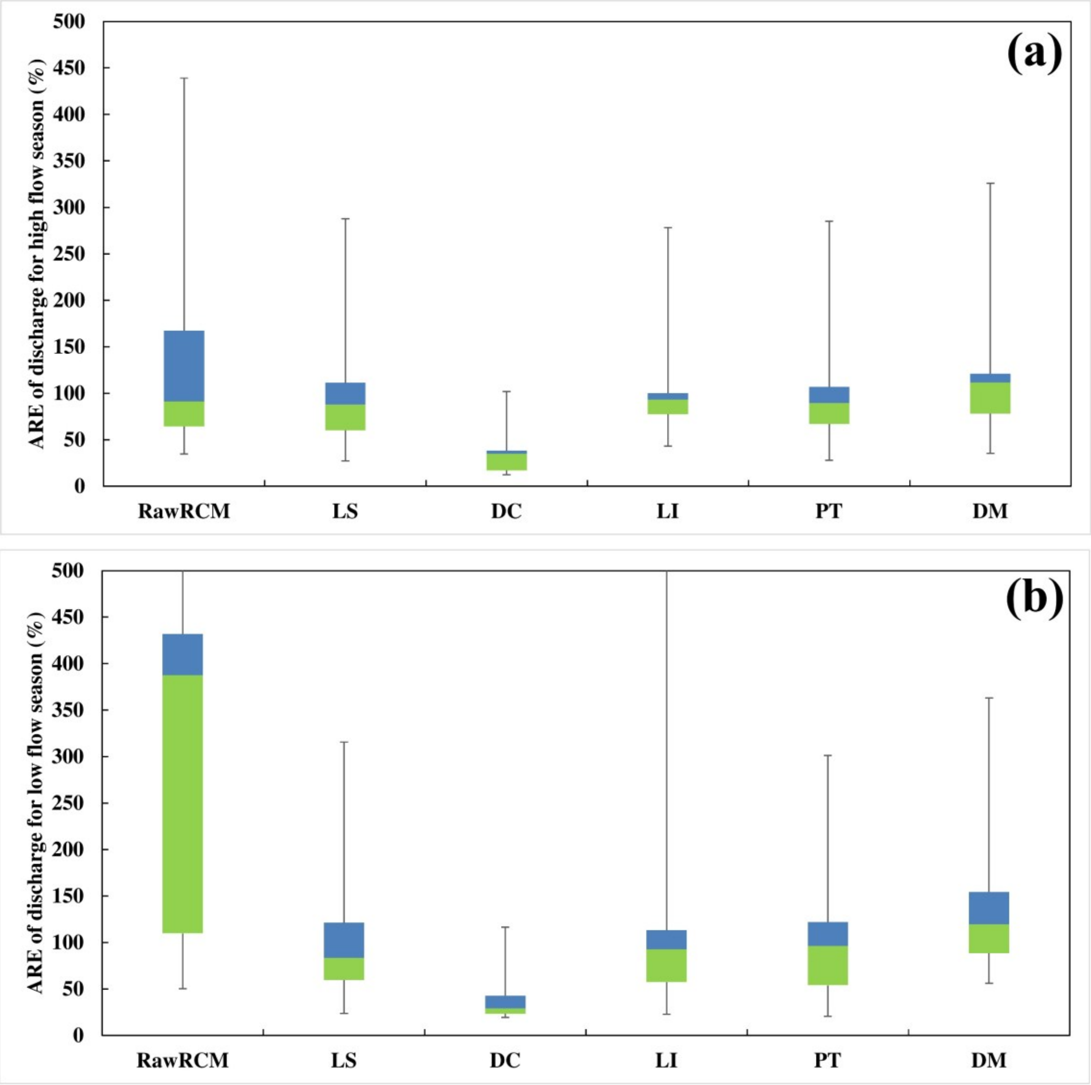

Fig. 4.7. Boxplot of the ARE of discharge for (a) high flow season; (b) low flow season

The performance evaluation metrics for daily streamflow time series across the nine river catchments is presented in Table 4.4. The NSE and R^2 between streamflow simulated by the raw-RCM and reference streamflow was not good. The study by Chen et al. (2013b) attempted to eliminate the bias of raw-RCM by calibrating the hydrological model with direct use of raw-RCM. Minor improvement in the simulation of streamflow was reported from the investigation. The direct use of raw-RCM in the SWAT hydrological model did not improve the simulation of streamflow in this study. The calibration of SWAT model using raw-RCM simulated streamflow was therefore not attempted. The LS, LI, PT, and DM methods failed to accurately represent the streamflow of the catchments in the Western Ghats.

The DC method performed well in correcting the bias of climatic variables (precipitation and temperature), and subsequently, the streamflow simulated using the DC method data performed well. It may be seen from Table 4.4 that, the streamflow using the DC method data yielded good results for five catchments. The NSE for Purna, Ulhas, Aghanashini, Netravathi, and Chaliyar were found to be 0.97, 0.64, 0.82, 0.89, and 0.90, respectively. The performance of the DC method was poor in the Kajvi and Vamanapuram catchments with NSE of 0.37 and 0.34, respectively. The DC method failed to perform in the Malaprabha and Tunga catchments. It was interesting to note that, the R^2 was very good (>0.70) in most of the catchments even when NSE was poor. This is because, the statistical goodness of fit is good, but, the bias correction methods are not capable of correcting the residual variance (noise) of the climatic variables (especially precipitation). The NSE determines the magnitude of the residual variance compared to the measured data variance. Hence, the inability of the bias correction methods in correcting the variance is highlighted in four of the catchments investigated i.e., Kajvi, Vamanapuram, Malaprabha, and Tunga.

Table 4.4. Performance of bias correction methods in correcting daily streamflow time series

Catchment	Raw RCM		LS		DC		LI		PT		DM	
	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE	R^2
Purna	-0.09	0.00	-1.02	0.01	***0.97***	***0.97***	-1.02	0.01	-0.96	0.02	-1.15	0.00
Ulhas	-0.04	0.06	-0.47	0.16	***0.64***	***0.86***	-0.47	0.16	-2.32	0.07	-0.74	0.10
Kajvi	0.03	0.14	-0.63	0.24	0.37	***0.82***	-0.63	0.24	-1.39	0.17	-0.85	0.17
Malaprabha	-0.06	0.08	-0.53	0.30	-0.19	***0.80***	-0.53	0.29	-2.06	0.16	-3.79	0.08
Aghanashini	0.05	0.09	0.13	0.26	***0.82***	***0.84***	0.12	0.26	-0.28	0.17	-0.36	0.13
Tunga	-0.02	0.03	-0.67	0.26	-0.18	***0.72***	-0.66	0.26	-	-	-2.29	0.13
Netravathi	-0.01	0.07	0.13	0.27	***0.89***	***0.90***	0.12	0.26	-0.30	0.17	-0.53	0.13
Chaliyar	-0.57	0.02	0.06	0.25	***0.90***	***0.96***	0.10	0.14	-0.54	0.14	-0.84	0.11
Vamanapuram	-1.32	0.01	-0.05	0.03	0.34	0.35	-0.08	0.03	-0.37	0.01	-0.47	0.01

Note: ***Bold italicized*** typeset indicates good performance

The bias correction methods do not work when the grid points are away from the basin/catchment. The continental circulation can be accurately modeled, whereas, the local storm paths could completely miss a watershed because the storms may occur north or south of grid points. To establish the basis of the bias correction methods, it is required to have a consistent temporal structure of the precipitation and the bias must remain constant to a certain degree. Most of the bias correction methods assume a constant bias and very few studies consider the temporal structure. The performance of bias correction methods is studied in the past by using the boundary conditions given by reanalysis data (Chen et al. 2013b; Teutschbein and Seibert 2012). When an RCM is driven by a GCM, the RCM bias is superimposed on the GCM bias at the boundary conditions. Also, the RCMs driven by GCMs tend to conceal the bias in the temporal structure. Therefore, when the rest of the bias correction methods fail to perform for the Western Ghats of India, the delta change method of bias correction performs very well.

4.4 CLOSURE

The performance evaluations of bias correction methods applied for precipitation (LS, DC, LI, PT, and DM) and temperature (LS, DC, VS, and DM) were carried out. The climatic variables (precipitation and temperature) simulated by the RCM are always biased and cannot be directly forced on hydrological models. The importance of correcting the frequency of wet days plays a major role in the projection of climate and the selection of appropriate bias correction method. The distribution based methods may not always be superior to the mean-based methods in hydrological simulations and projecting climate. The bias correction methods may not hold good when the climate models inaccurately reproduce the temporal structure of climatic variables. This is particularly true, when the bias correction is on a daily time step. It was found that, the delta change method is best suited for correction of RCM bias in the river catchments of the Western Ghats of India.

CHAPTER 5

TREND ANALYSIS OF HYDRO-METEOROLOGICAL VARIABLES

5.1 INTRODUCTION

Climate is the pattern of variation in temperature, humidity, atmospheric pressure, wind, precipitation, atmospheric particle count and other meteorological variables in a given region over a relatively longer period. The agriculture and allied sectors of India are critically dependent on the timely availability of sufficient rainfall. The changes in temperature affect the hydrological processes and climate change potentially influences the pattern of long-term rainfall. The changes in pattern of long-term rainfall causes a disparity in the supply and demand for water. These analyses are quite essential in light of managing the water resources in a region and the related hydro-infrastructure which are designed on the assumption of stationarity in climate. The changes to the rainfall due to climate change are bound to influence the streamflow patterns and necessitate the review of management practices in hydrology. The trend analysis of hydro-meteorological variables helps in the estimation of availability of water resources in the context of future water management. The meteorological variables such as the precipitation and temperature often exhibit seasonality due to the periodicity of weather. In the Western Ghats of India, this is due to the seasonal variation of temperature and precipitation along with the evapo-transpiration. The methods adopted to evaluate the trends, therefore, are required to consider the seasonality. This chapter presents the trend analysis of hydro-meteorological parameters (rainfall, temperature, potential evapo-transpiration, and streamflow) for river catchments of the Western Ghats of India.

The variability of rainfall owing to climate change has gained attention from researchers across the world (Babar and Ramesh 2014; Wagesho et al., 2013; Opiyo et al., 2014; Jain et al., 2017). Several efforts are being made to predict the changes in spatio-temporal variability of rainfall in light of climate change (Tabari et al., 2011). The tropical regions of the Western Ghats demonstrate the spatio-temporal variability of rainfall based on the intensity and size of the storm, which varies at the local scale. The convective rainfall is an important component of the tropical weather system and contributes to seasonal and spatial variability (Conway 2000; Tabari et al., 2015). The rainfall-runoff relationship such as the intensity of streamflow, time to peak and volume is solely dependent on the dynamic behavior of rainfall.

The detection of the trend can be carried out using either parametric or non-parametric tests. The linear trend in the parametric tests analyze whether the slope coefficient of linear regression varies significantly from zero and the sign of the slope coefficient determines a positive or negative trend. The hydro-meteorological time series are frequently encountered with non-normally distributed, censored, and missing data, making them more suitable for non-parametric methods as they are distribution free (Salas, 1993; Hirsch et al. 1992). Incorrect results leading to invalid inferences could be obtained with the use of parametric methods when the data is not normally distributed (MathSoft 1999). Several non-parametric methods are available for the trend detection of meteorological variables such as the Spearman's rank correlation test (Yue and Wang 2002), wavelet based trend analysis (Antoniadis et al. 1994; Craigmile et al. 2004), Locally Weighted Scatterplot Smoothing (LOWESS) (Champely and Doledec 1997) and seasonal Kendall test (Hirsch et al., 1982). The best non-parametric approach for trend detection is the Mann-Kendall test (WMO, 1988).

In this study, the modified Mann-Kendall trend test (Mann-Kendall test with pre-whitening of time series) is used for rectifying serially correlated data with 95% confidence interval. The magnitude of the trend in the annual and seasonal series is estimated using the Sen's slope estimator (Sen 1968). The Sen's slope estimator is a non-parametric approach and gives a robust estimate of the magnitude of a monotonic trend. The change in the mean of the sample over observation period is determined with an assumption of the trend to be linear. The average changes over a region give an estimate of the magnitude of the trend (Hirsch et al., 1982; Hirsch and Slack, 1984; Gan, 1998; Lettenmaier et al., 1994; Zhang et al., 2000; Yue et al., 2003). The Sen's slope estimator is a widely used tool in quantifying trend in hydro-meteorological time series (Lettenmaier et al., 1994; Yue and Hashino, 2003; Yunling and Yiping, 2005; Partal and Kahya, 2006; ElNesr et al., 2010; Tabari and Marofi, 2011; Tabari et al., 2011a). The details of the modified Mann-Kendall trend test are given in Hamed and Rao (1998).

5.2 METHODOLOGY

The IMD gridded data on daily rainfall and temperature were used to evaluate the historical trend of meteorological variables and the RCP 4.5 data was used to predict the trend of meteorological variables in the future. The trend analysis was carried out for two scenarios, i.e., trend analysis of historical daily rainfall, temperature, potential evapo-transpiration, streamflow data on an annual and seasonal basis for the period 1951 to 2005 (scenario 1) and the annual and seasonal trend analysis of RCP 4.5 forecasted hydro-meteorological variables for the period 2006 to 2060 (scenario 2). The magnitude of the trend was estimated using Sen’s Slope estimator. The trends were detected at 0.1% (extremely significant), 1% (significant), 5% and 10% significance levels. The annual and seasonal variations of rainfall and temperature for each station/grid point were computed with respect to the mean and the variations were plotted over time. The trend was examined by fitting linear regression line and slope of the simple least-square regression gave the rate of change of parameters. The trend analysis was carried out for the four principal seasons of India: Monsoon (June to September), post-monsoon or north-east monsoon (October to November), winter (December to February), and summer (March to May).

5.3 RESULTS AND DISCUSSION

5.3.1 Trend analysis of rainfall

The nine selected rivers originating from the Western Ghats of India were categorized as northern rivers (river Purna, Ulhas, and Kajvi), central (river Malaprabha, Aghanashini, and Tunga), and southern rivers (river Netravathi, Chaliyar, and Vamanapuram) based on their location in the Western Ghats. The temporal variation of rainfall was assessed using the annual rainfall and the standardized rainfall anomalies were plotted for the nine river catchments. The standardized rainfall anomaly provides a picture of how rainfall varies with respect to normal. A prolonged period of wet years (rainfall above normal) depicts flood and that of prolonged dry season depicts drought condition.

The standardized rainfall anomaly representing the inter-annual variation of annual rainfall for the northern rivers of the Western Ghats is presented in Fig. 5.1 (a). The river Purna did not portray significant inter-annual variation in the rainfall during Scenario 1 and 2. The observation was supported by the results of the modified Mann-Kendall trend test (Table 5.1).

The results indicated no trend in the annual rainfall during Scenario 1 and 2. In the river Ulhas, an increase in the annual rainfall was observed during Scenario 1 [Fig. 5.1 (b)]. The results of the trend test indicated an increase in annual rainfall by 3.96% (92 mm) per decade at 5% significance level (Table 5.1). It may be noted that, this increase in the annual rainfall was entirely contributed by the monsoon months, which recorded a 4% increase at the same significance level as of annual rainfall (5% significance level). Although standardized rainfall anomaly of river Ulhas indicated a slightly increasing trend of rainfall in Scenario 2, the increase was not statistically significant at the four tested levels. The rainfall anomaly for scenario 1 and 2 in the river Kajvi [Fig. 5.1 (c)] suggested lesser rainfall than normal. However, the changes in the rainfall were not statistically significant. The results indicate that, the rainfall variation over the rivers in the northern region of the Western Ghats is not very high. The amount of rainfall received by the rivers in the present time may be reasonably assumed for the future as well. It may, however, be noted that, these predicted changes do not consider the localized events such as heavy rainfall due to depressions in the Arabian Sea.

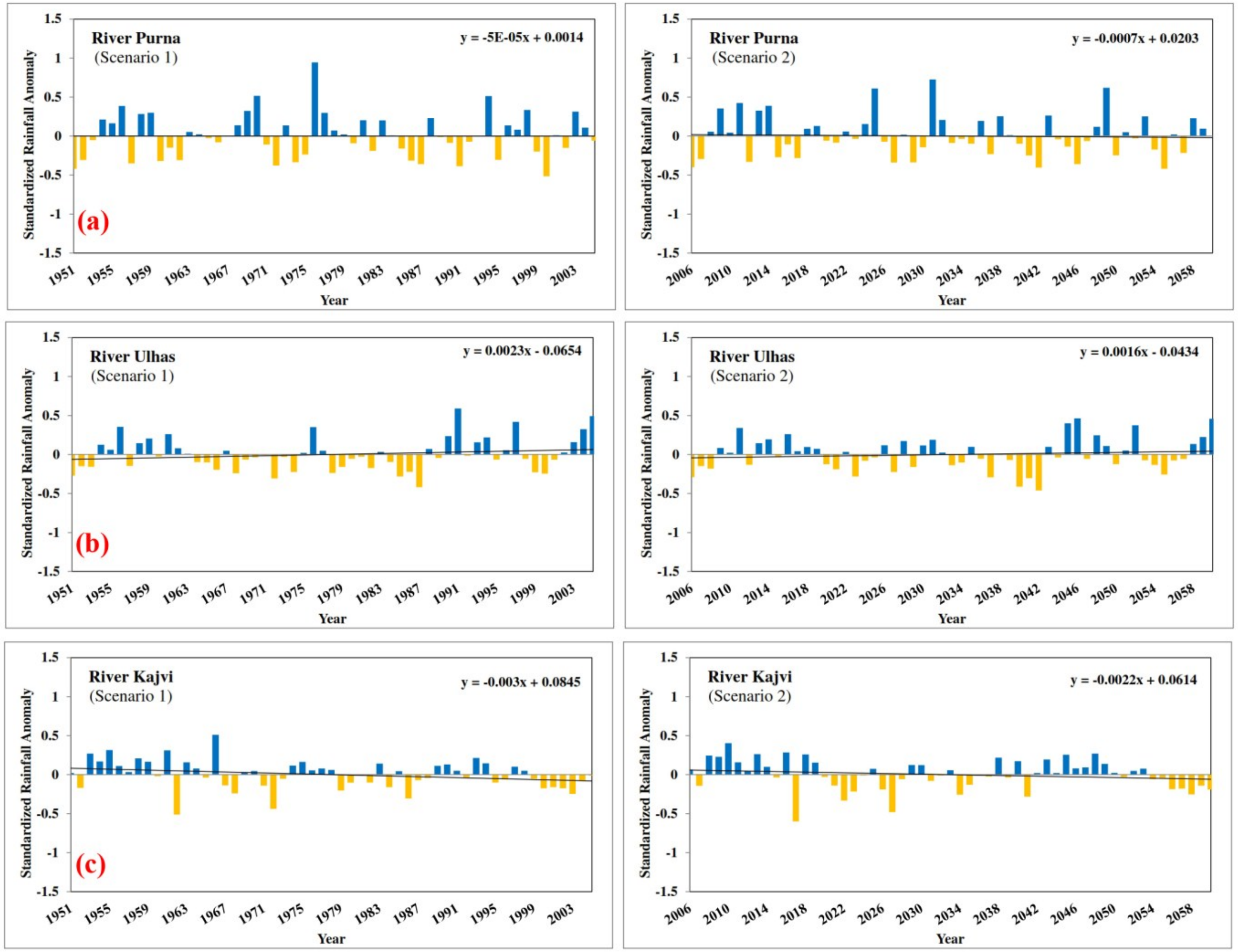

Fig 5.1. Standardized rainfall anomaly over northern catchments of the Western Ghats

Table 5.1. Trend analysis of rainfall over northern catchments of the Western Ghats

Scenario	Rainfall time series	Mean Rainfall (mm)	Statistic value	Sen's Slope Estimator (mm/decade)	Trend
			Purna River		
Scenario 1 1951-2005	Annual	1445	-0.15	4.84	No trend
	Monsoon	1371(94.85)	0.01	0.40	No trend
	Post-monsoon	60 (4.15)	0.23	0.63	No trend
	Winter	04 (0.30)	-0.35	0.00	No trend
	Summer	**10 (0.70)**	**-2.66[c]**	**1.10 (0.07)**	**Decreasing**
Scenario 2 2006-2060	Annual	1638	-0.22	9.87	No trend
	Monsoon	1546(94.38)	-0.17	7.04	No trend
	Post-monsoon	68 (4.20)	0.33	0.58	No trend
	Winter	06 (0.41)	0.17	0.00	No trend
	Summer	16 (1.01)	-1.86[a]	1.40	Decreasing
			Ulhas River		
Scenario 1 1951-2005	**Annual**	**2316**	**2.28[b]**	**91.75 (3.96)**	**Increasing**
	Monsoon	**2182(94.23)**	**2.30[b]**	**95.84 (4.13)**	**Increasing**
	Post-monsoon	106 (4.60)	0.52	2.52	No trend
	Winter	04 (0.17)	-	-	No trend
	Summer	**23 (0.99)**	**-2.77[c]**	**2.82 (0.12)**	**Decreasing**
Scenario 2 2006-2060	Annual	2683	0.58	32.21	No trend
	Monsoon	2521(93.95)	0.71	34.11	No trend
	Post-monsoon	128 (4.78)	-0.45	4.36	No trend
	Winter	5 (0.20)	-	-	No trend
	Summer	**29 (1.07)**	**-3.06[c]**	**4.27 (0.16)**	**Decreasing**
			Kajvi River		
Scenario 1 1951-2005	Annual	2611	-0.87	26.53	No trend
	Monsoon	2385(91.34)	-0.68	23.28	No trend
	Post-monsoon	161(6.17)	-1.10	6.12	No trend
	Winter	7 (0.27)	-	-	No trend
	Summer	58 (2.22)	-1.76[a]	4.71 (0.18)	Decreasing
Scenario 2 2006-2060	Annual	3785	-1.76[a]	106.14 (2.80)	Decreasing
	Monsoon	3512(92.79)	-1.73[a]	99.31 (2.61)	Decreasing
	Post-monsoon	205 (5.42)	-0.97	10.00	No trend
	Winter	10 (0.26)	-	-	No trend
	Summer	58 (1.53)	-1.45	-2.24	No trend

Note: Bold indicates statistically significant values;
[a] 10% significance level; [b] 5% significance level; [c] 1% significance level.
Values in parenthesis denote percentage of annual rainfall.

In the central portion of the Western Ghats, upper river catchments (river Malaprabha and Aghanashini) were observed to have an increase in the annual rainfall whereas the lower catchment (River Tunga), indicated decreased annual rainfall. The Malaprabha catchment revealed an increase in the annual rainfall during Scenario 1 and 2 [Fig. 5.2 (a)]. The monsoon season witnessed a 4% increase (at 5% significance level) in rainfall, but the increase did not contribute to the increase in annual rainfall during scenario 1 since the rainfall during summer season decreased at about 15 mm per decade (at 0.1% significance level). An increase at the rate of 31.50 mm per decade (i.e., 1.35% of annual rainfall) at 0.1% significance level (extremely significant) was observed in Scenario 2 (Table 5.2).

In the river Aghanashini [Fig. 5.2 (b)], statistically significant increase in the annual rainfall was observed during Scenario 1. The increase was estimated to be 3.30% per decade (i.e., 115 mm per decade) at 1% significance level. The increase in annual rainfall was contributed by the monsoon season, which increased at 3.45% per decade (1% significance level). No changes in the mean of annual rainfall were observed during Scenario 2. In the river Tunga, no change was observed during Scenario 1 [Fig. 5.2 (c)]. The river Tunga is an east flowing river that joins the river Bhadra and forms the Tungabhadra River. The Scenario 2 was observed to have prolonged dry years after the year 2030. The decrease in rainfall was estimated to 264 mm per decade (7% of annual rainfall per decade) at 1% significance level. This is because the contribution from monsoon season and summer season are expected to reduce by 7% (1% significance level) and 0.50% (5% significance level), respectively.

