IMPACT OF CLIMATE CHANGE AND WATERSHED DEVELOPMENT ON RIVER BASIN HYDROLOGY USING SWAT – A CASE STUDY

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KERALA, INDIA

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by

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THESIS

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2016

DECLARATION

I, hereby declare that this thesis entitled **"IMPACT OF CLIMATE CHANGE AND WATERSHED DEVELOPMENT ON RIVER BASIN HYDROLOGY USING SWAT – A CASE STUDY"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

Place: Tavanur **Anu Varughese**

Date: 18/10/2016 **(2013-28-101)**

CERTIFICATE

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Date:18/10/2016

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Dedicated to

The faculty of Agricultural Engineering

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ABBREVIATIONS USED

ASABE	:	American Society of Agricultural and Biological Engineers
Assoc.	:	Association
ASTER	:	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CGWB	:	Central Ground Water Board
CMIP	:	Coupled Model Inter comparison Project
CN	:	Curve Number
CORDEX	:	Coordinated Regional Climate Downscaling Experiment
CRC	:	Cooperative Research Centre
CWRDM	:	Centre for Water Resources Development and Management
DEM	:	Digital Elevation Model
Eng.	:	Engineering
ESRI	:	Environmental Systems Research Institute
et al.	:	and others
ET	:	Evapotranspiration
FAO	:	Food and Agricultural Organisation
Fig.	:	Figure
GCM	:	Global Climate Model
GFDL	:	Geophysical Fluid Dynamics Laboratory
GIS	:	Geographical Information System
GPS	:	Global Positioning System
$GtCO_2$	:	Giga tones of Carbon dioxide
HRU	:	Hydrologic Response Unit
IITM	:	Indian Institute of Tropical Meteorology
Int.	:	International
J.	:	Journal
ha	:	Hectare
km^3	:	Cubic kilometre
LISS	:	Linear Imaging Self Scanning Sensor

mm	:	Millimetre
m^3/year	:	Cubic metre per year
Mm^3	:	Million cubic metre
MSL	:	Mean Sea Level
NSE	:	Nash Sutcliffe Efficiency
PBIAS	:	Percentage Bias
Proc.	:	Proceedings
RCM	:	Regional Climate Model
RCP	:	Representative Concentration Pathway
RH	:	Relative humidity
RMSE	:	Root Mean Square Error
Sci.	:	Science
SCS	:	Soil Conservation Service
SD	:	Standard Deviation
Soc.	:	Society
SPI	:	Standardized Precipitation Index
SRTM	:	Shuttle Radar Topography Mission
SWAT	:	Soil and Water Assessment Tool
t/ha	:	tonnes per hectare
TIFF	:	Tagged Image File Format
USDA	:	United States Department of Agriculture
USGS	:	United States Geological Survey
USLE	:	Universal Soil Loss Equation
UTM	:	Universal Transverse Mercator Co-ordinate system
VCB	:	Vented Cross Bar
Viz.	:	Namely
WCRP	:	World Climate Research Programme
WMO	:	World Meteorological Organisation
WWDR	:	World Water Development Report

Introduction

CHAPTER I

INTRODUCTION

Land and water are the two primary natural resources which are becoming very scarce and limited in the 21st century. Among these two, availability of fresh water is critically limited in most parts of the world. According to FAO (2005), the largest share of fresh water in the world lies in America, having 45 percent, followed by Asia with 28 percent. In terms of per capita water availability in each continent, Asia stands in the fourth place with 3400 m^3/year, behind America, Europe and Africa in the first, second and third place respectively. Global water demand is mainly influenced by population growth, urbanization, socio-economic development and the consequent increase in consumption by different stake holders. This ever increasing demand has made water resource planning and management a complex and challenging task.

By the year 2050, the global water demand is projected to increase by about 55 percent, mainly due to growing demands from industries, thermal electricity generation and domestic use (WWDR, 2015). Due to this steady increase in demand, water scarcity is said to be one of the most challenging issues that the world would be facing in future. The water availability is also affected by other factors like seasonal variations in rainfall, changes in land use, shifts in the hydrologic cycle and climate change. Availability of water is inextricably linked to food security, health and sanitation and thus to the overall development of the society. The imbalance between the demand and resource availability will be exacerbated if proper interventions are not made in time.

Climate plays a major role in the hydrology of an area and thus on the livelihood and socio-economic development of the societies. Climate change is recognized as one of the most serious challenges mankind is facing today. It has a profound impact on the water cycle and water availability at the global, regional, basin, and local levels. The freshwater resources are highly vulnerable to climate change, with far reaching consequences on human societies and ecosystems (Bates *et al*., 2008). Climate change, rapidly increasing population and depletion of natural resources have become global challenges in the 21st century.

Several researchers have studied the variability and trends in temperature and rainfall across the globe. The temperature shows an increasing trend during the past and the global temperature has risen by 0.85°C (0.65 to 1.06) over the period 1880 to 2012 (IPCC, 2014). Fifteen of the 16 hottest years was recorded in this century, with 2015 being significantly warmer than the record-level temperatures seen in 2014 (WMO, 2016). The warmest five-year period was also recorded during 2011-15. The spatial and temporal pattern of Indian monsoon rainfall is strongly affected by the changes in the air and ocean temperatures (Jagadeesh and Anupama, 2014; Goswami *et al*., 2006). Increasing temperature regimes over long periods and changes in general rainfall pattern at local level need to be studied for understanding the regional scenarios.

Anthropogenic greenhouse gas (GHG) emissions since the pre-industrial era have given rise to large increases in the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Between the years 1750 and 2011, cumulative anthropogenic CO_2 emissions to the atmosphere were 2040 ± 310 $GtCO_2$, of which about half occurred in the last 40 years (IPCC, 2014). The other changes including sea level rise, melting of ice caps, and removal of many rare species are also likely to occur due to climate change. The changing climate affects the hydrologic cycle and water resources, which eventually influence the life of the people. To assess and simulate such potential changes, the hydrologic models require dependable meteorological variables (Teutschbein *et al*., 2011).

General Circulation Models (GCM's) are the reliable source for simulating future climate scenarios. Climate change occur at local scales, however, the models presently used for projecting climate change due to future greenhouse gas emissions scenario have an average spatial resolution of 2.6˚ x 3.0˚. These future climate change data available at a coarser spatial resolution need to be downscaled for regional uses. This information at local scale is indispensable for impact studies at watershed and river basin scales. The Regional Climate Model (RCM) simulations can be used for impact studies after doing bias correction (Teutschbein and Seibert, 2013).

A high resolution regional model simulation has been developed by World Climate Research Programme (WCRP) and through the Coordinated Regional Climate Downscaling Experiment (CORDEX) programme and is made available to the research community (Giorgi *et al*., 2009). The CORDEX-SA is launched specifically for the South Asian Region, and is available for different models and for different climate scenarios. RCM data is prepared by different modelling groups and is made available through the data portal of Centre for Climate Change Research of Indian Institute of Tropical Meteorology (IITM), Pune, India (Patwardhan *et al*., 2014).

It is predicted that climate change will have a significant impact on hydrology and water resources. Any study related to this requires data at the river basin scale or even at the subbasin level in the case of large rivers. Changes in temperature and precipitation alter the climatic conditions and subsequently the hydrological and watershed processes. The effects of changes due to climatic variability on hydrological responses need to be carried out at watershed and river basin scales for effective water resources planning.

There are large uncertainties in the vulnerability of the nations to the impact of climate change and water availability in future. It is predicted that two-third of the world's population will face water stressed condition by 2050 (Gosain *et al*., 2006). The water requirement in India by 2050 will be in the order of 1450 km^3, which is significantly higher than the estimated water availability of 1122 km^3/year (Misra, 2014). The abstraction of groundwater is progressing at a faster pace than is being replenished by natural recharge, resulting in unsustainable drawdown of aquifers.

A watershed is defined as a geohydrological unit draining to a common point by a system of drains. It is the land and water area, which contributes runoff to a common point. Detailed understanding of the hydrology of a watershed is inevitable for resource planning and management, for which, hydrologic modelling studies are extensively used. Geographic Information System (GIS) based spatial modelling has become a crucial tool in runoff and soil erosion studies, and thereby in the development of appropriate soil and water conservation strategies. Many hydrologic models are available for giving insight into various aspects of land and water management.