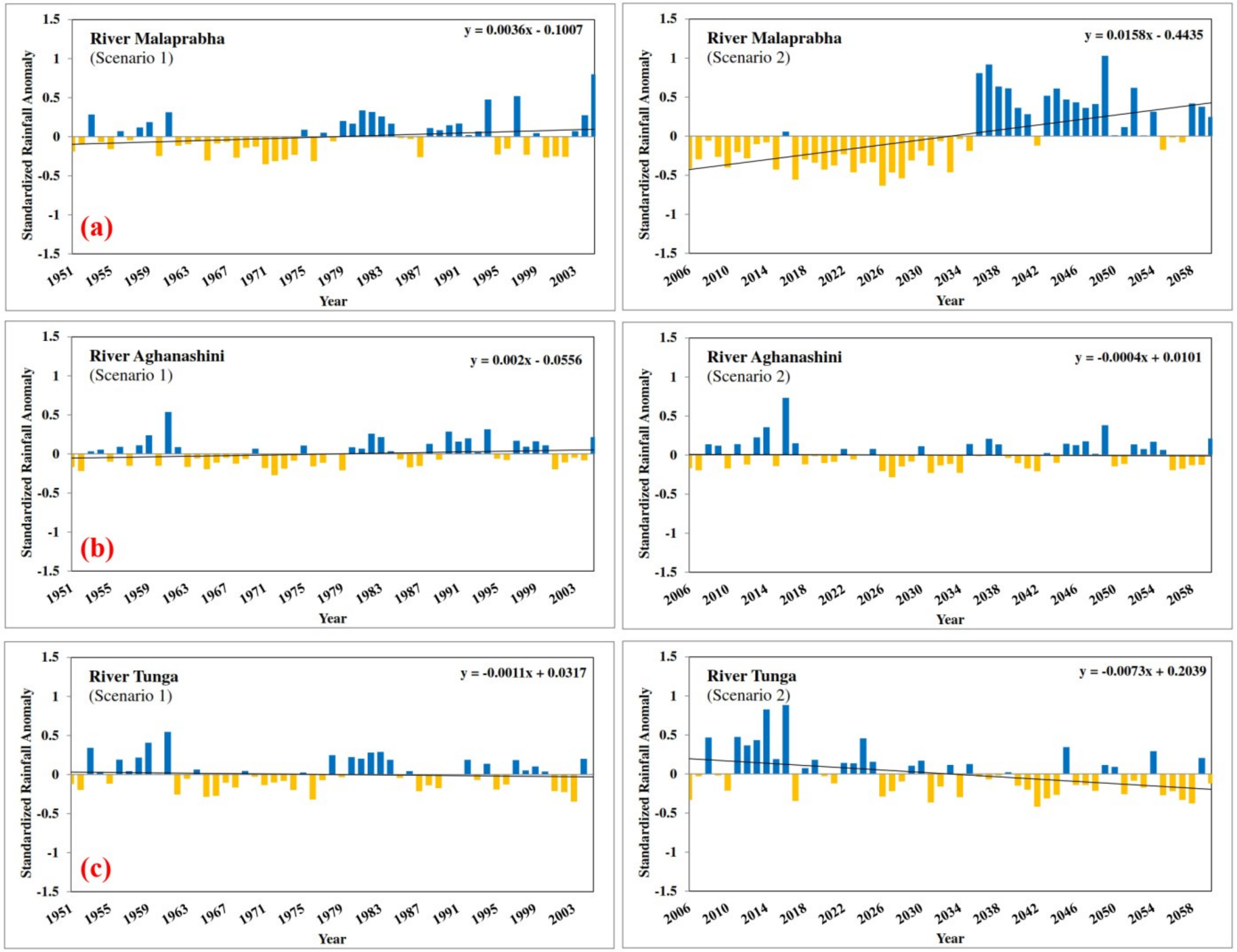

Fig. 5.2. Standardized rainfall anomaly over central catchments of the Western Ghats

Table 5.2. Trend analysis of rainfall over central catchments of the Western Ghats

Scenario	Rainfall time series	Mean Rainfall (mm)	Statistic value	Sen's Slope Estimator (mm/decade)	Trend
Malaprabha River					
Scenario 1	Annual	1899	1.26	53.57	No trend
1951-2005	**Monsoon**	**1621(85.36)**	**2.16**^{b}	**75.82 (3.99)**	**Increasing**
	Post-monsoon	158 (8.34)	-1.60	10.75	No trend
	Winter	7 (0.35)	-	-	No trend
	Summer	**113 (5.95)**	**-3.48**^{d}	**14.75 (0.77)**	**Decreasing**
Scenario 2	**Annual**	**2317**	**3.46**^{d}	**31.44 (1.35)**	**Increasing**
2006-2060	**Monsoon**	**1975(85.25)**	**3.44**^{d}	**31.01 (1.33)**	**Increasing**
	Post-monsoon	179 (7.73)	1.44	0.95	No trend
	Winter	14 (0.60)	-	-	No trend
	Summer	149 (6.43)	-0.75	-0.55	No trend
Aghanashini River					
Scenario 1	**Annual**	**3471**	**2.93**^{c}	**114.70 (3.30)**	**Increasing**
1951-2005	**Monsoon**	**3137(90.37)**	**3.08**^{c}	**119.76 (3.45)**	**Increasing**
	Post-monsoon	204 (5.87)	0.56	3.66	No trend
	Winter	11 (0.31)	1.33	0.10	No trend
	Summer	120 (3.45)	-1.28	6.73	No trend
Scenario 2	Annual	3479	0.29	12.62	No trend
2006-2060	Monsoon	3128(89.91)	0.42	20.52	No trend
	Post-monsoon	206 (5.91)	0.30	3.16	No trend
	Winter	14 (0.41)	0.95	0.03	No trend
	Summer	131 (3.77)	-1.68^a	12.76 (0.37)	Decreasing
Tunga River					
Scenario 1	Annual	2188	0.18	3.00	No trend
1951-2005	Monsoon	1791(81.89)	-0.08	2.35	No trend
	Post-monsoon	222 (10.16)	0.06	0.54	No trend
	Winter	15 (0.66)	1.02	0.51	No trend
	Summer	159 (7.28)	-1.61	8.39	No trend
Scenario 2	**Annual**	**3745**	**-2.95**^{c}	**263.68 (7.04)**	**Decreasing**
2006-2060	**Monsoon**	**3280(87.59)**	**-2.83**^{c}	**271.91 (7.26)**	**Decreasing**
	Post-monsoon	275 (7.35)	0.36	3.47	No trend
	Winter	17 (0.45)	1.03	0.51	No trend
	Summer	**173 (4.61)**	**-2.08**^{b}	**15.46 (0.41)**	**Decreasing**

Note: Bold indicates statistically significant values.

^{a} 10% significance level; ^{b} 5% significance level; ^{c} 1% significance level; ^{d}0.1% significance level.

Values in parenthesis denote percentage of annual rainfall.

The river catchments in the southern portion of the Western Ghats (river Netravathi, Chaliyar, and Vamanapuram) were observed to have a decreasing trend of annual rainfall all through Scenario 1 and 2 (Fig. 5.3). The results of the modified Mann-Kendall trend test are presented in Table 5.3. The decrease in the annual rainfall over the Netravathi catchment during Scenario 1 was observed to be 88 mm per decade (which accounts for 3% of the annual rainfall per decade) at a statistical significance level of 5%. It was observed that, the rainfall during monsoon season decreased at the rate of 3% per decade (5% significance level) and 17 mm per decade (10% significance level) during the summer season. Although the scenario 2 was also observed to have a decreasing trend, especially, during summer (2 mm per decade at 10% significance level), the decrease in annual rainfall was not statistically significant [Fig. 5.3 (a)].

The river Chaliyar portrayed a decrease of 66 mm per decade at 10% significance level in scenario 1 [Fig. 5.3 (b)]. The decrease in the annual rainfall was contributed by the monsoon months that portrayed a decrease of 52 mm per decade (at 10% significance level). The scenario 2 was seen to have a decrease by as much as 7% of annual rainfall per decade (224 mm per decade) at 1% significance level. The contributing seasons to the decrease were the monsoon (205 mm per decade at 1% significance level) and summer (16 mm per decade at 5% significance level). The annual rainfall over the river Vamanapuram [Fig. 5.3 (c)] also decreased at the rate of 76 mm per decade at 1% significance level. The rainfall during the monsoon season and the summer showers witnessed decrease at the rate of 52 mm per decade (1% significance level) at 20 mm per decade (5% significance level), respectively. The scenario 2 also witnessed a decrease in annual rainfall and monsoon rainfall at 70 mm per decade and 57 mm per decade (at 10% significance level), respectively.

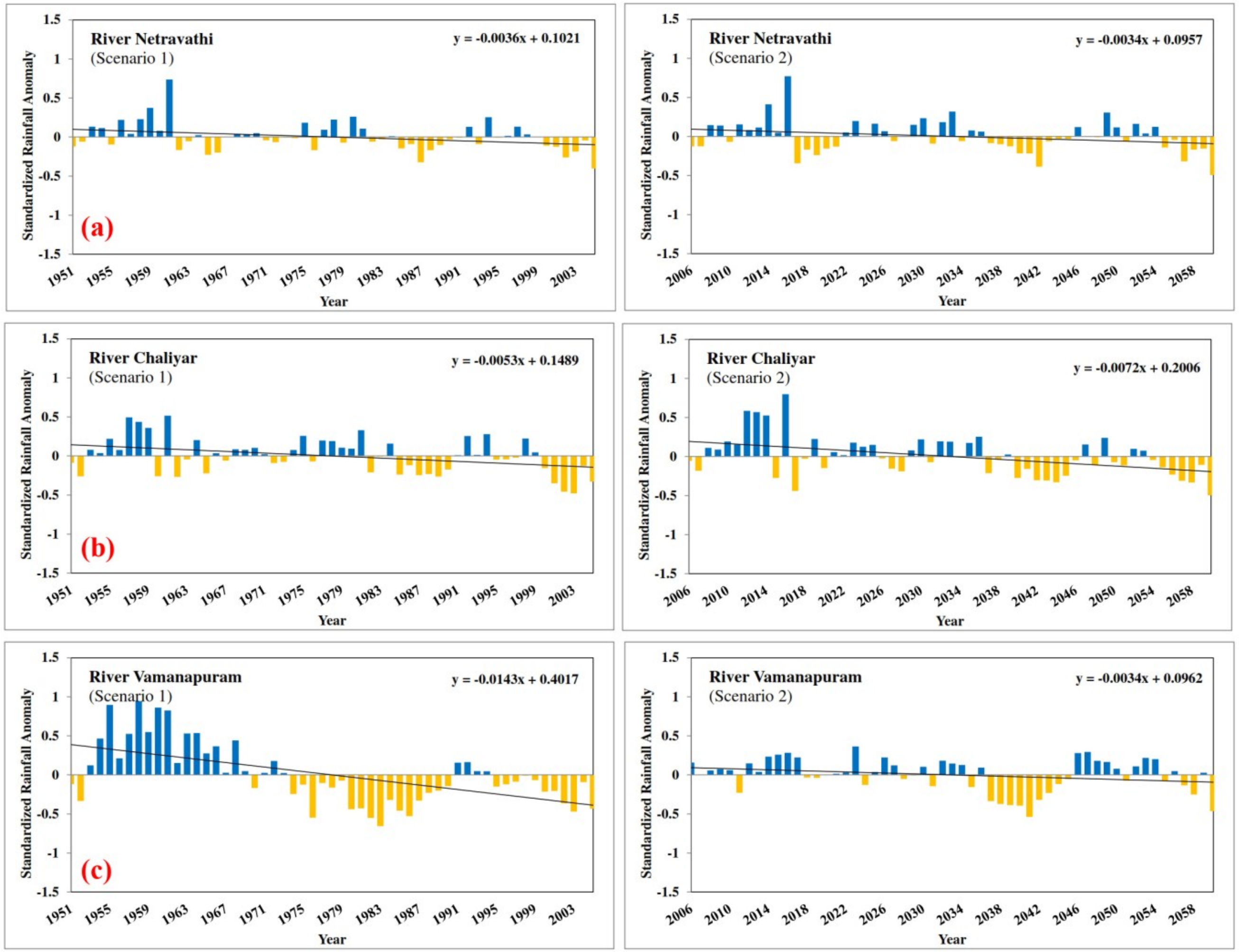

Fig. 5.3. Standardized rainfall anomaly over southern catchments of the Western Ghats

Table 5.3. Trend analysis of rainfall over southern catchments of the Western Ghats

Scenario	Rainfall time series	Mean Rainfall (mm)	Statistic value	Sen's Slope Estimator (mm/decade)	Trend
		Netravathi River			
Scenario 1	**Annual**	**3095**	**-2.06^{b}**	**87.82 (2.83)**	**Decreasing**
1951-2005	**Monsoon**	**2558(82.64)**	**-2.18^{b}**	**99.87 (3.22)**	**Decreasing**
	Post-monsoon	303 (9.78)	0.75	6.01	No trend
	Winter	19 (0.61)	0.57	0.63	No trend
	Summer	216 (6.97)	-1.73^{a}	17.09 (0.54)	Decreasing
Scenario 2	Annual	4366	-1.13	7.29	No trend
2006-2060	Monsoon	3866(88.55)	-1.10	5.36	No trend
	Post-monsoon	204 (4.68)	-0.81	0.44	No trend
	Winter	2 (0.04)	0.07	0.00	No trend
	Summer	294 (6.73)	-1.78^{a}	2.13 (0.04)	Decreasing
		Chaliyar River			
Scenario 1	Annual	2200	-1.83^{a}	65.63 (2.98)	Decreasing
1951-2005	Monsoon	1527(69.41)	-1.76^{a}	52.01 (2.36)	Decreasing
	Post-monsoon	390 (17.73)	-0.05	0.77	No trend
	Winter	60 (2.72)	-1.02	2.69	No trend
	Summer	223 (10.14)	-1.36	9.41	No trend
Scenario 2	**Annual**	**3324**	**-3.22^{c}**	**223.68 (6.79)**	**Decreasing**
2006-2060	**Monsoon**	**2561(77.03)**	**-3.15^{c}**	**205.02 (6.16)**	**Decreasing**
	Post-monsoon	458 (13.77)	0.07	1.17	No trend
	Winter	46 (1.37)	-0.36	0.82	No trend
	Summer	**260 (7.83)**	**-1.99^{b}**	**15.95 (0.47)**	**Decreasing**
		Vamanapuram River			
Scenario 1	**Annual**	**1746**	**-2.66^{c}**	**75.53 (4.32)**	**Decreasing**
1951-2005	**Monsoon**	**764 (43.78)**	**-2.98^{c}**	**51.95 (2.97)**	**Decreasing**
	Post-monsoon	502 (28.76)	-0.33	3.67	No trend
	Winter	139 (7.97)	-0.15	0.73	No trend
	Summer	**340 (19.49)**	**-2.23^{b}**	**19.69 (1.12)**	**Decreasing**
Scenario 2	Annual	2272	-1.81^{a}	69.91 (3.08)	Decreasing
2006-2060	Monsoon	1097(48.27)	-1.86^{a}	56.65 (2.49)	Decreasing
	Post-monsoon	601 (26.47)	0.25	4.01	No trend
	Winter	146 (6.43)	-0.26	2.04	No trend
	Summer	428 (18.83)	-1.77^{a}	25.19 (1.10)	Decreasing

Note: Bold indicates statistically significant values.

^{a} 10% significance level; ^{b} 5% significance level; ^{c} 1% significance level.

Values in parenthesis denote percentage of annual rainfall.

The Vamanapuram River in the southern part of the Western Ghats has the influence of south-west as well as north-east monsoons. About 44% of the total rainfall in the catchment is contributed by the south-west monsoon (June to September) and 29% of the rainfall is contributed by the north-east monsoon (October to November). The signals of climate change indicate a weakening of south-west monsoon, especially in central and southern parts of the Western Ghats of India. The number of rainy days (rainfall >2.5mm/day) in the Purna, Tunga, Netravathi, Vamanapuram river catchments was found to be 84, 142, 160, and 149 days, respectively (for scenario 1). This leads to the inference that, the central and southern portions of the Western Ghats receive more events of rainfall, but the intensity of rainfall is decreasing over time.

5.3.2 Trend analysis of temperature

The trend analysis of temperature was carried out on an annual and seasonal basis. The Scenario 1 represents the historical period from 1951 to 2005 and the scenario 2 represents the forecasted period from 2006 to 2060. The change points were detected using the Pettitt's test. Table 5.4 presents the results of trend analysis for northern river catchments of the Western Ghats of India. The annual temperature over the Purna catchment did not portray significant changes in the annual and seasonal mean temperature during scenario 1 and 2. The annual, monsoon and post-monsoon temperature in the Ulhas River catchment were found to increase at the rate of 0.05, 0.06 and 0.1°C per decade (at 5% significance level) during scenario 1. During scenario 2, annual and monsoon temperature was found to increase at 0.03°C per decade (10% significance level) and 0.06°C (5% significance level), respectively. In the Kajvi river catchment, the annual temperature during scenario 1 and 2 was found to increase at the rate of 0.07°C and 0.08°C (0.1% significance level), respectively. The average temperature during all the seasons was found to be increasing in the Kajvi river catchment. The regime shift of mean annual temperature during scenario 1 and 2 is presented in Fig 5.4.

Table 5.4. Trend analysis of temperature over northern catchments of the Western Ghats

River	Temperature time series	Mean Temp (°C)	Statistic value	Sen's Slope Estimator (°C/decade)	Trend
Purna River					
Scenario 1 1951-2005	Annual	26.85	0.90	0.02	No trend
	Monsoon	28.08	1.21	0.03	No trend
	Post-monsoon	26.50	1.32	0.07	No trend
	Winter	22.49	0.06	0.00	No trend
	Summer	29.74	0.64	0.02	No trend
Scenario 2 2006-2060	Annual	28.45	-0.35	0.01	No trend
	Monsoon	29.15	0.70	0.02	No trend
	Post-monsoon	27.61	0.70	0.05	No trend
	Winter	24.61	-0.91	0.05	No trend
	Summer	31.89	-0.55	0.02	No trend
Ulhas River					
Scenario 1 1951-2005	**Annual**	**25.89**	**2.57**^{b}	**0.05**	**Increasing**
	Monsoon	**26.14**	**2.29**^{b}	**0.06**	**Increasing**
	Post-monsoon	**25.72**	**2.00**^{b}	**0.10**	**Increasing**
	Winter	23.10	0.66	0.02	No trend
	Summer	28.42	1.33	0.05	No trend
Scenario 2 2006-2060	Annual	27.58	1.77^{a}	0.03	Increasing
	Monsoon	**27.56**	**2.18**^{b}	**0.06**	**Increasing**
	Post-monsoon	27.24	1.50	0.10	No trend
	Winter	25.22	-0.22	0.01	No trend
	Summer	30.18	0.32	0.01	No trend
Kajvi River					
Scenario 1 1951-2005	**Annual**	**26.13**	**3.96**^{d}	**0.07**	**Increasing**
	Monsoon	**25.71**	**3.26**^{c}	**0.08**	**Increasing**
	Post-monsoon	**26.07**	**2.63**^{c}	**0.12**	**Increasing**
	Winter	**24.41**	**2.16**^{b}	**0.06**	**Increasing**
	Summer	**28.45**	**2.24**^{b}	**0.06**	**Increasing**
Scenario 2 2006-2060	**Annual**	**28.31**	**3.51**^{d}	**0.08**	**Increasing**
	Monsoon	**27.71**	**3.43**^{d}	**0.10**	**Increasing**
	Post-monsoon	**28.34**	**2.02**^{b}	**0.12**	**Increasing**
	Winter	27.02	1.29	0.04	No trend
	Summer	30.36	1.90^{a}	0.07	Increasing

Note: Bold indicates statistically significant values.

^{a} 10% significance level; ^{b} 5% significance level; ^{c} 1% significance level; ^{d} 0.1% significance level

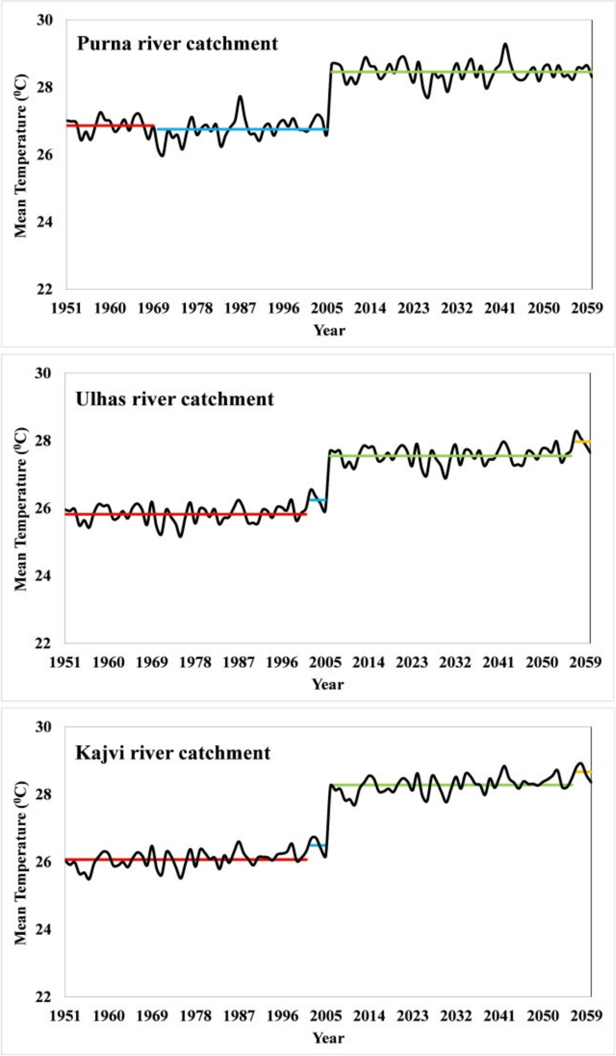

Fig. 5.4. Regime shift of temperature over northern catchments of the Western Ghats

The results of the trend analysis of annual and seasonal temperature for the central river catchments of the Western Ghats are given in Table 5.5. The annual temperature in all the rivers of the central portion of the Western Ghats portrayed a highly significant increase in temperature. In the scenario 1, the annual temperature in the Malaprabha and Tunga river catchments showed an increase at the rate of 0.08°C per decade (0.1% significance level) and the Aghanashini river catchment was observed to have an increase at 0.07°C (0.1% significance level). The scenario 2 followed a similar trend as that of the scenario 1 and a highly significant increase of temperature was predicted in the three catchments. The regime shift of mean annual temperature during scenario 1 and 2 is presented in Fig 5.5.

Table 5.5. Trend analysis of temperature over central catchments of the Western Ghats

River	Temperature time series	Mean Temp (°C)	Statistic value	Sen's Slope Estimator (°C/decade)	Trend
		Malaprabha River			
Scenario 1 1951-2005	**Annual**	**26.29**	**3.62**^{d}	**0.08**	**Increasing**
	Monsoon	**25.78**	**3.67**^{d}	**0.11**	**Increasing**
	Post-monsoon	**26.20**	**2.00**^{b}	**0.11**	**Increasing**
	Winter	24.86	1.92^{a}	0.06	Increasing
	Summer	**28.46**	**2.67**^{c}	**0.10**	**Increasing**
Scenario 2 2006-2060	**Annual**	**27.94**	**3.95**^{d}	**0.08**	**Increasing**
	Monsoon	**27.22**	**3.61**^{d}	**0.08**	**Increasing**
	Post-monsoon	**27.83**	**2.51**^{b}	**0.10**	**Increasing**
	Winter	**26.76**	**2.87**^{c}	**0.07**	**Increasing**
	Summer	**30.17**	**2.78**^{c}	**0.08**	**Increasing**
		Aghanashini River			
Scenario 1 1951-2005	**Annual**	**25.88**	**4.02**^{d}	**0.07**	**Increasing**
	Monsoon	**25.27**	**3.46**^{d}	**0.08**	**Increasing**
	Post-monsoon	**25.76**	**2.56**^{b}	**0.10**	**Increasing**
	Winter	**24.57**	**2.78**^{c}	**0.06**	**Increasing**
	Summer	**28.08**	**2.88**^{c}	**0.08**	**Increasing**
Scenario 2 2006-2060	**Annual**	**27.35**	**3.76**^{d}	**0.08**	**Increasing**
	Monsoon	**26.60**	**3.70**^{d}	**0.10**	**Increasing**
	Post-monsoon	**26.95**	**2.13**^{b}	**0.11**	**Increasing**
	Winter	**26.00**	**1.96**^{b}	**0.06**	**Increasing**
	Summer	**29.97**	**3.25**^{c}	**0.10**	**Increasing**
		Tunga River			
Scenario 1 1951-2005	**Annual**	**24.31**	**4.38**^{d}	**0.08**	**Increasing**
	Monsoon	**23.48**	**3.71**^{d}	**0.09**	**Increasing**
	Post-monsoon	**23.93**	**3.27**^{c}	**0.09**	**Increasing**
	Winter	**23.31**	**3.42**^{d}	**0.09**	**Increasing**
	Summer	**26.69**	**2.66**^{c}	**0.08**	**Increasing**
Scenario 2 2006-2060	**Annual**	**26.17**	**3.76**^{d}	**0.09**	**Increasing**
	Monsoon	**25.27**	**3.59**^{d}	**0.11**	**Increasing**
	Post-monsoon	**25.70**	**2.18**^{b}	**0.09**	**Increasing**
	Winter	**24.99**	**2.45**^{b}	**0.07**	**Increasing**
	Summer	**28.88**	**3.14**^{c}	**0.09**	**Increasing**

Note: Bold indicates statistically significant values.