The hydrologic models may be stochastic or deterministic, lumped or distributed, space or time dependent or independent. These models are usually developed for specific purposes and for particular areas. Most of them have certain advantages over others and at the same time exhibit a few drawbacks. The physically based semi-distributed hydrologic model, Soil and Water Assessment Tool (SWAT) is successfully used by many researchers worldwide for assessing the hydrologic behaviour of watersheds (Gassman, 2007; Santhi *et al*., 2006; Terrink *et al.,* 2010). It is also widely used to study the impact of various changes on the river basin hydrology (Teutschbein *et al*., 2011; Gosain *et al*., 2011; Li-Chi and Yuan, 2015).

Though the state of Kerala in India receives an average annual rainfall of about 3000 mm, the flow in the rivers during summer has become meagre. Rivers are the most dynamic agents which transport water, sediment and nutrients, and play a vital role in maintaining the global fresh water cycle. It acts as a source of water supply for various human activities across the globe. Despite its great role in environment protection and diverse uses, it is being exploited by man and is under severe threat. Bharathapuzha river in Kerala is a representative of many such rivers and faces severe drought and dearth of water (CWRDM, 2004; Raj and Azeez, 2009). Hence it is urgent to analyse the reasons for the meagre river flow during the non monsoon periods with the help of hydrologic models.

The Bharathapuzha river, popularly known as *Nila*, originates from the Anamalai hills in the Western Ghats and drains to the Arabian sea at Ponnani. The river is a sixth order stream (CGWB, 1992) and is considered as the cradle of civilisation in Kerala. The hydrology and ecology of the river basin is adversely affected by scrupulous sand mining, rapid growth of population and other changes brought about by the inhabitants in the area.

Sand mining has deepened the river bed in many reaches and has increased the river cross section leading to channelized faster river flow. The increase in flow velocity due to increased hydraulic gradient results in faster depletion of groundwater storage (Kumar and Sreeja, 2012). According to CGWB (2004), there is rapid decrease in the groundwater scenario in the state mainly due to the increased water use for domestic and non domestic purposes, reduction in recharge due to urbanization and also due to unscientific management practices. Thus, along with analyzing the long term trends of climate in the area, the changes in the groundwater levels also need to be monitored while studying the hydrology of the basin.

SWAT model used in this study is a physically based, continuous-time model capable of making long term simulations having high level of spatial detail. It is computationally efficient and simulates the hydrologic cycle in daily time steps and can be used for small watersheds as well as for large river basins. It can also be used effectively to predict the impact of land management practices on water, sediment, and agricultural chemical yields in watersheds with varying soils, land use, and management conditions over long time periods.

Watershed development activities in river basins help in conserving water in the upstream areas for agricultural and domestic uses. This is achieved by the construction of rainpits, percolation ponds, vented cross bars (VCB's), checkdams and other soil and water conservation works. When water is thus conserved in the upper reaches, the river flow will be certainly affected. The way it positively influences the components of the river flow depends on different factors comprising of watershed characteristics as well as climate of the area. Studies in this regard is essential in the Bharathapuzha river basin since the river channel has been dammed at several locations and a large number of checkdams and other water conservation structures are coming up within the catchment area day by day for conserving water in the tributaries for irrigation and domestic purpose.

Detailed study is needed to understand the change in hydrological characteristics of the river due to these measures.

The feasibility and performance evaluation of SWAT model is to be done for prediction of streamflow in Bharathapuzha river basin of Kerala. Rainwater conserved in the upper reaches of the river basin will increase the groundwater discharge and make the stream network live for a longer period of time. SWAT can also be used as a potential tool for estimating sediment yield at watershed or catchment scale. The feasibility of the model will also be assessed by comparing the sediment loss observed at different gauging stations with the simulated values. This research work was undertaken with the objective to assess the changes in the hydrological responses of the river basin due to climate change and watershed interventions. Under this context, this research work was taken up with the following specific objectives.

1. Downscaling and bias correcting a climate change scenario to analyse its impact on the water resources of the study area
2. Calibrating and validating the hydrologic model, SWAT for adaptation to the study area.
3. Study the watershed development activities in the basin and to analyse its impact on the river basin hydrology
4. To assess future impacts of climate change and watershed development on the river basin hydrology.

With this background, the impact of climate change and watershed development on the hydrologic behaviour of Bharathapuzha river basin is analysed and discussed in the forthcoming chapters.