^{a} 10% significance level; ^{b} 5% significance level; ^{c} 1% significance level; ^{d} 0.1% significance level

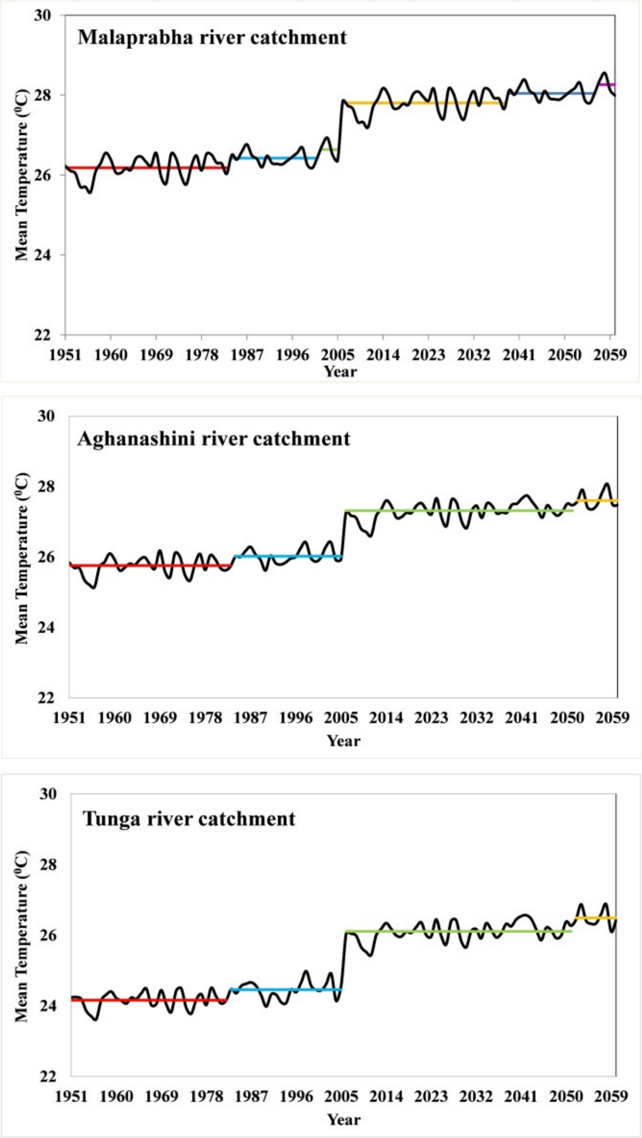

Fig. 5.5. Regime shift of temperature over central catchments of the Western Ghats

The results of the trend analysis of temperature in the southern river catchments of the Western Ghats suggested a maximum rate of increase. The annual temperature during scenario 1 for Netravathi, Chaliyar, and Vamanapuram river catchments portrayed an increase of 0.09°C, 0.11°C, and 0.12°C per decade, respectively (Table 5.6). It was interesting to note that, all these values were highly significant (0.1% significance level). During the monsoon season, the temperatures were found to have increased by as much as 0.13°C per decade in the Vamanapuram river catchment. The forecasted time series (scenario 2) revealed a similar picture wherein the rate of increase in annual mean temperature could possibly be as high as 0.12°C per decade (at 0.1% significance level). The temperature during the monsoon and summer portrayed a maximum rate of increase (0.14°C and 0.13°C per decade at 0.1% significance level). The increase in temperature observed across all the seasons indicate that, the central and southern rivers of the Western Ghats of India are more vulnerable to climate change and rising temperatures than the rivers in the northern Western Ghats. The regime shift of mean annual temperature of southern river catchments during scenario 1 and 2 is presented in Fig 5.6.

The study by Gopalakrishnan et al., (2011) reported central part of the Western Ghats of India (in Karnataka) to be more vulnerable to climate change due to rise in temperature by almost 3°C. Although the study was carried out on the forests, the present study confirms the results of Gopalakrishnan et al., (2011) and adds further that, the southern portion of the Western Ghats (in Kerala and Tamil Nadu) shows higher potential to rise in temperature along with the central portion.

Table 5.6. Trend analysis of temperature over southern catchments of the Western Ghats

River	Temperature time series	Mean Temp (°C)	Statistic Value	Sen's Slope Estimator (°C/decade)	Trend
Netravathi River					
Scenario 1 1951-2005	**Annual**	**24.04**	**5.34^{d}**	**0.09**	**Increasing**
	Monsoon	**23.36**	**4.50^{d}**	**0.10**	**Increasing**
	Post-monsoon	**23.58**	**3.82^{d}**	**0.11**	**Increasing**
	Winter	**22.93**	**3.90^{d}**	**0.09**	**Increasing**
	Summer	**26.39**	**3.14^{c}**	**0.09**	**Increasing**
Scenario 2 2006-2060	**Annual**	**25.98**	**5.15^{d}**	**0.10**	**Increasing**
	Monsoon	**24.93**	**4.34^{d}**	**0.11**	**Increasing**
	Post-monsoon	**25.82**	**3.91^{d}**	**0.11**	**Increasing**
	Winter	**25.17**	**4.00^{d}**	**0.10**	**Increasing**
	Summer	**28.30**	**3.44^{d}**	**0.09**	**Increasing**
Chaliyar River					
Scenario 1 1951-2005	**Annual**	**23.71**	**6.13^{d}**	**0.11**	**Increasing**
	Monsoon	**23.35**	**5.29^{d}**	**0.12**	**Increasing**
	Post-monsoon	**23.14**	**4.69^{d}**	**0.12**	**Increasing**
	Winter	**22.39**	**4.80^{d}**	**0.11**	**Increasing**
	Summer	**25.90**	**3.72^{d}**	**0.12**	**Increasing**
Scenario 2 2006-2060	**Annual**	**25.22**	**5.71^{d}**	**0.13**	**Increasing**
	Monsoon	**24.70**	**4.97^{d}**	**0.14**	**Increasing**
	Post-monsoon	**24.77**	**3.83^{d}**	**0.12**	**Increasing**
	Winter	**23.82**	**4.27^{d}**	**0.13**	**Increasing**
	Summer	**27.62**	**3.64^{d}**	**0.14**	**Increasing**
Vamanapuram River					
Scenario 1 1951-2005	**Annual**	**27.02**	**5.92^{d}**	**0.12**	**Increasing**
	Monsoon	**26.93**	**5.23^{d}**	**0.13**	**Increasing**
	Post-monsoon	**26.37**	**4.82^{d}**	**0.11**	**Increasing**
	Winter	**26.11**	**4.78^{d}**	**0.11**	**Increasing**
	Summer	**28.46**	**3.90^{d}**	**0.12**	**Increasing**
Scenario 2 2006-2060	**Annual**	**28.76**	**4.94^{d}**	**0.12**	**Increasing**
	Monsoon	**28.58**	**4.33^{d}**	**0.13**	**Increasing**
	Post-monsoon	**28.27**	**3.88^{d}**	**0.09**	**Increasing**
	Winter	**27.72**	**3.70^{d}**	**0.11**	**Increasing**
	Summer	**30.37**	**3.54^{d}**	**0.13**	**Increasing**

Note: Bold indicates statistically significant values.

^{c} 1% significance level; ^{d} 0.1% significance level

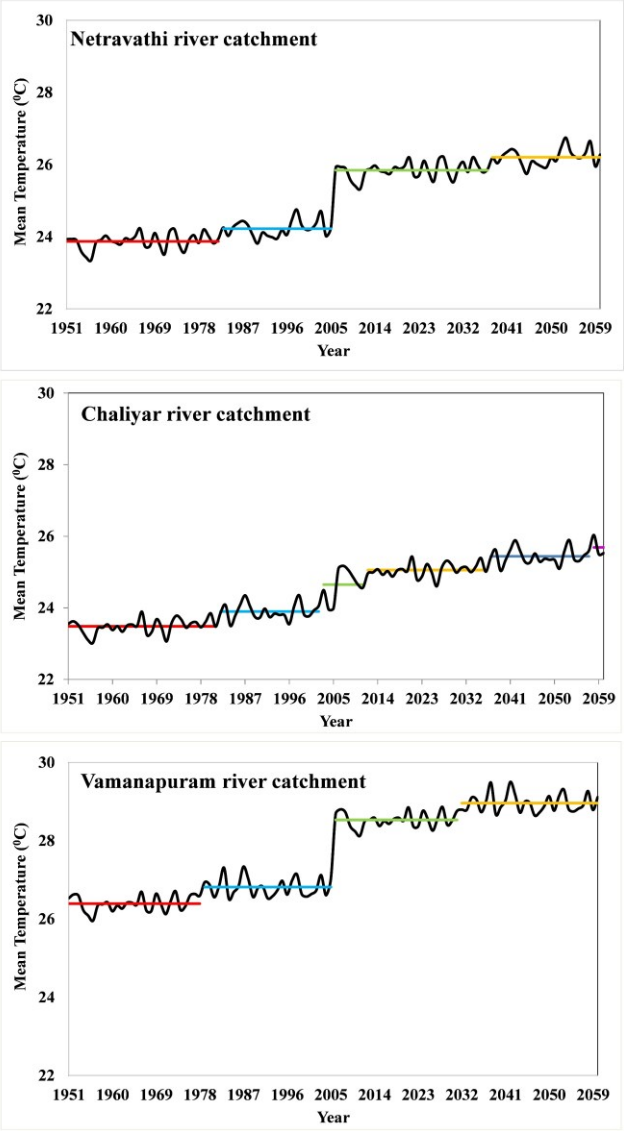

Fig. 5.6. Regime shift of temperature over southern catchments of the Western Ghats

5.3.3 Trend analysis of Potential Evapo-transpiration (PET)

The evapo-transpiration is the combined loss of water from the Earth's surface through evaporation from soil, water bodies, and the transpiration process of plants. The Potential Evapo-transpiration (PET) represents the loss of water that would occur in a catchment if sufficient source of water is available. The PET is affected by several meteorological parameters such as the humidity, wind speed, temperature, and sunlight. The data on PET is essential to calculate the crop water requirements and issues of water conservation are managed based on the analysis of PET. Several methods have been developed to estimate the PET such as the Penman-Monteith method (Penman and Monteith, 1965), Hargreaves method (Hargreaves and Samani, 1985), Priestley-Taylor method (Priestley and Taylor, 1972), and the Turc Method (Turc, 1961). The Hargreaves method was employed to calculate the potential evapo-transpiration in this study. The Hargreaves method is a temperature-based method for computing potential evapo-transpiration and gives reasonable results with global validity (Allen et al.1998). Although, the Penman-Monteith method is widely used for agriculture studies (Shukla et al. 2014), it requires an extensive database, which was not available for this study.

The trend analysis of the PET was carried out in order to assess the loss of water from the catchments of the Western Ghats. The results of the northern catchments of the Western Ghats are presented in Table 5.7. The Purna river catchment did not portray a change in the trend of PET during scenario 1. The PET during the monsoon season of scenario 2 was observed to increase with a magnitude of 7 mm per decade (10% significance level). In the Ulhas river catchment, the increase in annual PET during scenario 1 was estimated to be 12 mm per decade (5% significance level) and 2 mm per decade during summer (10% significance level). In the scenario 2, the annual PET increase was estimated to be 12 mm per decade (at 5% significance level) and 2 mm per decade (5% significance level) during summer. The increase in annual PET of the Kajvi River catchment was estimated to be 9.5 mm per decade during scenario 1 and increase at 10 mm per decade (5% significance level) was estimated during scenario 2.

Table 5.7. Trend analysis of PET over northern catchments of the Western Ghats

River	PET time series	Statistic value	Sen's Slope Estimator (mm/decade)	Trend
		Purna River		
Scenario 1	Annual	1.41	8.60	No trend
1951-2005	Monsoon	1.60	6.64	No trend
	Post-monsoon	0.42	0.48	No trend
	Winter	-0.06	0.04	No trend
	Summer	1.13	1.21	No trend
Scenario 2	Annual	1.54	9.37	No trend
2006-2070	Monsoon	1.79[a]	7.30	Increasing
	Post-monsoon	0.54	0.77	No trend
	Winter	-0.38	-0.23	No trend
	Summer	1.19	1.20	No trend
		Ulhas River		
Scenario 1	**Annual**	**2.56[b]**	11.90	**Increasing**
1951-2005	Monsoon	1.81[a]	7.22	Increasing
	Post-monsoon	1.79[a]	2.49	Increasing
	Winter	-0.19	-0.14	No trend
	Summer	1.84[a]	2.33	Increasing
Scenario 2	**Annual**	**2.54[b]**	**11.70**	**Increasing**
2006-2070	Monsoon	1.71[a]	6.60	Increasing
	Post-monsoon	1.83[a]	2.46	Increasing
	Winter	-0.29	-0.20	No trend
	Summer	**1.97[b]**	**2.37**	**Increasing**
		Kajvi River		
Scenario 1	Annual	1.81[a]	9.41	Increasing
t1951-2005	Monsoon	0.97	2.52	No trend
	Post-monsoon	1.88[a]	3.13	Increasing
	Winter	0.92	0.65	No trend
	Summer	1.44	3.52	No trend
Scenario 2	**Annual**	**1.97[b]**	**9.81**	**Increasing**
2006-2070	Monsoon	0.96	2.11	No trend
	Post-monsoon	**1.99[b]**	**3.18**	**Increasing**
	Winter	0.94	0.58	No trend
	Summer	1.50	3.72	No trend

Note: Bold indicates statistically significant values.

[a] 10% significance level; [b] 5% significance level.

In the central rivers, the Malaprabha river catchment was observed to have an increase in annual PET by 17 mm per decade (0.1% significance level) during scenario 1. The post-monsoon and summer seasons were estimated to have an increase at 5 mm and 8.5 mm per decade (5% significance level), respectively. The scenario 2 was observed to have an increasing trend in the annual PET as well as during winter and summer. The magnitude of increase was estimated to be 17 mm (1% significance level), 2 mm per decade (5% significance level), and 10 mm per decade (1% significance level), respectively. In the Aghanashini river catchment, the annual PET increased at the rate of 10 mm per decade (10% significance level) and 8.5 mm per decade (10% significance level) during scenario 1 and scenario 2, respectively. In the Tunga river catchment, the annual PET was found to be decreasing in scenario 1 at the rate of 29 mm per decade (0.1% significance level) and by 27 mm per decade (0.1% significance level) during monsoon season. In the scenario 2, the summer season portrayed a decrease in the PET by 7 mm per decade (5% significance level). The results of the trend analysis of PET for the central river catchments in presented in Table 5.8.

In the southern rivers (Table 5.9), no changes to the trend of PET were observed over the Netravathi river catchment. The Chaliyar river catchment was observed to have an increase in annual PET at the rate of 15.5 mm per decade (1% significance level) during scenario 1. The summer season was observed to have an increase in PET by 7 mm per decade (5% significance level). The scenario 2 followed a similar trend with an increase at 14.5 mm per decade (1% significance level) for annual PET and 7 mm per decade (5% significance level) for the summer season. In the Vamanapuram river catchment, the increase in annual PET was estimated to be 12 mm per decade (5% significance level) and 9 mm per decade (1% significance level) during the summer season. In the forecasted scenario (scenario 2), the rate of annual PET is expected to increase by 17 mm per decade (1% significance level) along with an increase during monsoon season and summer season at 6.5 mm per decade and 6 mm per decade (5% significance level), respectively.

Table 5.8. Trend analysis of PET over central catchments of the Western Ghats

River	PET time series	Statistic value	Sen's Slope Estimator (mm/decade)	Trend
		Malaprabha River		
Scenario 1	**Annual**	**3.40[d]**	**16.77**	**Increasing**
1951-2005	Monsoon	0.28	0.50	No trend
	Post-monsoon	**2.05[b]**	**4.85**	**Increasing**
	Winter	1.74[a]	1.51	Increasing
	Summer	**2.45[b]**	**8.44**	**Increasing**
Scenario 2	**Annual**	**3.11[c]**	**16.67**	**Increasing**
2006-2070	Monsoon	0.10	0.25	No trend
	Post-monsoon	1.55	3.24	No trend
	Winter	**2.05[b]**	**1.61**	**Increasing**
	Summer	**3.27[c]**	**9.71**	**Increasing**
		Aghanashini River		
Scenario 1	Annual	1.90[a]	10.18	Increasing
1951-2005	Monsoon	1.50	3.84	No trend
	Post-monsoon	1.03	2.52	No trend
	Winter	1.45	1.19	No trend
	Summer	1.41	5.02	No trend
Scenario 2	Annual	1.71[a]	8.43	Increasing
2006-2070	Monsoon	1.07	2.28	No trend
	Post-monsoon	1.63	3.15	No trend
	Winter	0.75	0.46	No trend
	Summer	0.86	4.02	No trend
		Tunga River		
Scenario 1	**Annual**	**-3.51[d]**	**29.38**	**Decreasing**
1951-2005	**Monsoon**	**-4.38[d]**	**26.66**	**Decreasing**
	Post-monsoon	-1.35	2.89	No trend
	Winter	0.28	0.26	No trend
	Summer	-0.74	2.44	No trend
Scenario 2	Annual	0.46	2.67	No trend
2006-2070	Monsoon	-1.61	-5.31	No trend
	Post-monsoon	0.01	0.04	No trend
	Winter	0.97	0.91	No trend
	Summer	**2.29[b]**	**6.99**	**Decreasing**

Note: Bold indicates statistically significant values.

[a] 10% significance level; [b] 5% significance level; [c] 1% significance level; [d] 0.1% significance level.

Table 5.9. Trend analysis of PET over southern catchments of the Western Ghats

River	PET time series	Statistic value	Sen's Slope Estimator (mm/decade)	Trend
		Netravathi River		
Scenario 1 1951-2005	Annual	0.78	3.24	No trend
	Monsoon	1.36	1.61	No trend
	Post-monsoon	-0.46	0.63	No trend
	Winter	0.41	0.25	No trend
	Summer	0.13	0.57	No trend
Scenario 2 2006-2070	Annual	0.90	2.92	No trend
	Monsoon	1.10	1.70	No trend
	Post-monsoon	-0.62	-0.63	No trend
	Winter	0.78	0.49	No trend
	Summer	0.80	1.49	No trend
		Chaliyar River		
Scenario 1 1951-2005	**Annual**	**3.06**[c]	**15.51**	**Increasing**
	Monsoon	1.58	5.63	No trend
	Post-monsoon	-0.06	-0.17	No trend
	Winter	0.86	1.24	No trend
	Summer	**2.44**[b]	**6.62**	**Increasing**
Scenario 2 2006-2070	**Annual**	**3.06**[c]	**14.48**	**Increasing**
	Monsoon	1.52	5.16	No trend
	Post-monsoon	0.00	-0.06	No trend
	Winter	1.02	1.37	No trend
	Summer	**2.38**[b]	**6.68**	**Increasing**
		Vamanapuram River		
Scenario 1 1951-2005	**Annual**	**2.05**[b]	**11.64**	**Increasing**
	Monsoon	**2.73**[c]	**9.21**	**Increasing**
	Post-monsoon	-0.60	1.24	No trend
	Winter	-0.36	0.59	No trend
	Summer	0.78	2.89	No trend
Scenario 2 2006-2070	**Annual**	**3.25**[c]	**17.37**	**Increasing**
	Monsoon	**2.11**[b]	**6.49**	**Increasing**
	Post-monsoon	0.28	0.62	No trend
	Winter	1.51	2.39	No trend
	Summer	**2.09**[b]	**5.95**	**Increasing**

Note: Bold indicates statistically significant values.

[b] 5% significance level; [c] 1% significance level.

5.3.4 Trend analysis of streamflow

The availability of water in the rivers plays a vital role in the design, planning, and maintenance of water resources. The streamflow in the river is affected by several factors such as anthropogenic activities, natural causes (such as changes in river course), and climate change. The following sections present the trend analysis of streamflow in rivers of the Western Ghats of India. The trends were estimated on an annual and seasonal basis for the historical data (Scenario 1) and forecasted streamflow (Scenario 2).

The results of the trend analysis of streamflow in the northern rivers of the Western Ghats are presented in Table 5.10. There were no changes observed to the streamflow in the river Purna during scenario 1 and 2. In the river Ulhas, the summer streamflow portrayed a decreasing trend across scenario 1 and scenario 2. However, the magnitude of the trend was found to be negligible since the river Ulhas is a non-perennial river and almost runs dry during the summer months. In the river Kajvi, the annual streamflow in the past (scenario 1) portrayed a decreasing trend at the rate of 4% per decade (5% significance level). The streamflow during monsoon and summer also decreased by 0.14 Mm^3 per decade (10% significance level) and 0.67% per decade (5% significance level). In the scenario 2, the annual streamflow in the river was seen to decrease by 3.42% per decade (5% significance level). The streamflow during the monsoon, winter, and summer also witnessed a decreasing trend although the magnitude was not very high. The changes to the water availability in the northern rivers are graphically represented in Fig. 5.7. It may, however, be noted that, the graphical representation does not account for the serially correlated times series.

Table 5.10. Trend analysis of streamflow in northern rivers of the Western Ghats

Scenario	Streamflow time series	Mean flow (Mm^3)	Statistic value	Sen's Slope Estimator (Mm^3/decade)	Trend
Purna River					
Scenario 1 1951-2005	Annual	3.97	-0.64	0.06	No trend
	Monsoon	8.77	-0.46	0.12	No trend
	Post-monsoon	3.61	-0.37	0.03	No trend
	Winter	1.36	-0.19	0.01	No trend
	Summer	0.32	-0.05	0.00	No trend
Scenario 2 2006-2070	Annual	4.85	-0.16	0.00	No trend
	Monsoon	11.04	-0.16	0.10	No trend
	Post-monsoon	4.03	-0.07	0.00	No trend
	Winter	1.48	0.48	0.00	No trend
	Summer	0.36	0.57	0.00	No trend
Ulhas River					
Scenario 1 1951-2005	Annual	4.63	1.13	0.13	No trend
	Monsoon	13.15	0.96	0.32	No trend
	Post-monsoon	1.17	0.48	0.03	No trend
	Winter	0.02	-1.41	0.00	No trend
	Summer	**0.01**	**-3.50**[d]	**0.00**	**Decreasing**
Scenario 2 2006-2070	Annual	7.16	-0.07	0.01	No trend
	Monsoon	20.32	0.04	0.04	No trend
	Post-monsoon	1.79	-0.23	0.02	No trend
	Winter	0.02	-0.20	0.00	No trend
	Summer	**0.03**	**-2.54**[b]	**0.00**	**Decreasing**
Kajvi River					
Scenario 1 1951-2005	**Annual**	**1.48**	**-2.08**[b]	**0.06 (4.05)**	**Decreasing**
	Monsoon	4.01	-1.87[a]	0.14	No trend
	Post-monsoon	0.63	-0.78	0.03	No trend
	Winter	0.03	-1.77[a]	0.00	No trend
	Summer	**0.05**	**-2.06**[b]	**0.01**	**Decreasing**
Scenario 2 2006-2070	**Annual**	**2.63**	**-1.96**[b]	**0.09 (3.42)**	**Decreasing**
	Monsoon	7.33	-1.92[a]	0.26	No trend
	Post-monsoon	0.87	-0.91	0.05	No trend
	Winter	**0.03**	**-2.38**[b]	**0.00**	**Decreasing**
	Summer	0.05	-1.74[a]	0.00	No trend

Note: Bold indicates statistically significant values.

[a] 10% significance level; [b] 5% significance level; [d] 0.1% significance level.

Values in parenthesis denote percentage of annual flow.

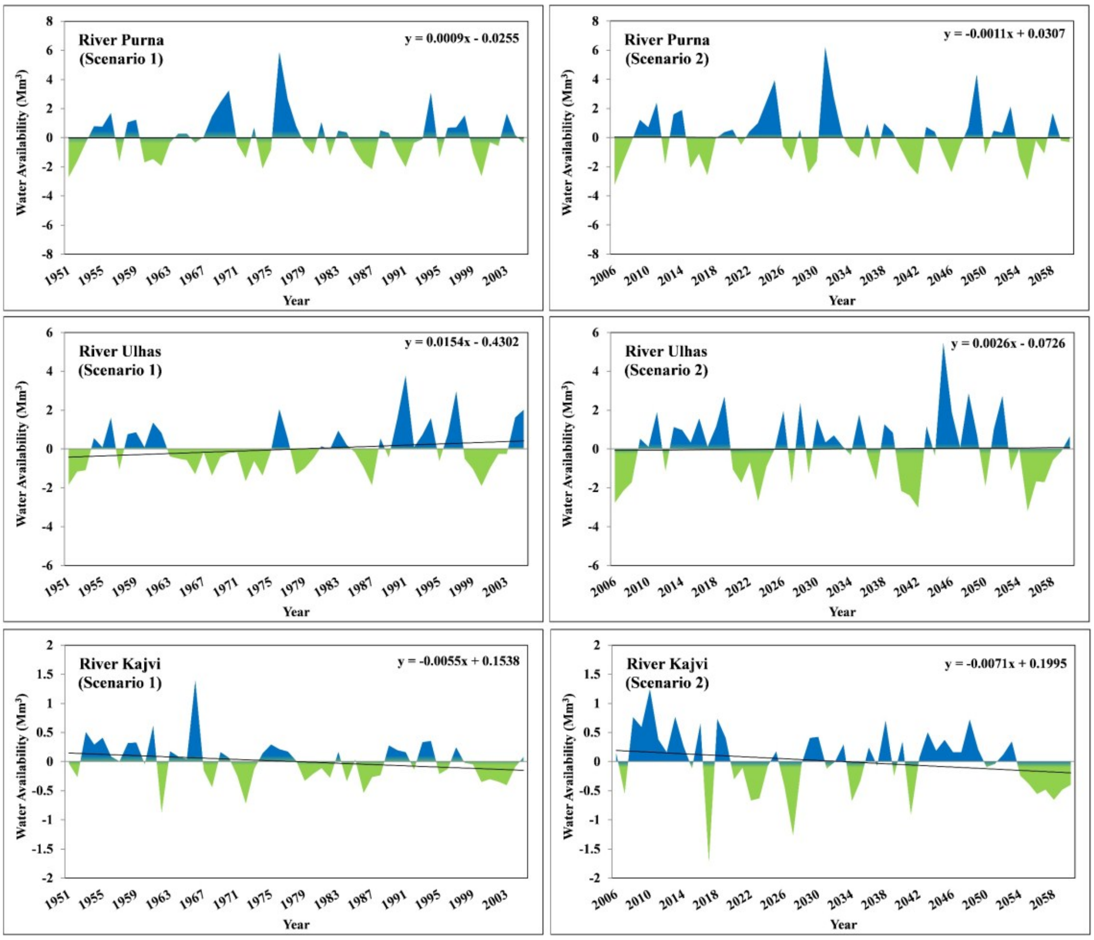

Fig. 5.7. Anomaly of water availability in northern rivers of the Western Ghats

In the central rivers of the Western Ghats, two rivers (river Malaprabha and Aghanashini) showed an increase in the streamflow and the third (river Tunga) had a decreasing trend. The results of the trend analysis are tabulated in Table 5.11 and the changes to water availability are presented in Fig. 5.8. The river Malaprabha was observed to have an increase in monsoon streamflow during scenario 1 although, the increase in monsoon season did not reflect on the annual streamflow. The increase was estimated to be 0.24 Mm^3 per decade (at 10% significance level). During scenario 2, the annual and post-monsoon streamflow was observed to increase by 17.4% per decade and 7% per decade (at 0.1% significance level), respectively. The monsoon season also portrayed an increase at 43% per decade (1% significance level).

Table 5.11. Trend analysis of streamflow in central rivers of the Western Ghats

Scenario	Streamflow time series	Mean flow (Mm^3)	Statistic value	Sen's Slope Estimator (Mm^3/decade)	Trend
Malaprabha River					
Scenario 1 1951-2005	Annual	1.55	1.55	0.08	No trend
	Monsoon	4.12	1.92^{a}	0.24	No trend
	Post-monsoon	0.81	-0.75	0.02	No trend
	Winter	0.06	-0.94	0.00	No trend
	Summer	**0.04**	**-3.14^{c}**	**0.00**	**Decreasing**
Scenario 2 2006-2070	**Annual**	**2.01**	**3.43^{d}**	**0.35 (17.41)**	**Increasing**
	Monsoon	**5.37**	**3.14^{c}**	**0.87 (43.29)**	**Increasing**
	Post-monsoon	**1.02**	**3.32^{d}**	**0.14 (6.96)**	**Increasing**
	Winter	**0.06**	**3.18^{c}**	**0.00**	**Increasing**
	Summer	0.09	0.89	0.00	No trend
Aghanashini River					
Scenario 1 1951-2005	**Annual**	**9.26**	**3.05^{c}**	**0.66 (7.12)**	**Increasing**
	Monsoon	**25.93**	**3.06^{c}**	**1.93 (20.84)**	**Increasing**
	Post-monsoon	2.66	1.25	0.18	No trend
	Winter	0.11	1.03	0.00	No trend
	Summer	0.24	-1.26	0.00	No trend
Scenario 2 2006-2070	Annual	12.45	1.45	0.38	No trend
	Monsoon	34.96	1.34	1.08	No trend
	Post-monsoon	3.13	1.21	0.19	No trend
	Winter	**0.14**	**2.06^{b}**	**0.01 (0.08)**	**Increasing**
	Summer	0.43	-0.61	0.00	No trend
Tunga River					
Scenario 1 1951-2005	Annual	13.63	0.77	0.21	No trend
	Monsoon	36.55	0.52	0.34	No trend
	Post-monsoon	6.73	-0.43	0.10	No trend
	Winter	0.24	1.53	0.01	No trend
	Summer	**0.51**	**-2.06^{b}**	**0.03 (0.22)**	**Decreasing**
Scenario 2 2006-2070	**Annual**	**29.59**	**-3.75^{d}**	**3.66 (12.36)**	**Decreasing**
	Monsoon	**81.02**	**-3.67^{d}**	**10.74 (36.29)**	**Decreasing**
	Post-monsoon	11.40	-0.45	0.17	No trend
	Winter	0.36	1.13	0.01	No trend
	Summer	1.22	-1.18	0.04	No trend

Note: Bold indicates statistically significant values.

^{a} 10% significance level; ^{b} 5% significance level; ^{c} 1% significance level; ^{d} 0.1% significance level.

Values in parenthesis denote percentage of annual flow.

The river Aghanashini portrayed an increase in the annual streamflow (7% per decade at 1% significance level) and monsoon streamflow (21% per decade at 1% significance level) during scenario 1. There were no changes observed to the streamflow of river Aghanashini in the scenario 2 except from the winter season that increased at 0.08% per decade (1% significance level). The river Tunga was found to have a decreasing trend during the summer (0.22% per decade at 5% significance level) during scenario 1. The annual and seasonal flow did not exhibit a shift in trend. Whereas, in the scenario 2, extremely significant (0.1% significance level) decreasing trend in annual and monsoon streamflow was detected. The magnitude of decrease was estimated to be 12% and 36%, respectively for annual and monsoon.

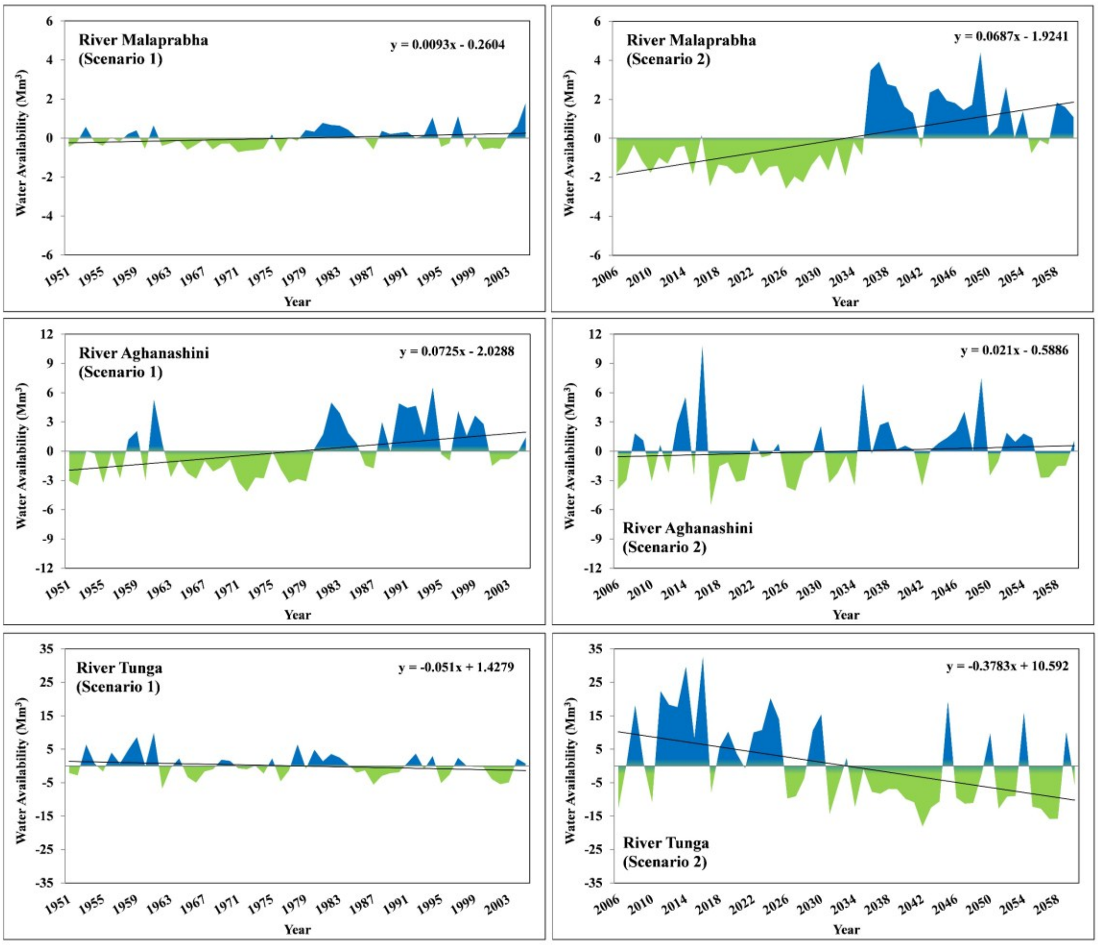

Fig. 5.8. Anomaly of water availability in central rivers of the Western Ghats

The results of trend analysis of streamflow for the southern rivers of the Western Ghats are presented in Table 5.12. It was observed that, all the rivers in the southern part of the Western Ghats are facing a decrease in the availability of streamflow. The results of the trend analysis show a decreasing trend of streamflow across all the rivers in the south. In the river Netravathi, the annual and monsoon streamflow (in scenario 1) was found to be decreasing at the rate of 4% per decade (5% significance level) and 14.5% per decade (1% significance level), respectively. The scenario 2 also portrayed a similar decreasing trend with annual, monsoon and summer streamflow decreasing at the rate of 3.75%, 10%, and 1.20% per decade (at 5% significance level). The anomaly of water availability in the southern rivers is given in Fig. 5.9.

The historical streamflow data (scenario 1) of river Chaliyar showed that, the annual flow in the river is decreasing at the rate of 6.60% per decade (5% significance level). This is due to decrease in the monsoon flow at 17% per decade (5% significance level). The scenario 2 is also expected to have a decreasing trend of streamflow at the rate of 0.72 Mm^3 and 1.89 Mm^3 per decade (5% significance level). The results of the trend analysis of streamflow in river Vamanapuram exhibited a grave picture. The monsoon season flow was found to be decreasing by 37% per decade (0.1% significance level). The annual flow decreased by 18% per decade (1% significance level). The post-monsoon and summer season flows were found to decrease at the rate of 17% per decade (5% significance level) and 7% per decade (1% significance level), respectively. The scenario 2 is also expected to have a decreasing trend in annual, monsoon, and summer seasons with a decrease in flow at 5.5%, 8%, and 9.5% per decade (5% significance level), respectively. The results of the trend analysis across the rivers of the Western Ghats of India suggest that the rivers towards the southern portion of the Western Ghats are highly vulnerable to climate change.

Table 5.12. Trend analysis of streamflow in southern rivers of the Western Ghats

River	Streamflow time series	Mean flow (Mm^3)	Statistic value	Sen’s Slope Estimator (Mm^3/decade)	Trend
Netravathi River					
Scenario 1	**Annual**	**25.46**	**-2.37^{b}**	**1.05 (4.12)**	**Decreasing**
1951-2005	**Monsoon**	**63.47**	**-2.80^{c}**	**3.69 (14.49)**	**Decreasing**
	Post-monsoon	16.80	1.05	0.41	No trend
	Winter	2.41	1.63	0.09	No trend
	Summer	2.78	-0.42	0.04	No trend
Scenario 2	**Annual**	**29.29**	**-2.37^{b}**	**1.10 (3.75)**	**Decreasing**
2006-2070	**Monsoon**	**74.61**	**-2.10^{b}**	**2.94 (10.03)**	**Decreasing**
	Post-monsoon	15.70	-1.21	0.46	No trend
	Winter	1.69	-0.96	0.02	No trend
	Summer	**4.39**	**-2.43^{b}**	**0.35 (1.19)**	**Decreasing**
Chaliyar River					
Scenario 1	**Annual**	**9.39**	**-2.38^{b}**	**0.62 (6.60)**	**Decreasing**
1951-2005	**Monsoon**	**21.70**	**-2.29^{b}**	**1.58 (16.82)**	**Decreasing**
	Post-monsoon	9.48	-0.41	0.12	No trend
	Winter	0.70	-0.71	0.02	No trend
	Summer	1.35	-1.90^{a}	0.11 (1.17)	No trend
Scenario 2	**Annual**	**13.61**	**-2.00^{b}**	**0.72 (5.29)**	**Decreasing**
2006-2070	**Monsoon**	**32.63**	**-2.02^{b}**	**1.89 (13.89)**	**Decreasing**
	Post-monsoon	12.13	0.04	0.04	No trend
	Winter	0.63	-0.70	0.02	No trend
	Summer	1.81	-1.18	0.10	No trend
Vamanapuram River					
Scenario 1	**Annual**	**2.32**	**-3.21^{c}**	**0.41 (17.67)**	**Decreasing**
1951-2005	**Monsoon**	**3.63**	**-3.91^{d}**	**0.86 (37.06)**	**Decreasing**
	Postmonsoon	**4.11**	**-2.09^{b}**	**0.39 (16.81)**	**Decreasing**
	Winter	0.58	0.52	0.02	No trend
	Summer	**1.10**	**-2.85^{c}**	**0.16 (6.89)**	**Decreasing**
Scenario 2	**Annual**	**2.39**	**-2.31^{b}**	**0.13 (5.49)**	**Decreasing**
2006-2070	**Monsoon**	**3.38**	**-2.24^{b}**	**0.27 (7.98)**	**Decreasing**
	Postmonsoon	4.68	-0.62	0.09	No trend
	Winter	0.65	-0.70	0.02	No trend
	Summer	**1.26**	**-1.97^{b}**	**0.12 (9.52)**	**Decreasing**

Note: Bold indicates statistically significant values.

^{a} 10% significance level; ^{b} 5% significance level; ^{c} 1% significance level; ^{d} 0.1% significance level.

Values in parenthesis denote percentage of annual flow.

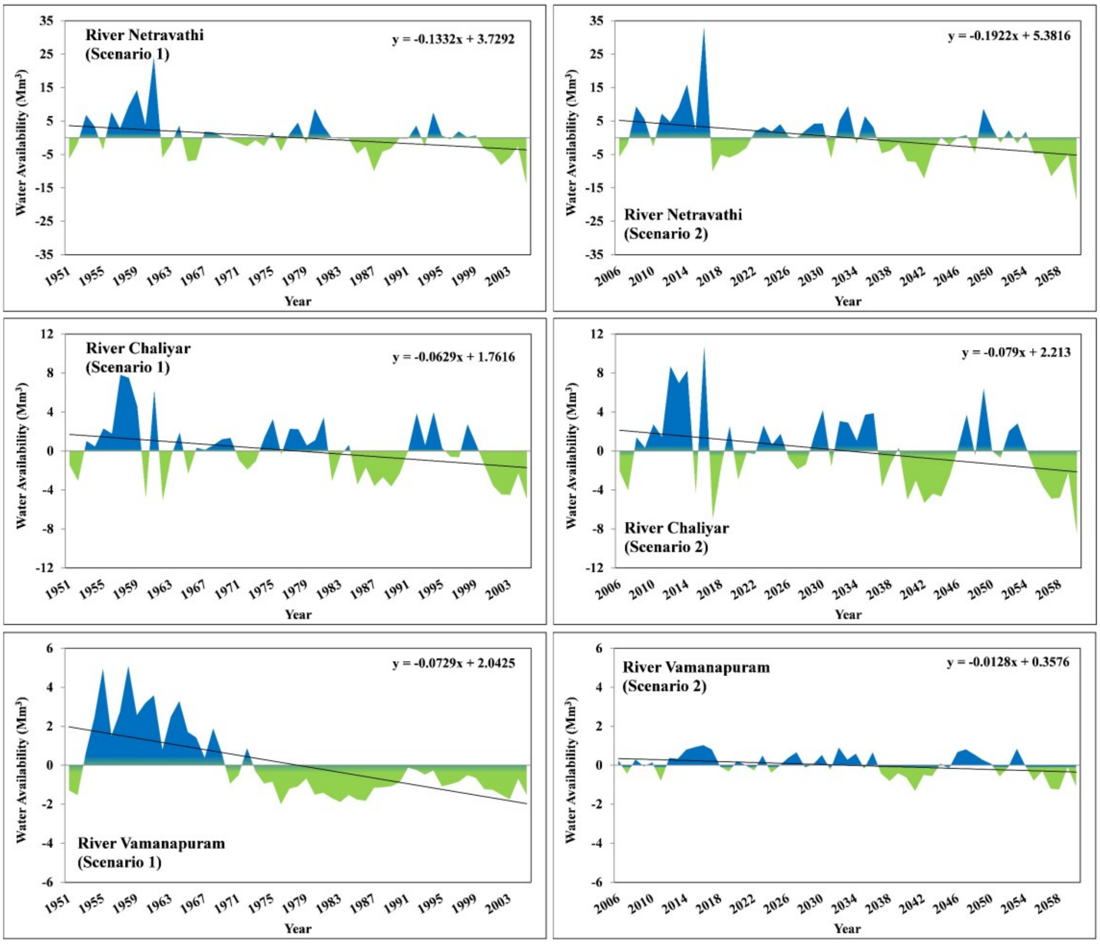

Fig. 5.9. Anomaly of water availability in southern rivers of the Western Ghats

It is important to note that, the relation of air temperature and thermal regime of rivers has been found to be a function of the stream type and timescale (Ahmadi-Nedushan et al., 2007; Caissie, 2006; Erickson and Stefan, 2000; Pilgrim et al., 1998; Stefan and Preud'homme, 1993; Webb et al., 2003). The perturbations of a warmer air temperature are likely to increase the river water temperature and would affect the aquatic habitat attributes, fisheries and ecological health of wetlands. Studies have demonstrated that, the reduction in the streamflow adversely affects the river temperature and evaporative cooling minimizes the effect of higher air temperatures on the water temperature (Bartholow, 1991; Caissie et al., 2005; Dymond, 1984; Hockey et al., 1982).

5.4 CLOSURE

The results of the trend analysis of hydro-meteorological variables indicate that, the temporal variability of rainfall, temperature, evapo-transpiration and streamflow is lesser in northern river catchments of the Western Ghats and the variability increases towards the south. It may be noted that, the rivers in northern and central portion are solely dependent on the south-west monsoon of India. The prognosis from the trend analysis indicates severe shortage of water in southern rivers of the Western Ghats of India in the future. The reduction in streamflow through excessive withdrawal (irrigation) and/or diversion (hydropower) may lead to deterioration of the general health of the riparian ecosystem.

CHAPTER 6

IMPACTS OF CLIMATE CHANGE ON HYDROLOGY

The quantification of impacts of climate change on the hydrological process is vital for the sustainable management of water resources. The changes in streamflow of rivers in water-stressed regions have a severe impact on societal activities such as drinking water, irrigation, food, energy requirement and hazard prevention. The past studies indicate that, the annual runoff would increase by about 10-40% at higher latitudes and decrease by 10-30% in semi-arid areas of lower latitudes and dry regions of middle latitudes by the year 2050 (Krol et al. 2011). The changes to the climate affect the high flow and routing time of the flood (Laurance, 1998; Prowse et al., 2006; Taye et al., 2013; Taye and Willems, 2013). The changes in land use and land cover alter the flow of surface and subsurface water and results in changes to the magnitude of annual and seasonal streamflow (Legesse et al., 2003; Bewket and Sterk, 2005; Descheemaeker et al., 2006; Nyssen et al., 2004; Zenebe et al., 2013). It is, therefore, important to note that, the development of water resources and the land use changes may mask the impacts of climate change.

The methodology adopted in this study to quantify the impact of climate change on the management of water resources involved the following steps:

1. Use of regional climate models to predict the future conditions at the local scale.
2. Bias correction of the regional climate model data.
3. Trend analysis of the historical (observed) data and the bias corrected data.
4. Hydrological analysis using the bias-corrected data to analyze the climate change impacts (local scale). The frequency analysis was carried out on the river flow to obtain flow quantiles at 10% duration intervals in the range 10% - 90%. The High flow index (HFI) (Q10/Q50) and the Low flow index (LFI) (Q90/Q50) were derived from the flow quantiles (Sahoo et al., 2016; Durbude et al., 2014). The HFI was used to characterize the relative magnitudes of peak flow (Q10) with reference to the median flow (Q50), while the LFI was used to

characterize relative magnitudes of low flow (Q90) to the median flow. The Q10 and Q90 classes of quantiles are adopted while designing large irrigation structures and drinking water scheme respectively, whereas, Q50 quantile is used to indicate the general water availability in the river.

This chapter presents the hydrological analysis for the river catchments originating in the Western Ghats of India. Additionally, the effect of topography on rainfall and streamflow is assessed.

6.1 EFFECT OF TOPOGRAPHY ON RAINFALL AND STREAMFLOW

The effect of topography on the rainfall and streamflow was studied on five river catchments viz., Purna, Aghanashini, Tunga, Netravathi, and Vamanapuram. The main focus of the study for the dependence of topography is the river Aghanashini. The Aghanashini River has a fall of 116 m (391 m to 275 m) at Unchalli, 38 km from the river origin. Later, the river flows through the estuary portion at the river mouth which is a flat expanse of water body with small islands and narrow creeks. The course of the river is through thick forested gorges and valleys with intermittent structures of rock bed, deep stagnant pools and channeled flow with island formation. The mainstream Aghanashini is one of the longest free-flowing and most pristine west flowing rivers along the west coast of India. The catchment is a natural laboratory for assessing the response of streamflow and its sensitivity to changes caused by elevation and topography.