Review of Literature

CHAPTER II

REVIEW OF LITERATURE

A critical review of the previous research done in hydrologic modelling with special reference to SWAT model, sensitivity analysis and calibration is presented in this chapter. Major studies conducted in India and abroad to analyse the impact of climate change and watershed interventions on the hydrology of a watershed are also discussed.

2.1 HYDROLOGY AND HYDROLOGIC CYCLE

Hydrology can be explained as the study of the components of the hydrologic cycle, which represents the endless circulation of large quantity of water between the earth and its atmosphere (Neitsch *et al*., 2005). Hydrologic cycle is referred to as the circulation of water from the oceans and land surface to the air, air to land, and back to the oceans over the land surface or underground (Murthy and Jha, 2011).

The main processes involved in the hydrologic cycle are precipitation, interception, evapotranspiration, runoff, infiltration, percolation, base flow, surface and groundwater movement. The transition of water through the different processes in the hydrologic cycle is influenced by human activities, and its adverse consequences threaten human existence. Such adverse impacts are numerous and modelling techniques are often employed for analysing and simplifying them.

2.2 HYDROLOGIC MODELS AND MODELLING

Models are simplified systems which represent the real world situations. For proper understanding of the hydrological processes and for quantifying the outputs of the system, simplified, conceptual representations of the hydrologic cycle or its major components are prepared, which are known as hydrologic models. The system that is modelled in case of hydrologic models may be a river basin, or a part of it.

Hydrologic models are classified into stochastic models and deterministic models based on the concept used for modelling. Based on the component of the hydrologic cycle that is modelled, they are also classified into surface water models, groundwater models and agricultural hydro-salinity models. Hydrologic models are also classified into distributed models and lumped models, space independent and space dependent models. The key aspects like model use, calibration and validation of around 25 hydrologic and water quality models have been compared and discussed by Moriasi *et al*. (2012). Hydrologic models are used world-wide for water resource management and are powerful tools in the planning and development of various watershed interventions.

2.2.1 Physically Based Distributed Hydrologic Models

Different hydrologic models have been developed for the analysis of runoff and water quality in the past which are highly useful in certain situations (Birsingh and Pandey, 2013). Hydrologic Engineering Centers' Hydrologic Modelling System (HEC-HMS), Storm Water Management Model (SWMM), Generalized River Modelling Package - Système Hydrologique Européen (MIKE-SHE), Hydrologic Simulation Program Fortran (HSPF), Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) and Soil and Water Assessment Tool (SWAT) are a few among them. Major constraint that has hindered the wide use of these models is the scarcity of consistent data in developing countries (Abdelhamid *et al*., 2011).

Most of the physically based distributed hydrologic models have limitations in simulating at appropriate temporal and spatial scale, inability to perform continuous-time simulations, inadequate maximum number of sub-watersheds, and inability to characterize the area in the needed spatial detail (Jha, 2011; Pechlivanidis *et al.,* 2011). It is difficult to assess which model is the best or which one is easy to use based on the documentation, and the performance of the models often depends on the specific scenario or condition of the watershed (Nyeko, 2015). Fully distributed, physically based models are data intensive and are suitable only for watersheds where high resolution data is available (Singh, 1995). Semi-distributed models have the capability of representing the data in space and can be used in areas where there is limited data availability (Mulligan, 2004). Due to the above said reasons, the semi-distributed hydrologic model, SWAT is often preferred for the study of the hydrology of a river basin in developing countries with limited data availability.

2.3 SOIL AND WATER ASSESSMENT TOOL- COMPONENTS

The SWAT model is a physically based semi-distributed river basin model developed by United States Department of Agriculture (USDA) Agriculture Research Service in 1998 (Arnold *et al*., 1998) and has been revised several times over the years. This model is found to be computationally efficient and is successful in simulating the hydrology and water quality in continuous time periods (Neitsch *et al*., 2005; Arnold *et al*., 2012). SWAT offers high level of spatial detail, large number of watershed subdivisions and can be used for daily simulation of river flow and its constituent components (Jha, 2011). SWAT model is used for impact studies of areas ranging from big river basins (Santhi *et al*., 2001; Gosain *et al*., 2011; Devkota and Gyawali, 2015) to small catchment areas of meso-scale catchment type (Teutschbein and Seibert, 2012; Baker and Miller, 2013).