6.1.1 Elevation based stratification of rainfall

The analysis of SRTM DEM revealed that, the Aghanashini catchment is characterized by flat plains on the west (area bounded between 74^0 20’ N to 74^0 30’ N) with a typical elevation not exceeding 10 m above MSL. The central portion of the catchment is characterized by the 116 m elevation drop with steep slopes. The eastern portion has a comparatively lesser slope at higher elevations (Fig. 3.4). The longitudinal profile of the river Aghanashini and the hydro-meteorological stations in the catchment are presented in Fig 6.1. The temporal variation of the rainfall in the Aghanashini River was similar to other coastal rivers originating in the Western Ghats. The months of June and July receive the heaviest rainfall followed by August and September which receive moderate rainfall. The intensity and magnitude of rainfall gradually decrease after September. Several theories are suggested to explain the mechanism of temporal variation of rainfall in the Western Ghats of India. Xavier et al., (2007) suggest the high troposphere temperature gradient over northern India during summer months as the cause of high rainfall intensities during the monsoon. The concentration of aerosols including marine aerosol concentration (sea salt) have found to play a role in the onset, advancement and withdrawal of Indian monsoon (Bollasina et al., 2008; Konwar et al., 2012, 2014; Lau and Kim, 2006; Sivaprasad and Babu, 2012).

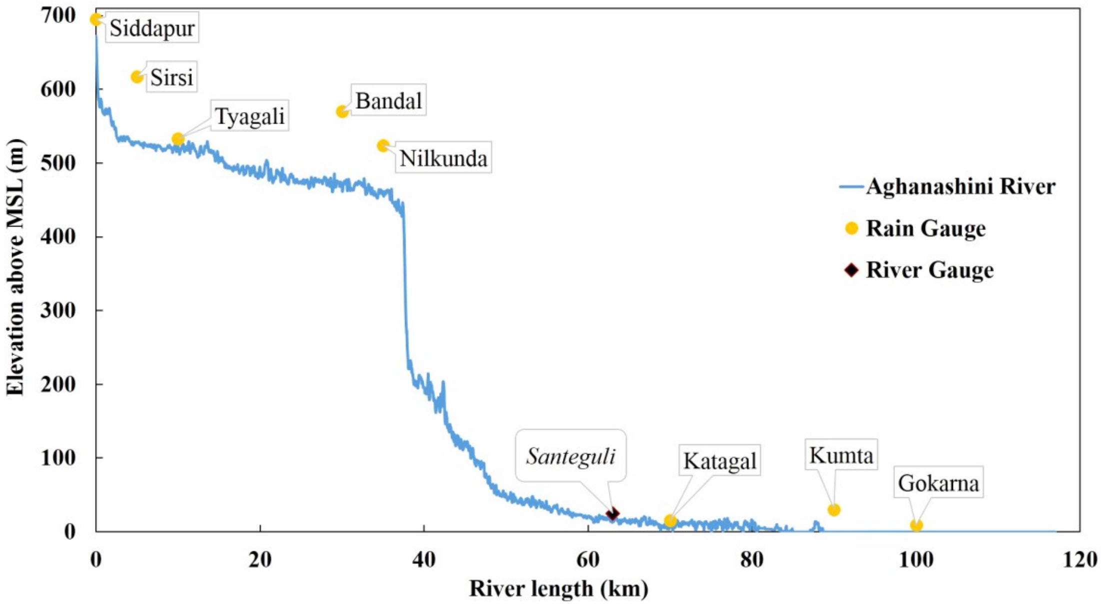

Fig. 6.1. Longitudinal profile of river Aghanashini

The stratification in elevation and rainfall over the Aghanashini catchment was found to be quite distinct with the regard to the topography, land use and land cover. The spatial distribution of long-term annual average rainfall over the Aghanashini catchment presents interesting results as shown in Fig. 6.2 (a). The catchment was spatially divided into three zones of rainfall and the nomenclature for the rainfall zones was with accordance to the elevation [Fig. 6.2 (b)].

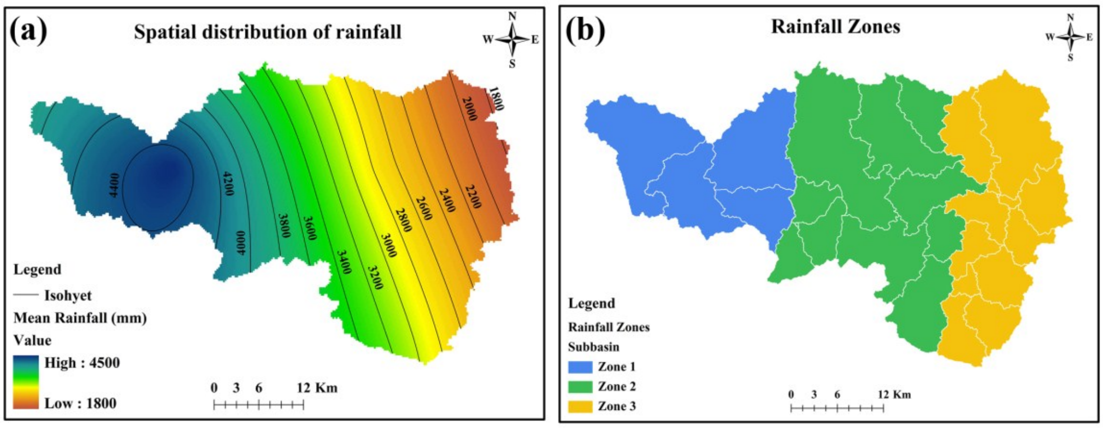

Fig. 6.2. (a) Spatial distribution of rainfall; (b) Rainfall zones in the Aghanashini catchment

Zone 1 is the portion of the catchment having lowest elevation starting from the confluence of the River with the Arabian Sea up to the flat plains (average slope of 3.3 m per km) of the catchment. The land use and land cover in the Zone 1 of the catchment are mainly deciduous forests, built-up areas, and agriculture. It receives the highest average annual rainfall varying between 3600 mm to 4500 mm. Zone 2 is the portion of the catchment from the flatter plains to the top of Unchalli fall. The Zone 2 is densely populated by evergreen broadleaf forests followed by agriculture along the river banks and receives an average annual rainfall of 2800 mm to 3600 mm. Zone 3 is the upper reaches of the Aghanashini catchment which is from the from the top of Unchalli fall to the highest elevation in the catchment. Owing to the high elevations, the Zone 3 is dominated by mixed forests and shrub lands and receives the least amount of rainfall (average annual rainfall varying between 1800 mm to 2800 mm). The broad mountains are usually attributed to the lesser rainfall in the upper reaches. Studies have suggested that, the windward side of Western Ghats in Karnataka are broad and consequently, the upper reaches and leeward sides receive very less rainfall intensities (<4 mm per day) (Tawde and Singh, 2015). It is interesting to observe that, the maximum intensity of rainfall in the Aghanashini catchment is not at the highest elevation, but at some distance from the crest on the windward side [Fig. 6.2 (a)]. Similar results were observed by Das (1968) which suggested a peak of monsoon rains to be around 50 km on the windward side from the crest in the Western Ghats of India.

The spatial distribution of rainfall over other four river basins of the Western Ghats are presented in Fig. 6.3. On comparison of results of river Aghanashini with the other rivers of the Western Ghats, it was found that, the observations of Das (1968) are limited to the windward side of the Western Ghats. The peak of rainfall in the west flowing rivers Purna [Fig. 6.3 (a)], Netravathi [Fig. 6.3 (c)], and the Vamanapuram catchments [Fig. 6.3 (d)] were at a distance from the crest of the Western Ghats on the windward side. Whereas, the east-flowing Tunga river [Fig. 6.3 (b)] received maximum rainfall at the crest and started decreasing on the leeward side from the Western Ghats. The response of the Aghanashini catchment to rising temperatures is likely to be affected severely by its hypsometry as the changes in elevation and the variability of rainfall through time would affect the local response of streamflow pattern.

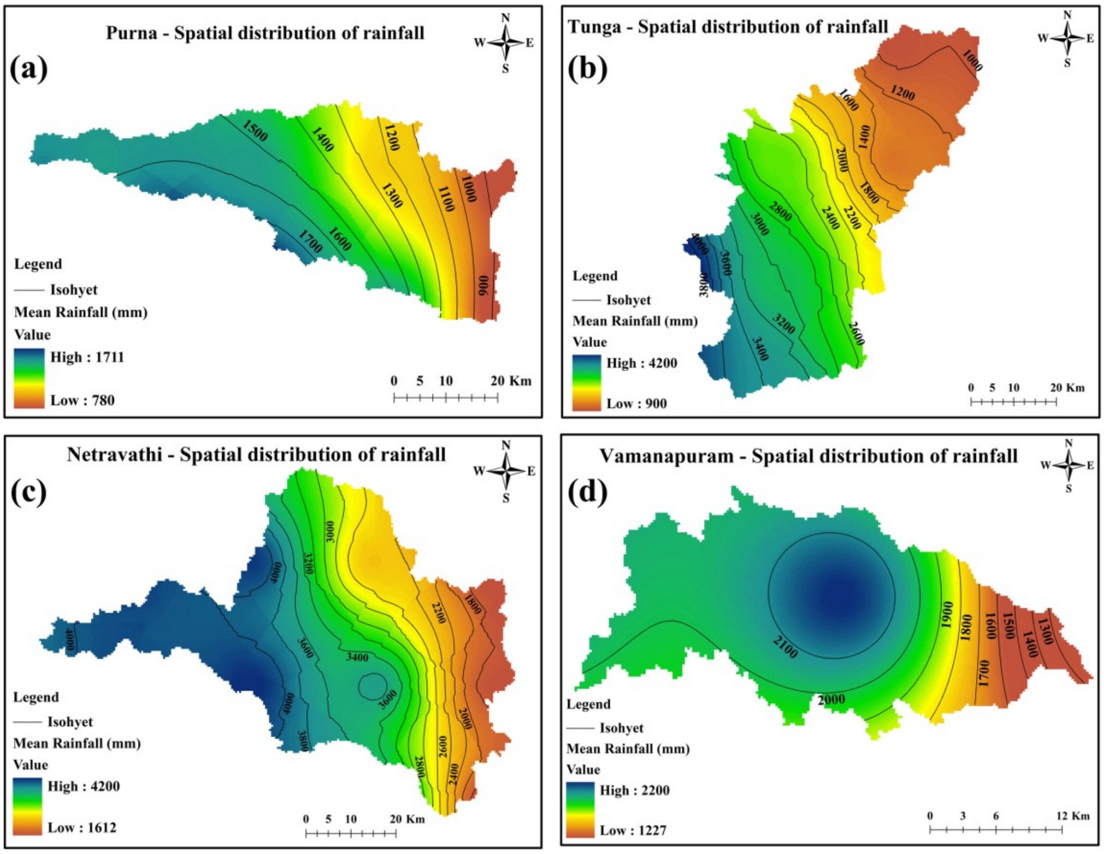

Fig. 6.3. Spatial distribution of rainfall in rivers (a) Purna; (b) Tunga; (c) Netravathi; (d) Vamanapuram

The results of the modified Mann-Kendall (chapter 5) analysis over historical data revealed that, the average rainfall over the Aghanashini catchment increased at the rate of 115 mm per decade (1% significance level) from 1951 to 2005 (Chapter 5, Table 5.11). The monsoon and post-monsoon seasons contribute to about 96.25% of the total rainfall in the catchment. The number of rainy days (>2.5mm/day) over the entire catchment was found to be 129 days per year. The number of rainy days along the western coast of India is generally about 140 days per year (Jain et al., 2007) and the results obtained in the present study were found to be in concurrence with several studies which state increasing trend of rainfall in the west coast with decreasing number of rainy days (Dash et al., 2007; Goswami et al., 2006; Khan et al., 2000; Kumar et al., 2010; Lal, 2003; Min et al., 2003; Mirza, 2002; Shrestha et al., 2000).

Table 6.1 presents the rainfall statistics and the modified Mann-Kendall test results for annual and seasonal rainfall over the three rainfall zones of the Aghanashini catchment considered in this study. Out of three zones, two zones showed an increase in annual as well as monsoon rainfall. Zone 1 is the western portion of the river catchment and it was observed to have the maximum increase in annual and monsoon rainfall. The annual rainfall shows a very prominent increase of 226 mm per decade (at a significance level of 0.1%) in the 55 years from 1951 to 2005. The rate of increase is about 6% of annual average rainfall. The analysis of intra-annual fluctuation of rainfall showed that, the monsoon season (June to September) contributes to 92% of rainfall in the zone 1 which is increasing at 6% per decade. The increase in the average annual rainfall may be attributed to the increase in rainfall during the monsoon. The winter has no contribution to the annual rainfall, whereas the post-monsoon and summer months contribute to about 8% of the rainfall in the zone. No changes with regard to trend were observed during post-monsoon and summer months. The zone 1 has 127 rainy days (with rainfall intensity >2.5mm/day) which is the major contributor of available water in the catchment.

Table 6.1. Trend analysis of rainfall over the zones of Aghanashini catchment

Zone	Rainfall time series	Mean Rainfall (mm)	Statistic value	Sen's Slope Estimator (mm/decade)	Trend
Zone 1	**Annual**	**4020**	**3.91^{d}**	**225.7 (5.61)**	**Increasing**
	Monsoon	**3690 (91.79)**	**4.16^{d}**	**229.1 (5.69)**	**Increasing**
	Post-monsoon	207 (5.14)	0.18	0.9 (0.02)	No trend
	Winter	9 (0.22)	0.62	0.00	No trend
	Summer	114 (2.85)	-1.16	-6.7 (-0.16)	No trend
Zone 2	Annual	2755	1.77^{a}	72.1 (2.61)	Increasing
	Monsoon	2470 (89.67)	1.66^{a}	75.1 (2.72)	Increasing
	Post-monsoon	175 (6.35)	0.64	3.9 (0.14)	No trend
	Winter	10 (0.36)	1.38	0.00	No trend
	Summer	100 (3.62)	-1.49	-7.0 (-0.25)	No trend
Zone 3	Annual	1445	0.47	14.4 (0.99)	No trend
	Monsoon	1160 (80.28)	0.65	15.21 (1.05)	No trend
	Post-monsoon	163 (11.28)	0.27	2.02 (0.13)	No trend
	Winter	10 (0.69)	1.95^{a}	0.26 (0.17)	Increasing
	Summer	**112 (7.75)**	**-1.97^{b}**	**-7.76 (0.53)**	**Decreasing**

Note: Bold indicates statistically significant values.
^{a}10% significance level; ^{b}5% significance level; ^{d}0.1 % significance level
Values in parenthesis denote the percentage of annual rainfall.

The zone 2 is the portion of the catchment having the 116 m drop in elevation. The average rainfall in the zone was found to be 2800 mm and with maximum contribution from the monsoon months (90% of annual rainfall). The results of trend analysis in the zone 2 were quite similar to the zone 1 with an increase of 3% per decade (75 mm per decade) in the monsoon rainfall. This, in turn, has led to an increase in the annual rainfall by 72 mm per year (3% of annual rainfall). Interestingly, the number of rainy days in the zone was found to be 116 per year. The zone 3 lies in the upper reaches of the Western Ghats and was found to have the least rainfall in the catchment. The average annual rainfall was 1445 mm with 100 rainy days per year and no trend could be detected in the annual as well as monsoon rainfall. The winter and summer rainfall contribute to 8.5% of the total rainfall in the zone. An increasing trend was detected during winter and decreasing trend was observed during the summer. The change in the rainfall during winter and summer was found to be negligible (<0.6%) compared to the total rainfall.

6.1.2 Response of streamflow to climate change and elevation

This section discusses the sensitivity of streamflow to the elevation stratification and highlights the characteristics of streamflow in each of the contemporary rainfall zones. The Aghanashini River is rich in terms of ecology and conservation of wetlands and the changes in elevation along with the warming climate over the Aghanashini catchment would exert an influence on the local patterns of streamflow. In order to assess the response of streamflow to climate change and the elevation, the flow from each zone was subjected to trend analysis. It was observed that, the demarcated contemporary rainfall zones would have a different meaning on the streamflow characteristics, as the mechanism of streamflow is highly dependent on the time of concentration. In essence, the demarcated zone 1 would represent the characteristics of the complete Aghanashini catchment. The zone 2 represents the combined response of zone 2 and zone 3 (79.5% of the catchment area) and the zone 3 is standalone representing the initial 32.5% of the catchment area.

The results of the modified Mann-Kendall test for streamflow (1951-2005) are presented in Table 6.2. The annual stream flow of the Aghanashini catchment as a whole for zone 1 was found to be increasing and indicating more availability of water in the river. The decadal increase in the streamflow was estimated at 7.5% of the mean flow (0.7 Mm^3 per decade at 0.1% significance level). The monsoon flow indicated a decadal increase of 21.5% of the mean flow (2 Mm^3 per decade at 0.1% significance level). The zone 2 representing 79.5% of the catchment area, also indicated an increase in the annual and monsoon flow with magnitudes of 5.3% and 15.7% of the mean flow of zone 2 (0.34 and 1 Mm^3 per decade at 1% significance level). The zone 3 was found to have an increase in annual flow by 3% and monsoon flow by 14.5% (0.14 and 0.38 Mm^3 per decade at 5% significance level). Although, the above two zones and the entire Aghanashini catchment showed increasing trend of stream flow, it is important to note their significance levels. The portion of the catchment at the highest elevation has the least statistical significance and the significance increases in the downstream direction. The results are quite concurrent to the increased rainfall over the catchment.

Table 6.2. Trend analysis of streamflow in the zones of Aghanashini catchment

Zone	Streamflow time series	Mean flow (Mm^3)	Statistic value	Sen's Slope Estimator (Mm^3/decade)	Trend
Zone 1	**Annual**	**9.56**	**3.80^d**	**0.71 (7.42)**	**Increasing**
	Monsoon	**26.78**	**3.82^d**	**2.05 (21.44)**	**Increasing**
1295 km^2	Post-monsoon	2.73	1.36	0.16 (1.67%)	No trend
(100%)	Winter	0.11	1.93^a	0.00	Increasing
	Summer	0.22	-0.71	0.00	No trend
Zone 2	**Annual**	**6.40**	**2.93^c**	**0.34 (5.31)**	**Increasing**
	Monsoon	**17.91**	**2.72^c**	**1.01 (15.78)**	**Increasing**
1030 km^2	Post-monsoon	1.89	1.25	0.10 (1.56)	No trend
(79.53%)	**Winter**	**0.08**	**2.12^b**	**0.00**	**Increasing**
	Summer	0.13	-0.71	0.00	No trend
Zone 3	**Annual**	**2.63**	**2.47^b**	**0.14 (5.32)**	**Increasing**
	Monsoon	**7.32**	**2.21^b**	**0.38 (14.44)**	**Increasing**
421 km^2	Post-monsoon	0.86	1.07	0.04 (1.52)	No trend
(32.5%)	**Winter**	**0.03**	**2.41^b**	**0.00**	**Increasing**
	Summer	0.05	-0.87	0.00	No trend

Note: Bold indicates statistically significant values.
^{a}10% significance level; ^{b}5% significance level; ^{d}0.1 % significance level
Values in parenthesis denote percentage of annual streamflow.

In the rivers with mid to high range of elevation stratification, the increase in temperature is related to changes in the frequency and magnitude of flows and the probability of flash floods is higher (Goode et al., 2013; Hassan et al., 2006). The studies have demonstrated the changing rate of water in the stream channels are linked to have an influence on the phenological events of ecosystems and increased scouring of stream bed, especially during the winter season (Davis et al., 2013; Goode et al., 2013; Hauer et al., 1997; Isaak and Rieman, 2013; Rieman et al., 2007). These changes in the flow regimes of the Aghanashini River may possibly modify the patterns of bed scour and sediment transport.

The catchments dominated by high rainfall events have shown seasonal variation in the base flow and the effect of timing of rainfall onto streamflow over the catchments have an influence on the water quality and the rate of chemical weathering (Tennant et al., 2015). It is, therefore, essential to analyze the variation of rainfall to streamflow channel routing in the different elevation zones. The lags between percentiles of rainfall and streamflow are used in the present study as the evaluation metrics for assessing the storage of precipitation and the conversion of rainfall into stream flow. The lags between 25th percentiles of rainfall and streamflow provide an insight of how quickly the rainfall is converted into streamflow. The cumulative distribution plots for the delivery timing of rainfall and streamflow are presented in Fig. 6.4. It may be noted that, the values have been computed by considering daily mean rainfall and streamflow for 55 years (1951-2005). The cumulative distribution is separately plotted (Fig. 6.4) for the two rainfall zones (Zone 2 and Zone 3) and the entire Aghanashini catchment (Zone 1). The thick portion of the plot indicates a higher inter-quartile range.

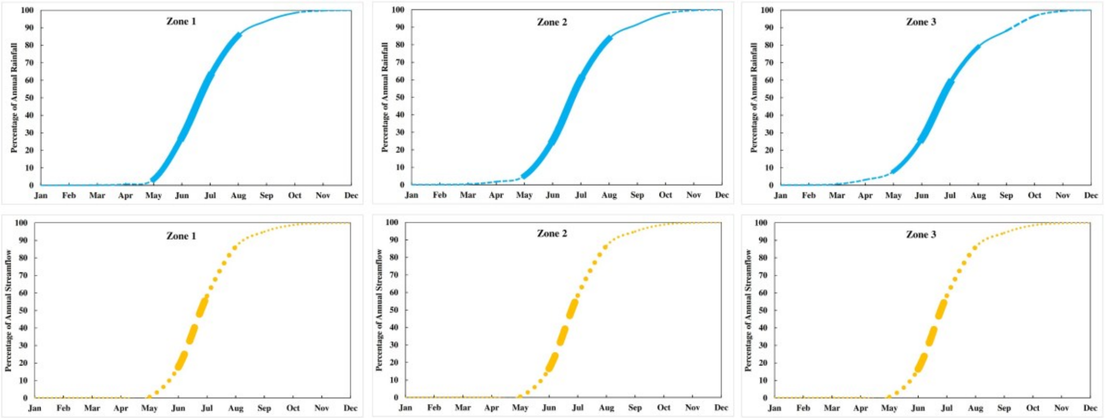

Fig. 6.4. Cumulative distribution plots for rainfall and streamflow in the Aghanashini catchment

In the Aghanashini River, the lag time between rainfall event and resulting run-off for the catchment was found to be directly proportional to the elevation. The lags for the zones 1, 2, and 3 were found to be 10, 20 and 30 days, respectively (Fig. 6.4). These lags are influenced by factors, such as topography, since steeper slopes are associated with the quicker delivery of rainfall into streamflow. This is also true for the intensity and duration of the rainfall which affects groundwater storage and base flow. The shorter lags in the zone 1 and 2 may be due to the steep slope in the zone 2. The intensity of heavy rainfall events (>100 mm) and number of rainy days in the zones 1 and 2 are more than the in the zone 3. Similar lag times were observed in four rain dominated catchments of the U.S.A. (Tennant et al., 2015). The changes in the land use and land cover of the river Aghanashini would affect the time of concentration as well. The observations from the other rivers of the Western Ghats show the greater impact of climate change.

6.2 IMPACT OF CLIMATE CHANGE ON STREAMFLOW

In order to evaluate the hydrologic response of climate change on intra-annual flow, the average monthly rainfall and streamflow in the river catchments were plotted for each of the river catchments. The bar charts (with primary axis) represent the rainfall and the curves (secondary axis) represent the streamflow. The annual cycles were plotted for four time steps to exemplify the historical and forecasted scenarios. The rainfall and streamflow for years 1951-1975 (red color) and 1976-2005 (yellow color) represent the historical conditions (scenario 1) and years 2006-2035 (blue color) and 2036-2060 (green color) represent the forecasted conditions (scenario 2).

6.2.1 Impact assessment on northern rivers

River Purna

The annual cycle of discharge in the river Purna is shown in Fig. 6.5. It was observed that, the maximum rainfall occurred during the months of June, July, August, and September (monsoon months) in scenario 1 and consequently, the peak streamflow in the river Purna was during the month of July and August. The percentages of average streamflow during July, August, September, and October were 24%, 27%, 21%, and 20%, respectively during the years 1951 to 1975. In the forecasted scenario, the maximum rainfall was observed during the month of June and July. Subsequently, the peak streamflow is higher in the month of July (32% of annual streamflow) during 2006-2035. It was also predicted that, the water availability in the river starts from mid-May and begins to recede by end of September.