In SWAT, a watershed is divided into sub basins which are adjacent to one another and holds specific geographical positions. The sub basins are further divided into areas called Hydrological Response Units (HRU's) with homogeneous topography, land use and soil (Neitsch *et al*., 2005). HRU is the smallest computational unit in SWAT and the simulations of SWAT model are based on the water balance concept (Neitsch *et al*., 2011). Different components of the hydrologic cycle (Fig. 2.1) are modelled based on scientific theories.

2.3.1 Estimation of Runoff

Runoff from a watershed in terms of quantity and quality is mainly governed by the precipitation as well as the land and water management practices occurring in the watershed. The runoff from an area need to be estimated for various reasons such as conserving the water for irrigation or drinking purpose, increasing the groundwater recharge, reducing the peak flow and thus to prevent floods or erosion (Jain *et al.*, 2010).

SWAT provides two methods for estimating surface runoff: the SCS curve number procedure and the Green & Ampt infiltration method. SCS curve number model is an empirical model; it provides a consistent basis for estimating runoff in different land use and soil type. The Green & Ampt equation was developed to predict infiltration assuming excess water at the surface at all times. The equation assumes that the soil profile is homogenous and antecedent moisture is uniformly distributed in the profile. As water infiltrates into the soil, the model assumes that the soil above the wetting front is completely saturated, and there is a sharp break in moisture content at the wetting front. For estimating the peak discharge, the Rational method is used in SWAT.

Research conducted in river basins and watersheds worldwide has proved that SWAT model provides a useful tool for runoff estimation and soil erosion assessment and facilitates proper planning for water resources management (Shen *et al*., 2009; Tibebe and Bewket, 2010; Wenjie *et al.*, 2011).

Mohammed *et al.* (2013) conducted studies to re-conceptualize the theoretical inconsistencies in the CN method in SWAT. A modified curve number method using the derivative of time for deriving runoff volume, gave more realistic results for soil moisture accounting when incorporated to the SWAT source code. It is suggested that detailed experimentations need to be done for validating the modified SWAT model under heterogeneous scenarios.

The rainfall-runoff process in the Tapi sub-catchment area (Burhanpur watershed) located in inter-state basin of Madhya Pradesh and Maharashtra, India, was simulated using SWAT model (Shivhare *et al*., 2014). The model performance was evaluated based on the simulated flows at the basin outlet using statistical methods. The coefficient of determination of the monthly values for the years 1992-93 to 1995-96 were reported as 0.82, 0.68, 0.92 and 0.69, indicating good performance of the model.

2.3.2 Estimation of Evapotranspiration

Evapotranspiration includes evaporation from rivers and lakes, bare soil and vegetative surfaces, transpiration and sublimation from ice and snow surfaces. Potential soil water evaporation is estimated as a function of potential evapotranspiration and leaf area index (area of plant leaves relative to the area of the Hydrologic Response Unit (HRU)). Potential evapotranspiration (PET) is the rate at which evapotranspiration would occur from a large area, completely and uniformly covered with growing vegetation, that has access to an unlimited supply of soil water. This rate is assumed to be unaffected by microclimatic processes such as advection or heat-storage effects. The model offers three options for estimating potential evapotranspiration: Hargreaves (Hargreaves *et al*., 1985), Priestley-Taylor (Priestley and Taylor, 1972), and Penman-Monteith (Monteith, 1965). The plant transpiration and the evaporation from the soil is estimated separately and then added together to estimate the evapotranspiration. The potential evapotranspiration is corrected to conditions of vapour pressure deficits and then to water content in soil so as to estimate transpiration (Pereira *et al*., 2014).

Izady *et al.* (2013) estimated the ET at a regional scale on an annual basis by using SWAT model in the Neishaboor watershed in North-east Iran. They reported that during the ten year period of study from 2000 to 2010, the actual evapotranspiration to precipitation ratio at mountainous part of watershed was 99 percent, 80 percent and 77 percent for 2000-2001 as a dry year, 2001-2002 as a normal year and 2004-2005 as a wet year, respectively. Mean of ten years actual evapotranspiration and precipitation was estimated as 230 and 270 mm, respectively.

Alemayehu *et al.* (2013) investigated the possibility of estimating spatial variability of ET in Mara river basin between Kenya and Tanzania using SWAT model as well as using remote sensing products from MODerate Resolution Imaging Spectroradiometer (MODIS). The MODIS patterns showed spatially consistent ET variability compared to the SWAT simulated ET flux. It is suggested that, in data scarce areas, the prediction abilities of hydrologic models can be improved by using ET estimates from remote sensing data during calibration and validation.