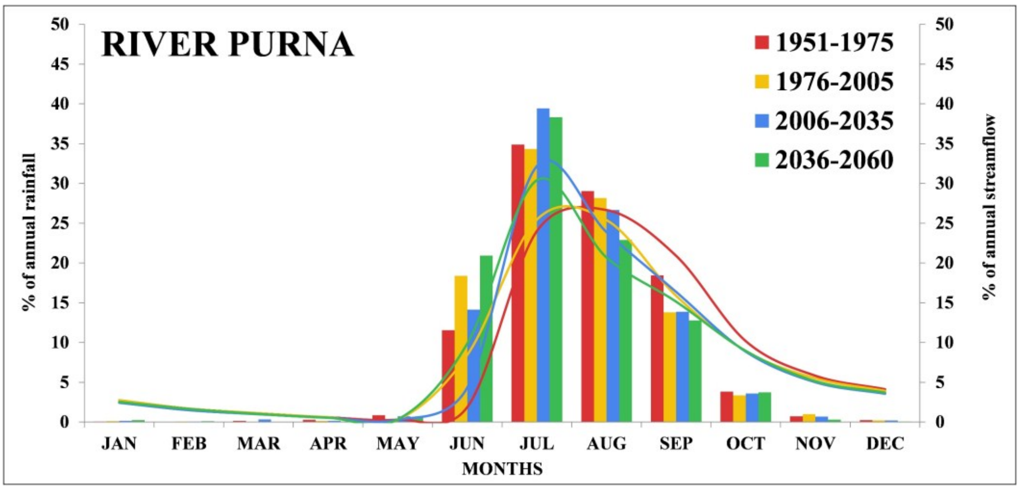

Fig. 6.5. Monthly precipitation and streamflow for river Purna

Fig 6.6 presents the box-whisker plots of the scenario 1 (1951-2005) and scenario 2 (2006-2060). The peak forecasted flow in the river Purna is higher from the month of July and August to the month of July in the scenario 2. A significant decrease of streamflow was observed during the monsoon months and the month of May was found to have an increased flow.

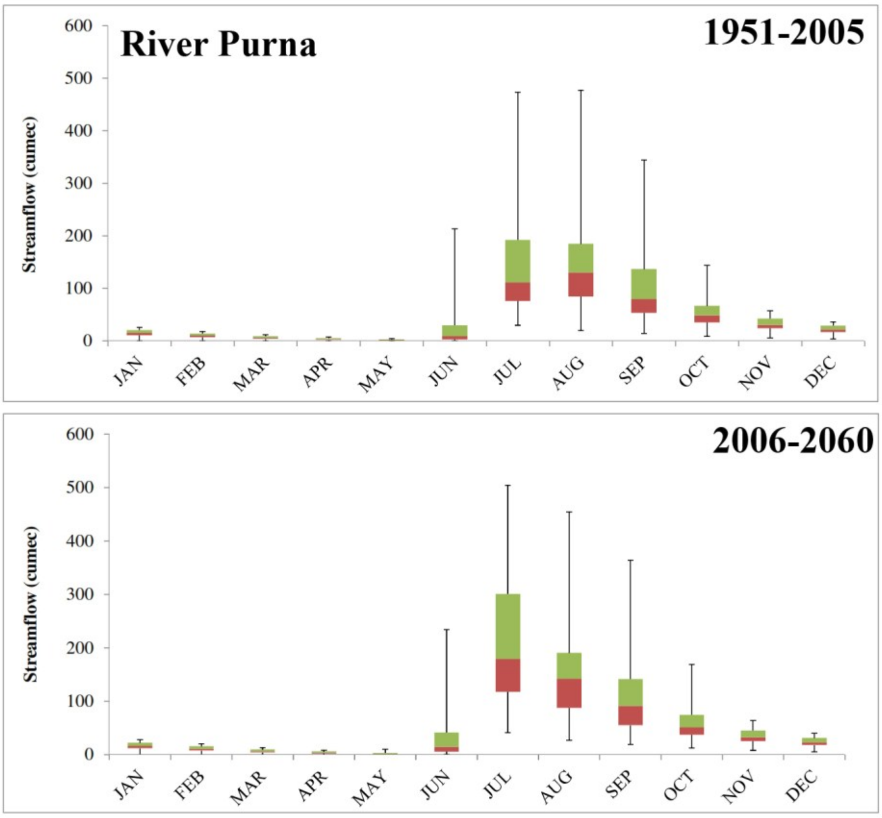

Fig. 6.6. Monthly flow analysis of river Purna

River Ulhas

In the river Ulhas, there were no significant changes to the rainfall and streamflow on the monthly time step during scenario 1 and scenario 2 (Fig 6.7). The peak streamflow was during the month of July. It was however found that, the rainfall during the month of September was less in scenario 2 (2006-2060) and increased in the month of October. The contribution of summer showers increased the availability of streamflow during the month of May and the maximum availability of streamflow in the river was from May to September. The contribution during the month of May increased from 0.03% during 1951-1975 to about 0.2% during the years 2006-2060. The streamflow during September decreased from 13% during 1951-1975 to 10.5% during the years 2006-2060. The box-whisker plots for the river Ulhas are given in Fig. 6.8 and increased streamflow during the month of May is evident.

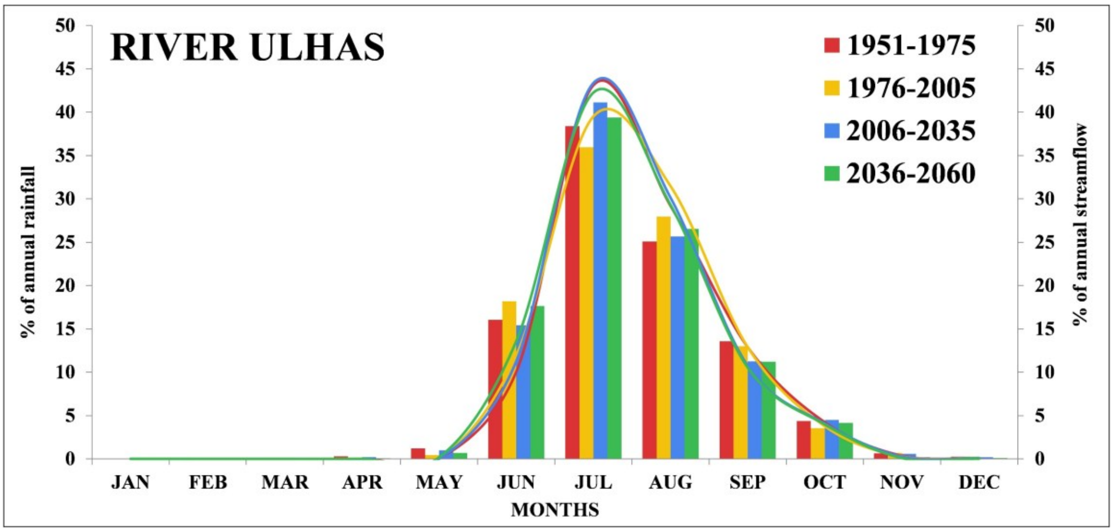

Fig. 6.7. Monthly precipitation and streamflow for river Ulhas

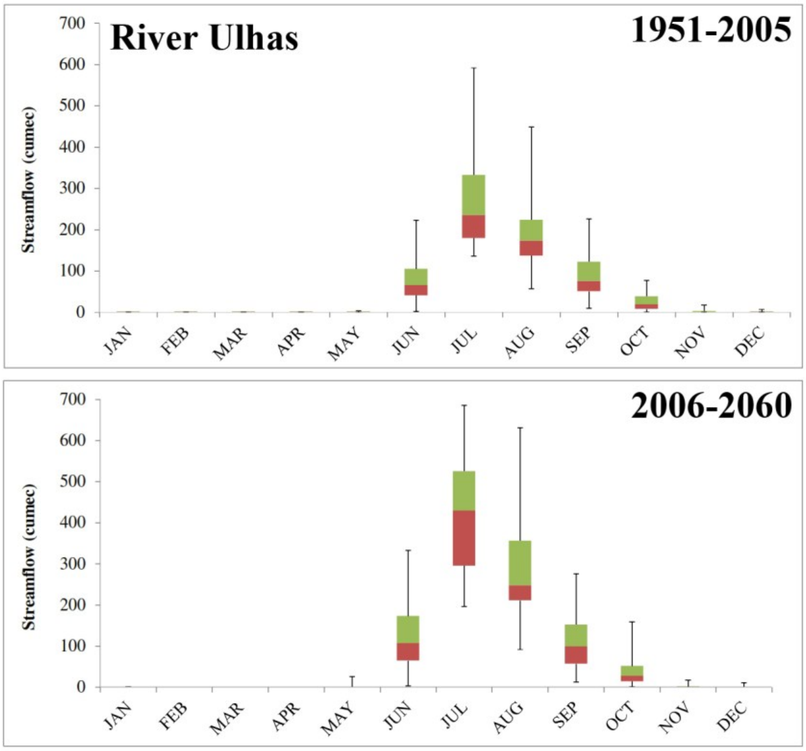

Fig. 6.8. Monthly flow analysis of river Ulhas

River Kajvi

The change in the peak streamflow of river Kajvi was not substantial in the scenario 1 and scenario 2 (Fig 6.9). However, the availability of streamflow in the scenario 2 appears to have slightly preponed to the months of May and June. The box-whisker plots (Fig 6.10) also represented increased contribution of streamflow during the month of May and June.

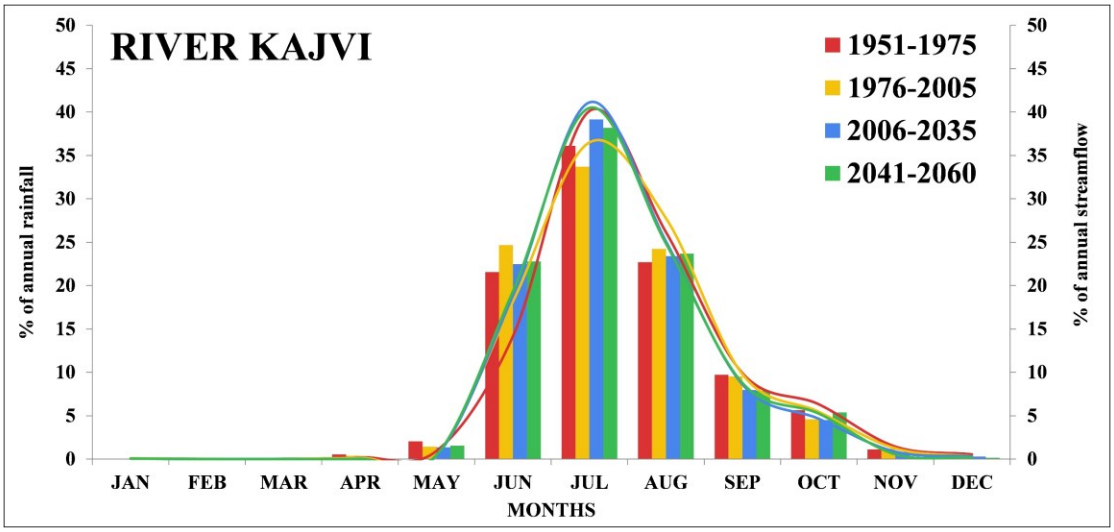

Fig. 6.9. Monthly precipitation and streamflow for river Kajvi

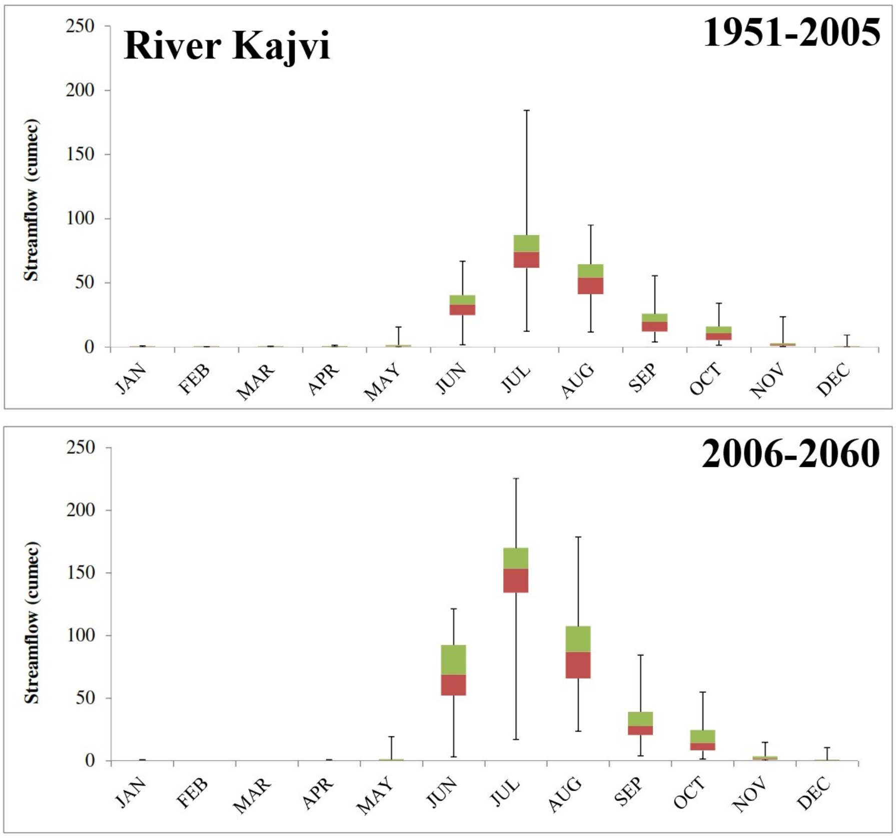

Fig. 6.10. Monthly flow analysis of river Kajvi

6.2.2 Frequency and flow quantiles for the northern rivers

The decadal variation of mean streamflow for the northern rivers (Table 6.3) revealed that, the variation of streamflow across the decades is not very substantial. The mean flow increased in the Purna, Ulhas and Kajvi rivers. The decadal changes could be attributed to the natural variation in the flow of rivers.

Table 6.3. Decadal variation of streamflow for northern rivers (Mm^3)

Period	River Purna		River Ulhas		River Kajvi	
	Mean Flow	% Change	Mean Flow	% Change	Mean Flow	% Change
1951-1960	3.80	-	4.51	-	1.63	-
1961-1970	4.42	16.32	4.36	-3.33	1.58	-3.07
1971-1980	4.42	0.00	4.21	-3.44	1.39	-12.03
1981-1990	3.62	-18.10	4.62	9.74	1.36	-2.16
1991-2000	3.90	7.73	5.21	12.77	1.49	9.56
2001-2010	4.18	7.18	5.51	5.76	2.16	44.97
2011-2020	4.76	13.88	7.92	43.74	2.75	27.31
2021-2030	5.02	5.46	6.85	-13.51	2.41	-12.36
2031-2040	5.55	10.56	7.23	5.55	2.64	9.54
2041-2050	4.51	-18.74	7.61	5.26	2.77	4.92
2051-2060	4.70	4.21	6.76	-11.17	2.36	-14.80

In order to assess the impact of climate change on extreme flow conditions, the streamflow was subjected to frequency analysis at 10-year time interval by calculating the flow quantiles. Prior to the calculation of flow quantiles, bias correction of the RCP data was carried out using the delta-change correction method followed by basic frequency analysis hypothesis verification. The statistical properties of discharge time series of the RCP 4.5 scenario were fairly reproduced in the observed period (Chapter 4). The decadal flow quantiles calculated for the northern river catchments of the Western Ghats are listed in Table 6.4. The Q10 in the Purna and Ulhas rivers increased across different decades and very few changes were observed in the Kajvi river. This indicated that flood events could be experienced in the Purna river in the future. The median flow (Q50) showed an increase in the Purna river whereas no changes were observed in the rivers Ulhas and Kajvi. The High Flow Index (HFI) and Low Flow Index (LFI) were calculated and are presented in Table 6.5. The high flow index was found to be increasing in Ulhas (from 446 to 749) and Kajvi (46 to 103) rivers.

Table 6.4. Decadal variation of flow quantiles for northern rivers (cumecs)

Decade	River Purna			River Ulhas			River Kajvi		
	Q_{10}	Q_{50}	Q_{90}	Q_{10}	Q_{50}	Q_{90}	Q_{10}	Q_{50}	Q_{90}
1951-1960	82.06	16.46	0.46	173.70	0.39	0.01	63.49	1.37	0.02
1961-1970	80.13	16.47	1.16	164.20	0.31	0.01	53.72	1.13	0.03
1971-1980	84.91	19.74	1.93	146.30	0.35	0.00	53.90	1.06	0.02
1981-1990	79.73	15.95	1.02	164.00	0.23	0.00	50.69	0.80	0.02
1991-2000	79.88	16.51	1.78	175.50	0.23	0.00	56.13	1.01	0.02
2001-2010	82.95	16.91	0.12	208.10	0.22	0.01	71.58	0.89	0.02
2011-2020	96.50	20.60	1.85	281.20	0.38	0.02	111.30	1.18	0.02
2021-2030	88.66	19.25	1.46	251.60	0.27	0.01	87.85	0.69	0.01
2031-2040	99.96	20.85	1.93	256.50	0.32	0.01	101.30	0.74	0.01
2041-2050	91.19	19.32	1.36	258.40	0.20	0.01	103.90	0.69	0.01
2051-2060	90.28	19.35	1.43	233.60	0.31	0.01	79.63	0.77	0.01

Table 6.5. Decadal variation of high and low flow indices for northern rivers

Decade	River Purna		River Ulhas		River Kajvi	
	HFI	LFI	HFI	LFI	HFI	LFI
1951-1960	4.99	0.03	445.73	0.03	46.51	0.02
1961-1970	4.87	0.07	529.85	0.02	47.58	0.02
1971-1980	4.30	0.10	418.60	0.01	50.99	0.02
1981-1990	5.00	0.06	720.25	0.01	63.66	0.02
1991-2000	4.84	0.11	759.08	0.02	55.63	0.02
2001-2010	4.91	0.01	925.30	0.02	80.59	0.02
2011-2020	4.68	0.09	730.58	0.04	94.64	0.01
2021-2030	4.61	0.08	932.89	0.02	127.01	0.02
2031-2040	4.79	0.09	804.33	0.02	136.36	0.01
2041-2050	4.72	0.07	1321.74	0.03	151.35	0.02
2051-2060	4.67	0.07	748.72	0.02	103.42	0.01

6.2.3 Impact assessment on central rivers

River Malaprabha

In the Malaprabha river catchment, it was evident that, the contribution of rainfall is increasing during May, June, and July in scenario 2 (Fig. 6.11). And the result of these pre-monsoon showers is that the availability of streamflow in the river would also change slightly. The streamflow availability would be more during the period from May to August in scenario 2 as compared to the availability of water from June to September in scenario 1 (Fig 6.12).

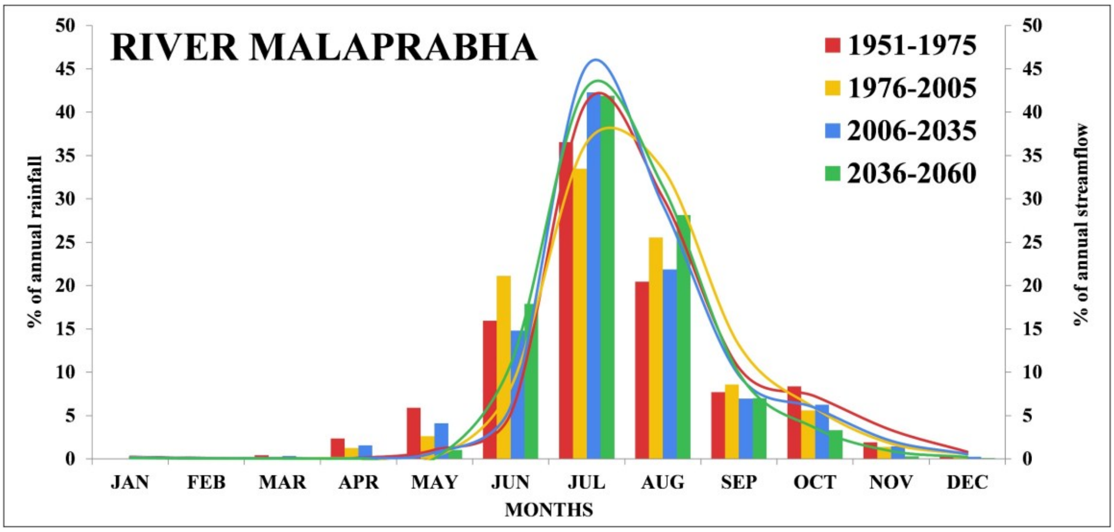

Fig. 6.11. Monthly precipitation and streamflow for river Malaprabha

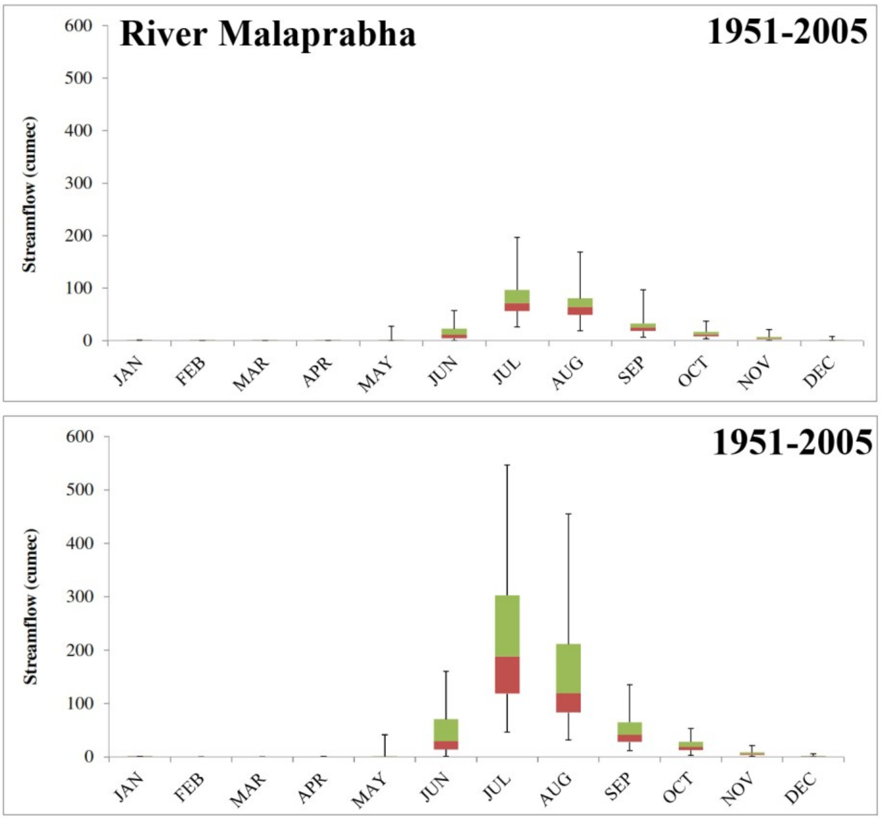

Fig. 6.12. Monthly flow analysis of river Malaprabha

River Aghanashini

In the river Aghanashini, the changes to the monthly contribution of rainfall and streamflow were negligible. The maximum contribution to streamflow was during the month of June, July, and August (Fig 6.13). It was observed from the box-whisker plots that, the streamflow during the month of May increased to some extent (Fig 6.14).

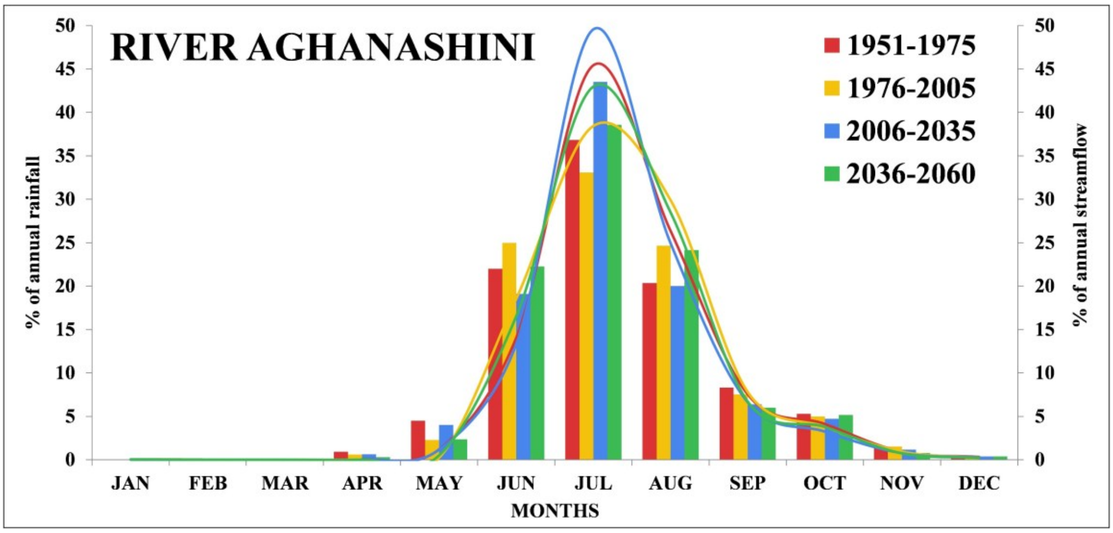

Fig. 6.13. Monthly precipitation and streamflow for river Aghanashini

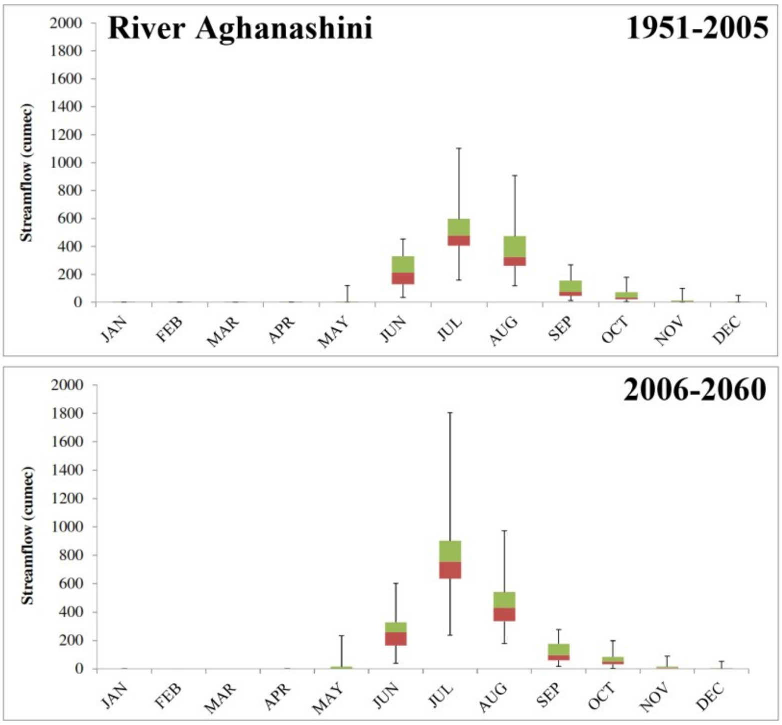

Fig. 6.14. Monthly flow analysis of river Aghanashini

River Tunga

The maximum contribution of rainfall was during the months of June and July in the river Tunga (Fig. 6.15). The availability of streamflow in the river was highest during July. Similar observations were inferred from the box plots as well (Fig. 6.16).

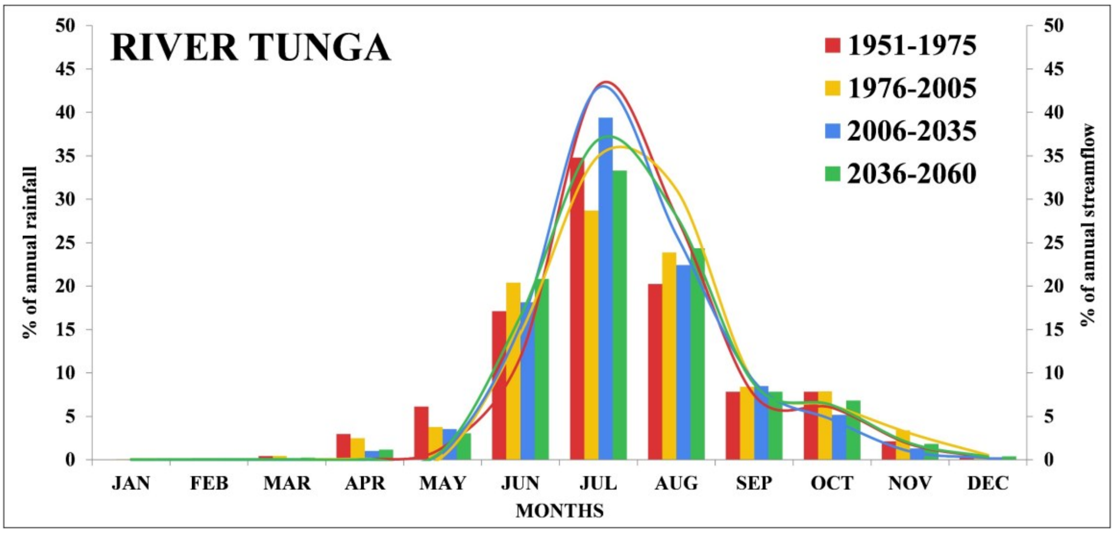

Fig. 6.15. Monthly precipitation and streamflow for river Tunga

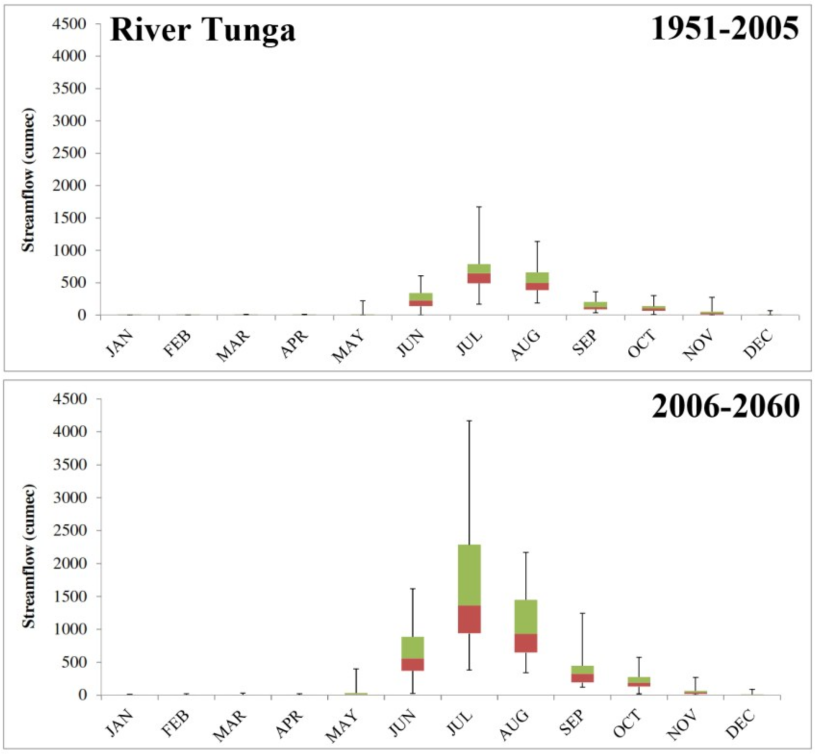

Fig. 6.16. Monthly flow analysis of river Tunga

6.2.4 Frequency and flow quantiles for the central rivers

The analysis of the decadal variation of mean streamflow in central rivers of the Western Ghats (Table 6.6) indicated an increase of streamflow in the Malaprabha and Aghanashini rivers during 1981-1990. The river Malaprabha showed a significant increase during the 2031-2040 as well. In the case of river Tunga, the increased streamflow was observed during 2001 to 2020 and the remaining decades portrayed a decrease in streamflow.

Table 6.6. Decadal variation of streamflow for central rivers (Mm^3)

Period	River Malaprabha		River Aghanashini		River Tunga	
	Mean Flow	% Change	Mean Flow	% Change	Mean Flow	% Change
1951-1960	1.47	-	8.00	-	14.80	-
1961-1970	1.32	-10.20	8.46	5.75	12.65	-14.53
1971-1980	1.31	-0.76	6.91	-18.32	13.23	4.58
1981-1990	1.83	39.69	11.05	59.91	12.15	-8.16
1991-2000	1.65	-9.84	12.09	9.41	13.03	7.24
2001-2010	2.08	26.06	9.96	-17.62	19.76	51.65
2011-2020	2.38	14.42	12.83	28.82	43.65	120.90
2021-2030	1.92	-19.33	11.61	-9.51	35.37	-18.97
2031-2040	4.51	134.90	12.82	10.42	22.50	-36.39
2041-2050	5.28	17.07	13.46	4.99	23.87	6.09
2051-2060	4.36	-17.42	12.21	-9.29	22.86	-4.23

The Q10 flow in all the three central rivers increased across the decades (Table 6.7). The river Tunga was found to have extreme events of Q10 during 2011 to 2030. The Q50 (median flow) indicated an increase in general water availability in the central rivers. The dependable flows (Q90) did not portray large variations. The High Flow Index (HFI) and Low Flow Index (LFI) for the central rivers is presented in Table 6.8. The high flow index in the Malaprabha river increased from 37 to 107 and 52 to 60 in the Tunga river. HFI was found to be higher in the Aghanashini river during 2001-2010. The low flow index did not exhibit variation in the three rivers.

Table 6.7. Decadal variation of flow quantiles for central rivers (cumecs)

Decade	River Malaprabha			River Aghanashini			River Tunga		
	Q_{10}	Q_{50}	Q_{90}	Q_{10}	Q_{50}	Q_{90}	Q_{10}	Q_{50}	Q_{90}
1951-1960	51.89	1.40	0.16	274.40	1.43	0.07	475.20	9.20	0.16
1961-1970	49.08	1.39	0.16	284.50	2.16	0.08	413.00	6.16	0.16
1971-1980	51.28	1.27	0.13	261.50	2.56	0.08	505.20	11.47	0.18
1981-1990	65.34	1.02	0.13	405.10	1.12	0.07	432.40	5.92	0.15
1991-2000	62.18	1.17	0.15	446.90	3.33	0.09	472.00	6.39	0.17
2001-2010	65.65	1.18	0.14	324.60	1.01	0.07	598.80	5.24	0.13
2011-2020	76.05	1.65	0.22	391.60	2.78	0.10	1649.00	15.39	0.28
2021-2030	63.49	1.52	0.16	385.80	2.76	0.09	1373.00	9.00	0.21
2031-2040	156.80	1.52	0.18	465.70	3.62	0.09	898.20	20.88	0.26
2041-2050	210.90	1.63	0.17	487.10	2.92	0.10	813.50	13.93	0.25
2051-2060	170.20	1.59	0.15	404.40	2.55	0.09	772.90	12.84	0.23

Table 6.8. Decadal variation of high and low flow indices for central rivers

Decade	River Malaprabha		River Aghanashini		River Tunga	
	HFI	LFI	HFI	LFI	HFI	LFI
1951-1960	37.01	0.11	192.02	0.05	51.67	0.02
1961-1970	35.23	0.12	132.02	0.04	67.01	0.03
1971-1980	40.38	0.11	102.23	0.03	44.05	0.02
1981-1990	64.25	0.13	362.02	0.06	73.04	0.03
1991-2000	53.05	0.13	134.41	0.03	73.83	0.03
2001-2010	55.78	0.12	320.43	0.07	114.38	0.02
2011-2020	46.09	0.13	141.02	0.04	107.15	0.02
2021-2030	41.66	0.10	139.78	0.03	152.64	0.02
2031-2040	103.43	0.12	128.75	0.03	43.02	0.01
2041-2050	129.39	0.11	167.04	0.03	58.40	0.02
2051-2060	106.78	0.10	158.46	0.03	60.19	0.02

6.2.5 Impact assessment on southern rivers

River Netravathi

The impact of climate change on the streamflow availability of the river Netravathi was found to be very significant (Fig. 6.17). It was observed that, the contribution of pre-monsoon rainfall (month of May) is increasing during the scenario 2 (2006-2060). The contribution of rainfall during the months of August, September, and October reduced significantly. This would limit the maximum streamflow during the months of June and July only. The second half of the Indian southwest monsoon of India and the post-monsoon season (October and November) could witness a rapid decrease of rainfall and streamflow. Although, a minor alteration in the rainfall and streamflow towards the month of May was witnessed in the northern and central rivers, the contribution of pre-monsoon showers was very evident in the river Netravathi. The box plots of monthly streamflow (Fig 6.18) show that, the streamflow during May, June, and July are higher during the scenario 2 and quite less in the remaining months.

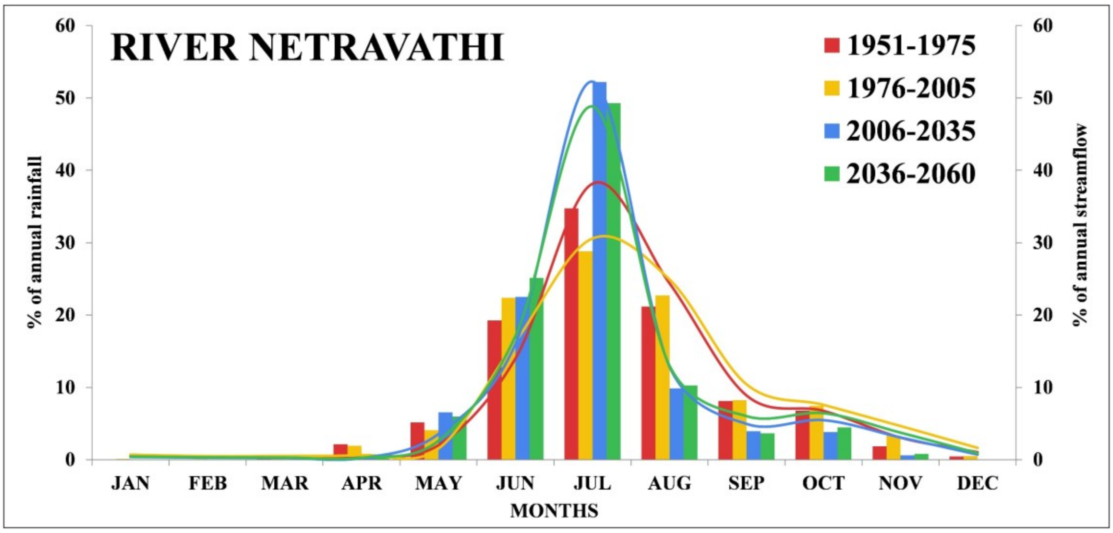

Fig. 6.17. Monthly precipitation and streamflow for river Netravathi

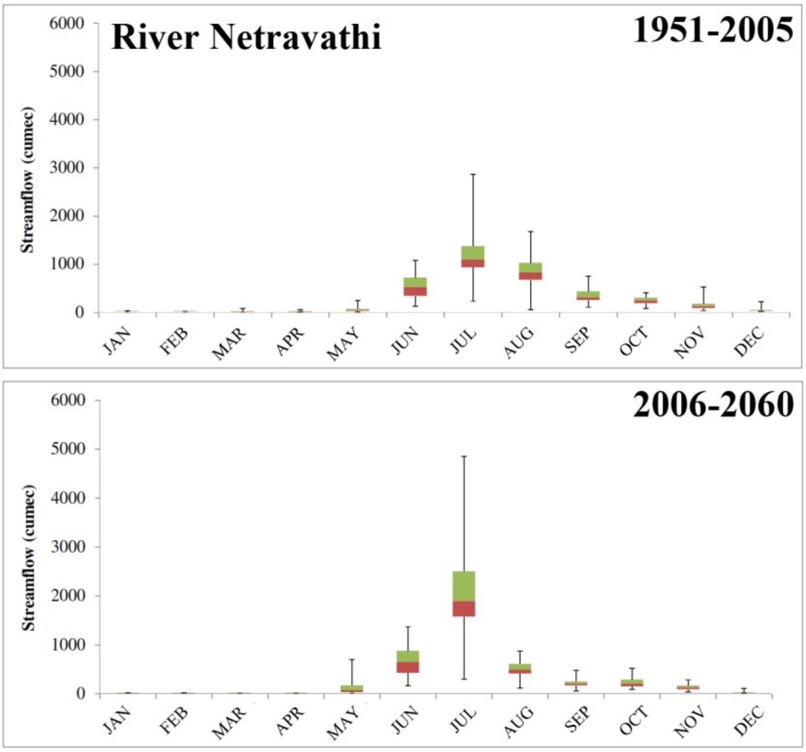

Fig. 6.18. Monthly flow analysis of river Netravathi

River Chaliyar

The rainfall and streamflow for the river Chaliyar showed similar results to the river Netravathi. It was observed that, major contribution of rainfall over the Chaliyar catchment was during June, July, and August during scenario 2 (Fig 6.19). The contribution of rainfall during May is slightly higher. During the withdrawal of southwest monsoon (i.e., September), the rainfall contribution was observed to decrease. The streamflow availability in the river would be higher during May and the recession would begin by the end of August in scenario 2 (Fig 6.20). The influence of northeast monsoon season on river Chaliyar could be noticed during the month of October in Fig 6.19 and 6.20.

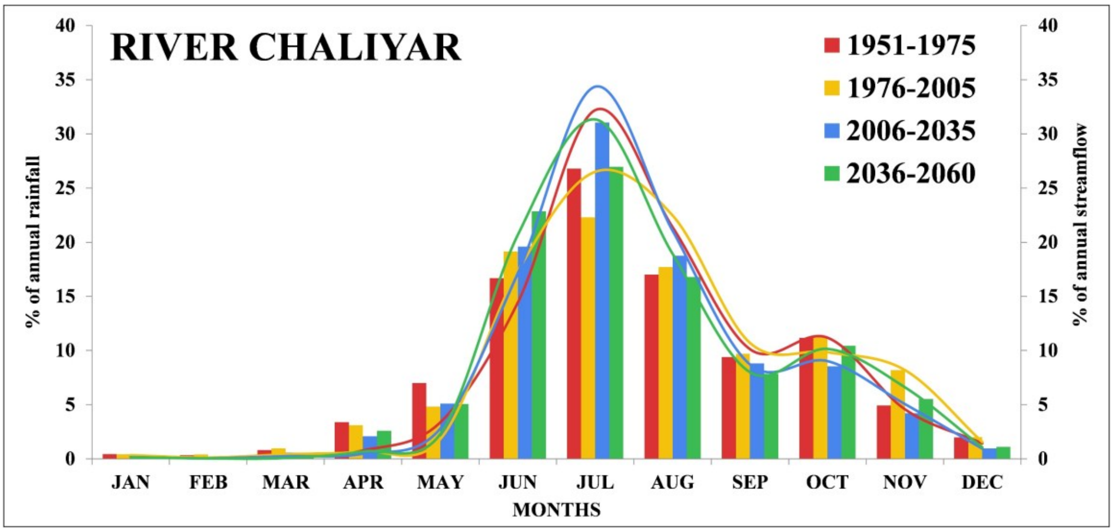

Fig. 6.19. Monthly precipitation and streamflow for river Chaliyar

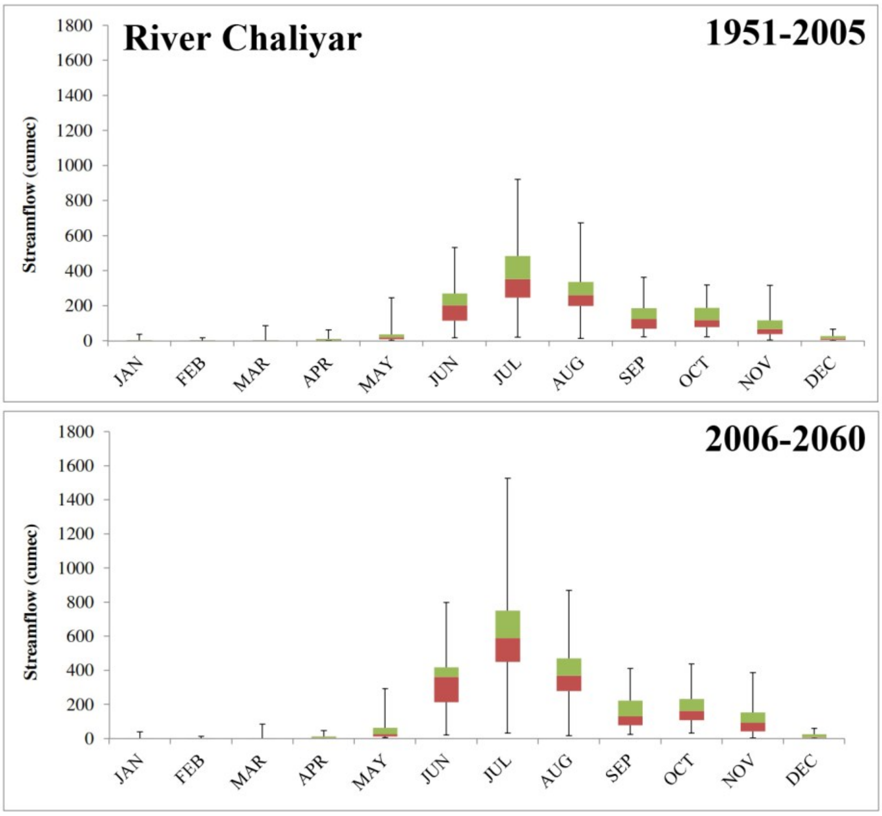

Fig. 6.20. Monthly flow analysis of river Chaliyar

River Vamanapuram

The Vamanapuram River in the southern part of the Western Ghats has the influence of southwest as well as north-east monsoons. About 44% of the total rainfall in the catchment is contributed by the southwest monsoon (June to September) and 29% of the rainfall is contributed by the north-east monsoon (October to November). From the monthly analysis of rainfall (Fig. 6.21), it was observed that, the rainfall contribution during June and July would increase in scenario 2 and could possibly lead to the maximum flow of water during June and recede by July. During the north-east monsoon season, the maximum streamflow would be during the month of October only (Fig. 6.22). August and September were found have relatively lesser streamflow.

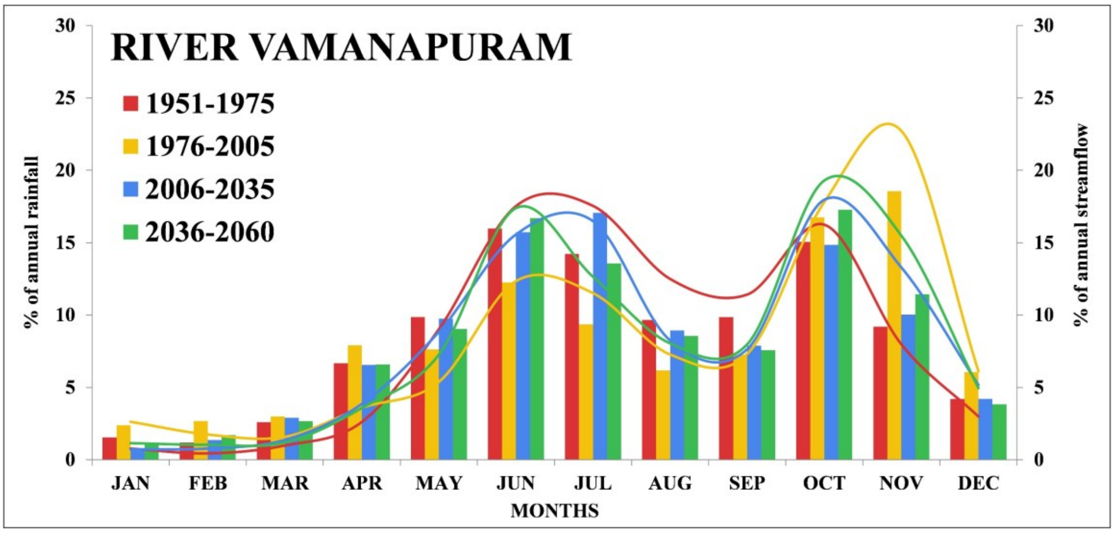

Fig. 6.21. Monthly precipitation and streamflow for river Vamanapuram

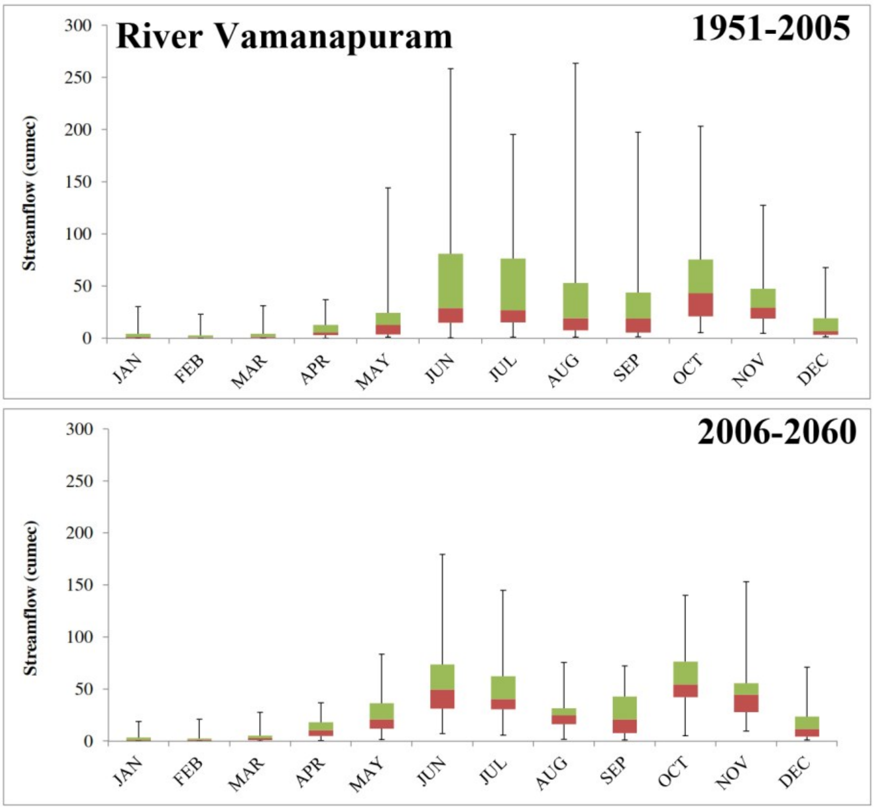

Fig. 6.22. Monthly flow analysis of river Vamanapuram

6.2.6 Frequency and flow quantiles for the southern rivers

The decadal analysis of mean streamflow in the southern rivers revealed a decrease in streamflow across most decades (Table 6.9). The flow quantiles for the southern rivers of the Western Ghats is given in Table 6.10. The Q10 flow in the three catchments decreased which could be due to weakening of the monsoon with lesser number of rainy days having intensity >100 mm and 80-100 mm range. The Q90 flow showed a decrease across different decades. The median flow (Q50) indicated an alternate increasing and decreasing trend throughout Scenario 1 and 2 for the catchments. The median flow and its relative change showed a decreasing trend in all the three river catchments. This could be due to more number of rainy days with intensity < 20mm, which may lead to the losses including percolation with minimal / no streamflow. The HFI and LFI were calculated and are presented in Table 6.11. The high flow index was found to be increasing (from 10.82 to 11.09) for Netravathi whereas it was decreasing for the river Chaliyar (11 to 9.50).

Table 6.9. Decadal variation of streamflow for southern rivers (Mm^3)

Period	River Netravathi		River Chaliyar		River Vamanapuram	
	Mean Flow	% Change	Mean Flow	% Change	Mean Flow	% Change
1951-1960	29.10	-	11.00	-	4.40	-
1961-1970	26.41	-9.24	9.78	-11.09	3.89	-11.59
1971-1980	25.75	-2.50	10.06	2.86	1.54	-60.41
1981-1990	23.28	-9.59	7.72	-23.26	0.93	-39.61
1991-2000	26.26	12.80	10.35	34.07	1.73	86.02
2001-2010	24.39	-7.12	9.37	-9.47	1.72	-0.58
2011-2020	34.05	39.61	15.90	69.69	2.72	58.14
2021-2030	31.27	-8.16	14.24	-10.44	2.52	-7.35
2031-2040	29.23	-6.52	13.95	-2.04	2.37	-5.95
2041-2050	27.63	-5.47	12.62	-9.53	2.38	0.42
2051-2060	24.15	-12.60	11.48	-9.03	1.94	-18.49

Table 6.10. Decadal variation of flow quantiles for southern rivers (cumecs)

Decade	River Netravathi			River Chaliyar			River Vamanapuram		
	Q_{10}	Q_{50}	Q_{90}	Q_{10}	Q_{50}	Q_{90}	Q_{10}	Q_{50}	Q_{90}
1951-1960	869.90	80.40	11.23	365.30	22.26	0.44	149.10	13.60	0.47
1961-1970	778.50	61.87	13.03	325.60	21.77	0.58	117.60	15.72	0.64
1971-1980	881.20	79.01	13.84	349.10	25.15	0.26	46.34	5.48	0.29
1981-1990	745.10	58.66	13.89	268.60	16.47	0.22	28.52	3.44	0.26
1991-2000	843.60	86.30	15.72	365.00	18.75	0.24	51.72	5.12	0.46
2001-2010	675.20	61.26	8.60	315.00	14.35	0.17	53.78	4.60	0.37
2011-2020	769.90	89.52	11.63	485.60	29.81	0.33	80.88	11.11	0.57
2021-2030	859.30	73.55	9.60	514.90	26.14	0.29	76.98	11.02	0.49
2031-2040	883.70	68.27	11.64	492.70	25.09	0.10	71.18	10.20	0.26
2041-2050	769.00	67.84	10.08	450.80	17.96	0.15	74.06	8.44	0.40
2051-2060	631.10	56.90	9.79	395.20	19.05	0.18	60.07	6.31	0.34

Table 6.11. Decadal variation of high and low flow indices for southern rivers

Decade	River Netravathi		River Chaliyar		River Vamanapuram	
	HFI	LFI	HFI	LFI	HFI	LFI
1951-1960	10.82	0.14	16.41	0.02	10.96	0.03
1961-1970	12.58	0.21	14.96	0.03	7.48	0.04
1971-1980	11.15	0.18	13.88	0.01	8.46	0.05
1981-1990	12.70	0.24	16.31	0.01	8.28	0.08
1991-2000	9.78	0.18	19.47	0.01	10.10	0.09
2001-2010	11.02	0.14	21.95	0.01	11.70	0.08
2011-2020	8.60	0.13	16.29	0.01	7.28	0.05
2021-2030	11.68	0.13	19.70	0.01	6.99	0.04
2031-2040	12.94	0.17	19.64	0.00	6.98	0.03
2041-2050	11.34	0.15	25.10	0.01	8.78	0.05
2051-2060	11.09	0.17	20.75	0.01	9.52	0.05

6.3 CLOSURE

The impacts of climate change were assessed on nine river catchments originating in the Western Ghats of India. In addition to assessing the hydrological impacts of climate change, an attempt was made to evaluate the effects of topography on rainfall and streamflow. The flow quantiles and the indices derived from the quantiles (high flow and low flow index) were further used to describe the flow regime. The spatial distribution of rainfall indicated higher rainfall at some distance from the crest of the Western Ghats and the lags between rainfall and streamflow generation were found to directly relate the elevation. For the northern rivers (Purna, Ulhas and Kajvi) and central rivers (Malaprabha and Aghanashini), a gradual increase in high flow events is predicted. More rainfall and streamflow during the pre-monsoon season was predicted in all the catchments. In the southern catchments, the changes in the flow regimes were quite evident. When flow regime changes, peculiar adaptations may be required to endure the new situation, which involve life histories, behaviors, and morphologies of plants and animals (Lytle and Poff, 2004). An overview of advantages and disadvantages of different adaptations to flooding and drought for a range of organisms can be found in Lytle and Poff (2004).

CHAPTER 7

SUMMARY AND CONCLUSIONS

The focus of the present study was to assess the impacts of climate change on rivers originating in the Western Ghats of India. Nine river catchments were selected for the purpose of representing the rivers originating from the entire range of the Western Ghats of India. The SWAT hydrological model was used for modeling the hydrology of the river catchments based on climatic variable. The study employed the RCA4 simulations (RCP 4.5 scenario) for predicting the future climatic scenarios for the river basins. The RCM simulations generally require pre-processing (bias correction) and therefore, the performance of bias correction methods was evaluated. The best suited bias correction method for the Western Ghat catchments was adopted after the comparative analysis. In order to examine the trend of hydro-meteorological variables, the historical and bias-corrected future scenarios were subjected to modified Mann-Kendall trend test. The hydrological analysis was carried out to understand the uncertainties in the future climate. Also, the dependence of rainfall and streamflow on the topography of Western Ghats of India was examined.

This chapter presents the conclusions drawn from the present investigation. The conclusions are presented sequentially in line with the framed objectives for convenience. Further, the limitations of the present study and scope for further research are also highlighted.

7.1 BIAS CORRECTION FOR PRECIPITATION AND TEMPERATURE

This work is aimed to evaluate the appropriate bias correction methods for the catchments spread over the temperate zone along the west coast of India. The Indian economy being primarily dependent on the monsoon rains, the hydrological impact of climate variables play a crucial role. The Western Ghats are the tropical forest ranges covering the entire west coast of India. Many rivers originate in these mountain ranges and flow west or eastwards to join the Arabian Sea and the Bay of Bengal respectively.

The bias correction methods adopted and compared in this study are the linear scaling (LS), delta change correction (DC), local intensity scaling (LI), power transform (PT), variance scaling (VS), and the distribution mapping (DM) method. Out of the above, five bias correction methods were applied for precipitation (LS, DC, LI, PT, and DM) and four methods were applied for temperature (LS, DC, VS, and DM). The performance of the correction methods was assessed based on the precipitation and temperature simulated by an RCM driven by GCM and the following conclusions may be drawn from this study:

1. The precipitation obtained from the raw-RCM is biased compared to the observed precipitation. No improvement was observed in the statistic of mean wet-day precipitation using the LS, LI, PT and DM methods except the DC method. The DC method corrects the frequency of wet days since the anomalies between the simulated results are super-imposed over the observed time series. The improvement in correcting the mean wet-day precipitation was significant as NSE for Purna, Ulhas, Kajvi, Aghanashini, Netravathi, and Chaliyar were found to be 0.96, 0.95, 0.75, 0.76, 0.92, and 0.73, respectively.

2. Comparing the season-wise performance, the raw-RCM tends to underestimate the heavy rainfall and overestimate the light precipitation events and precipitation frequencies. The DC method significantly improved the ARE during monsoon (45%) and post-monsoon (35%) compared to other methods. However, the method was unable to perform exceptionally good during monsoon and post-monsoon seasons because of the inherent property of RCMs to underestimate Indian southwest monsoon rainfall. The temperature is simulated better than precipitation in the climate models. The DC method was capable of representing the mean daily temperature accurately.

3. The streamflow estimated using the DC method yielded good results for five catchments. The NSE for Purna, Ulhas, Aghanashini, Netravathi, and Chaliyar were found to be 0.97, 0.64, 0.82, 0.89, and 0.90, respectively. Hence, the performance of the RCM was found to be better for the catchments on the

windward side of the Western Ghats which flow across larger elevation difference.

4. The performance of the DC method was poor in the Kajvi and Vamanapuram catchments with NSE of 0.37 and 0.34, respectively. The DC method failed to perform in the Malaprabha and Tunga catchments which are on the leeward side of the Western Ghats. When the RCM was applied way outside the computational boundaries i.e., in the case of plateau regions, the problem was more pronounced. Hence, the RCM is more appropriate to simulate orographic precipitation than the precipitation in the plateau regions (leeward side of Western Ghats).

5. The over-estimation for the river Vamanapuram may be because, it is one of the southernmost rivers of India which is influenced by both the southwest as well as north-east monsoons. It may, therefore, be noted that, the hydrology of a catchment is very sensitive to precipitation and a small bias could lead to large deviation in the hydrological components. Hence, there is a need for validation of pre-processing (bias correction) methods prior to studying the impacts of climate variables specific to the region depending on its climate pattern. This work concludes that, the delta correction method is the most appropriate method of bias correction for the impact analysis of climate variables for the catchments of the Western Ghats.

7.2 TREND ANALYSIS OF HYDRO-METEOROLOGICAL VARIABLES

The trend analysis of hydro-meteorological variables was carried out for the purpose of understanding the variation of hydro-meteorology in the past and in order to reasonably predict the future trend under changing climatic conditions. The design of infrastructure for management of water resources needs an exhaustive understanding of the behavior of hydro-meteorological variables over a long period of time. The outcome of the present study was aimed at filling this gap. The components of the hydrological cycle viz., rainfall, temperature, potential evapo-transpiration and the streamflow were subjected to trend analysis. The trend analysis was carried out for two scenarios depicting the historical (scenario 1; 1951-2005) and the future climatic conditions (scenario 2; 2006-2060). The modified Mann-Kendall test was used to detect the trend in the hydro-meteorological variables and the Sen's slope estimator was employed to quantify the magnitude of the trend. The standardized rainfall anomalies were calculated in to assess the wet and dry years. The following conclusions are drawn from this study:

1. The results of the trend analysis of annual rainfall indicate that, the temporal variability of rainfall is lesser in northern river catchments of the Western Ghats and variability increases towards the south. The annual rainfall increased in the Ulhas and Aghanashini river catchments by 4% and 3% per decade respectively whereas, the annual rainfall in the Netravathi and Vamanapuram catchment decreased by 3% and 7% per decade.

2. The number of rainy days (rainfall >2.5mm/day) in the Purna, Tunga, Netravathi, Vamanapuram river catchments were found to be 84, 142, 160, and 149 days, respectively (for scenario 1). This leads to the inference that, the central and southern portions of the Western Ghats receive more events of rainfall, but the intensity of rainfall is decreasing over time. The prognosis from the trend analysis indicates a severe shortage of rainfall over southern river catchments of the Western Ghats of India.

3. The contribution of southwest monsoon rains is approximately 90% in the northern river catchments. In the Purna and Ulhas river catchments, the monsoon contributes to about 95% of annual rainfall. Although no trend was detected in the Purna catchment, the Ulhas catchment was found to have increased monsoon rainfall by 4% per decade.

4. A similar increase in monsoon season rainfall was found in the Malaprabha and Aghanashini river catchments which increased at 4% and 3.5% per decade, respectively. The monsoon rainfall in Netravathi and Vamanapuram catchments

decreased at 3% per decade and over Chaliyar catchment by 2.5% per decade. The signals of climate change, therefore, indicate a weakening of Indian southwest monsoon, especially in southern parts of the Western Ghats of India.

5. The annual temperature over river catchments of the Western Ghats of India is increasing and could potentially lead to an acceleration of thermally driven hydrological processes. The increase in annual and seasonal mean temperature was estimated between 0.01^0C to 0.14^0C per decade. The historical annual temperature (1951-2005) over the northern river catchments increased at the rate of 0.05^0C to 0.07^0C per decade.

6. The increase in historical annual temperature of the central catchments of the Western Ghats was estimated between 0.07^0C and 0.08^0C per decade and it increased by 0.09^0C and 0.12^0C per decade in the southern catchments. It could, therefore, be inferred from the results that, the southern portion of the Western Ghats (in Kerala and Tamil Nadu) has witnessed a higher rate of increase in annual temperature than the central (in Karnataka) and northern portion (in Gujarat and Maharashtra).

7. The rate of increase in the seasonal temperature (especially monsoon and post-monsoon season) is higher than the increase in annual temperature. This was found true for most of the Western Ghat catchments. In the northern river catchments, the mean post-monsoon temperature increased by 0.10^0C and 0.12^0C per decade (Ulhas and Kajvi catchments), respectively. In the central catchments, the post monsoon temperature increased by 0.11^0C per decade in Malaprabha catchment.

8. In the southern catchments, the monsoon temperature in Vamanapuram catchment increased by 0.13^0C per decade. This would mean that, the monsoon and post-monsoon seasons are becoming warmer compared to the past. Surprisingly, the rate of increase in temperature during summer season was

lesser than the monsoon and post-monsoon seasons (in northern and central catchments).

9. In the southern river catchments, the temperature during summer season witnessed an increase at 0.12^0C per decade. The southern catchments were found to be more vulnerable to increase in temperature. The variation in seasonal temperature was found to be similar during the forecasted scenario as well. The rate of increase could be as high as 0.14^0C during monsoon and summer season.

10. The rate of warming is lesser in the northern and central river catchments and higher in the southern catchments. As a consequence of warming, the potential evapotranspiration (PET) is increasing across the catchments of the Western Ghats. The perturbations of a warmer air temperature are likely to increase the river water temperature and would affect the aquatic habitat attributes, fisheries and ecological health of wetlands.

11. The impacts of climate change on streamflow in the southern portion of the Western Ghats were quite discernible. The mean annual flow in Vamanapuram, Chaliyar, and Netravathi was found to be decreasing at the rate of 18%, 7%, and 4% per decade. The central and southern rivers are more vulnerable to climate change and the river Aghanashini showed better resilience in coping with the rising temperatures.

12. The streamflow in the river Aghanashini increased at the rate of 7.5% per decade. Although the river Malaprabha did not exhibit an increase in the historical period, it is expected to have an increase in annual streamflow at 17.5% per decade in the future. In the northern portion of the Western Ghats, the river Kajvi witnessed a decrease at 3% per decade in the historical scenario and it is further expected to decrease by 3.5% per decade in the future. The anthropogenic interventions in the form of excessive withdrawal (irrigation) and/or diversion (hydropower) in the rivers (especially in southern rivers of

Western Ghats) is bound to disrupt the health of the riparian ecosystem. The study, thus, brings out the impact of climate change on hydro-meteorology of rivers originating in the Western Ghats of India.

7.3 IMPACTS OF CLIMATE CHANGE ON HYDROLOGY

The assessment of hydrological impacts of climate change was based on the recent climate change simulations (RCP 4.5) on a catchment scale. The results indicate a reduction in the availability of water resources and variation in the hydrological cycle, especially in the southern rivers of the Western Ghats. The SWAT model was found to be a valuable operational tool for the assessment of hydrological impacts of climate change. In addition to assessing the hydrological impacts of climate change, the influence of elevation-stratification on rainfall and streamflow were assessed.

1. The spatial distribution of rainfall indicated that, the maximum intensity of rainfall over the west-flowing rivers of the Western Ghats of India is not at the highest elevation, but at some distance from the crest on the windward side. Whereas, in the case of the east-flowing rivers, the maximum rainfall is at the crest and decreases on the leeward side from the Western Ghats. The lag time between the rainfall event and the resulting runoff were found to be directly proportional to the topography and elevation stratification of the basin.

2. The major contributing months to Indian southwest monsoon were found to be June and July in the forecasted climate conditions. The contribution from the second half of the monsoon season (August and September) was found to be decreasing. As a consequence of the variations in rainfall pattern, the peak flow in the several rivers of the Western Ghats was observed to be more during the month of July itself, rather than during July to August.

3. The decadal variation of streamflow in the rivers revealed that the mean streamflow in the northern and central rivers of Western Ghats is likely to increase by the year 2060. On the other hand, there is a decrease in mean

streamflow of the southern rivers (especially river Netravathi and Vamanapuram).

4. From the frequency analysis, it was found that the Q10, Q50, and Q90 flows are predicted to increase in the central rivers of the Western Ghats. In the Malaprabha river, Q10 increased from 52 cumecs to 170 cumecs. In the Aghanashini river, it was predicted to increase from 274 to 404 cumecs and Q10 increased from 475 to 773 cumecs in the Tunga river.

5. The southern rivers (Netravathi and Vamanapuram) indicated a decrease in the Q10 from 879 to 631 cumecs and 149 to 60 cumecs respectively. Although the Chaliyar river depicted decadal variations, the Q10 and Q50 did not vary significantly. The Q90, however, decreased prominently across all the southern rivers. The lesser flow in the rivers, i.e., the decrease in Q90 could potentially hinder the water quality and ecosystem of the rivers.

6. The indices derived from the flow quantiles, i.e., the High Flow Index (HFI) and Low Flow Index (LFI) did not fluctuate in the Purna river. The Ulhas and Kajvi rivers witnessed an increase in the HFI. The HFI increased in the Malaprabha and Tunga rivers and decreased in the Aghanashini river. The changes to LFI were negligible in the northern and central rivers. In the southern rivers, HFI increased marginally in the Netravathi river (10.82 to 11.09) and Chaliyar river (16.40 to 21) and decreased in the Vamanapuram river (11 to 9.50). The LFI increased in the Netravathi and Vamanapuram rivers.

7.4 LIMITATIONS OF THE STUDY

1. The SWAT models were calibrated using data from single river gauge on each river. The availability of a larger database would have permitted the multi-site (multi-gauge) calibration of the SWAT model.

2. During the calibration and validation of the SWAT model, it was found that the SWAT model could not simulate the extreme streamflow events at certain times.

3. None of the bias correction methods used in this study could correct the variance in some of the basins selected.

4. One scenario and RCM are used in the study and there is no guarantee that the historic trend will repeat for future in a climate change perspective.

5. The focus of the present study is to throw light on the general behavior of the river under changed climate conditions and not the extreme events. Also, the focus was not to study the uncertainty.

6. The projected changes on land use and land cover are not considered over the forecasted period.

7. The major limitation of the study was the lack of groundwater recharge evaluation under changed climate conditions.

7.5 SCOPE FOR FUTURE RESEARCH

1. The changes to the water quality may be taken up under climate change scenarios as reduced streamflow might possibly increase the contamination of water.

2. The hydrological and ecological impacts of extreme rainfall events can be studied.

3. Detailed field study of elevation-based stratification of rainfall and streamflow by setting up monitoring network designed specifically for montane river catchments may be carried out.

4. The extreme events under changed climate change scenarios may be studied.

5. Multiple RCMs may be used to assess the uncertainty in the climate change scenarios.

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PUBLICATIONS

International Journals

1. **Amogh Mudbhatkal** and Mahesha Amai. (2017). "Regional climate trends and topographic influence over the Western Ghat catchments of India.", RMetS's International Journal of Climatology.
   DOI Permalink: http://onlinelibrary.wiley.com/doi/10.1002/joc.5333/full

2. **Amogh Mudbhatkal** and Amai Mahesha. (2017). "Evaluation of bias correction methods for hydrologic impact studies over the Western Ghat basins of India", ASCE's Journal of Hydrologic Engineering, 23 (2).
   DOI Permalink: http://ascelibrary.org/doi/abs/10.1061/(ASCE)HE.1943-5584.0001598

3. **Amogh Mudbhatkal**, R.V. Raikar, B. Venkatesh and A. Mahesha. (2017). "Climate change impact on varied river flow regimes of southern India", ASCE's Journal of Hydrologic Engineering, 22 (9).
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4. Sharannya T. M, **Amogh Mudbhatkal**, and A. Mahesha, "Assessing climate change impacts on river hydrology – a case study in the Western Ghats of India", *Journal of Earth System Science.* (Under Review)

International Conferences

1. **Amogh Mudbhatkal** and A. Mahesha, (2017) "Climate change impacts on flow regimes of Western Ghats, India", *3rd World's Large River Conference on the "Status and Future of the World's Large Rivers"*, India Habitat Centre, New Delhi, India, 18-21 April 2017

2. **Amogh Mudbhatkal**, Rajkumar Raikar, B. Venkatesh and Amai Mahesha, (2017) “Impact of climate change on hydrology of west flowing river of Western Ghats, India”, *ICHES-2017*, KLE Dr. MSSCET, Belgaum, India, 23-25 March 2017

3. **Amogh Mudbhatkal** and A. Mahesha, (2016) “Performance of bias correction methods for Malaprabha catchment, India”, *HYDRO 2016 INTERNATIONAL*, CWPRS Pune, India, 8-10 December 2016

4. **Amogh Mudbhatkal**, Venkatesh. B., R. V. Raikar, and A. Mahesha, (2015) “Climate change impact on small-scale Western Ghat catchment, India”, *HYDRO 2015 INTERNATIONAL*, IIT Roorkee, India, 17-19 December 2015

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