In the semi arid climate of New Mexico, based on SWAT simulation, Heo *et al*. (2015) reported that the change in evapotranspiration rate was relatively similar to the rate of change of precipitation. During the study period (1970-2009), the evapotranspiration accounted for 93.4 percent of the precipitation received. The change in evapotranspiration is primarily governed by the change in precipitation and not by the changes in temperature, as reported in many studies.

2.3.3 Estimation of Soil Erosion

The primary cause of land degradation is the removal of top soil by soil erosion. Geographic Information System (GIS) and SWAT can be used for simulating soil erosion in a better way (Gassman *et al*., 2007). Several studies have shown the robustness of SWAT to predict surface runoff and soil erosion at different watershed scales (Srinivasan *et al*., 1998; Santhi *et al*., 2001; White and Chaubey, 2005; Behera and Panda, 2006; Cheng *et al*., 2006; Tibebe and Bewket, 2010).

In SWAT, soil erosion caused by rainfall and runoff is computed by the Modified Universal Soil Loss Equation (MUSLE):

$$sed = 11.8 \times (Q_{surf} \times q_{peak} \times area_{hru})^{0.56} \times K_{USLE} \times C_{USLE} \times P_{USLE} \times LS_{USLE} \times CFRG$$

where: *sed* is the sediment yield on a given day (metric tons), *Qsurf is* the surface runoff volume (mm ha^{-1}), q_{peak} is the peak runoff rate (m^3 s^{-1}), $area_{hru}$ is the area of the HRU (ha), K_{USLE} is the USLE soil erodibility factor, C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor, and *CFRG* is the coarse fragment factor.

In the routing phase, SWAT uses Manning's equation to calculate the rate and velocity of flow. Water is routed through the channel network using the variable storage routing method or the Muskingum river routing method. The crop growth model in SWAT is a simplification of the EPIC (Erosion Productivity Impact Calculator) model with the concepts of phenological crop development based on daily accumulated energy units, harvest index for partitioning grain yield, Monteith's approach for potential biomass and water, nutrient and temperature stress adjustments.

Tibebe and Bewket (2010) estimated soil erosion rates for a small watershed in the Awash River basin of Ethiopia by using SWAT model. Surface runoff generation was generally high in parts of the watershed characterized by heavy clay soils with low infiltration capacity, agricultural land use and slope gradients of over 25 per cent. The estimated soil loss was comparable to the observed rates.

Two widely used models, the Water Erosion Prediction Project (WEPP) and the Soil and Water Assessment Tool (SWAT) were applied in the Zhangjiachong Watershed, Three Gorges Reservoir Area in China (Shen. *et al*., 2009) to simulate runoff and sediment yield. The models were evaluated on the basis of Nash-Suchliffe efficiency (NSE) and it was found that even though NSE values of WEPP model was slightly higher than that of SWAT model, the results of both models were acceptable.

SWAT model also provides a useful tool for quantifying soil erosion from watersheds with varying size, and facilitates planning for a sustainable land and water management. (Tibebe and Bewket, 2010).

The major advantages of SWAT model over other hydrologic models are:

1. Watersheds with no monitoring data (e.g. stream gauge data) can be modelled (Arnold *et al*., 1998)
2. Changes in climate, land use/ land cover or other management practices, vegetation, etc. on the quantity and quality of runoff or other variables of interest can be quantified (Shah and Patel, 2015)
3. Enables the use of weather generator file in situations where adequate weather data is not available

4. Uses readily available inputs that are commonly available from government agencies.
5. The model is computationally efficient and simulation of very large basins is possible.
6. Enables the users to study long-term impacts (Jeark and Ariel, 2012).

2.4 IMPROVING THE PREDICTIVE ACCURACY OF THE MODEL

To improve the predictive accuracy, it is important that the hydrologic models must undergo calibration before they are used for simulations (Lorraine *et al.*, 2014). SWAT model, if properly calibrated, can be used efficiently to support water management policies (Abdelhamid *et al.*, 2011). All model inputs may not be available to the desired precision, and this emphasizes the need of model calibration. Further, to build confidence into the model prediction and to improve predictive accuracy, the models must be validated with an independent set of observed data. The term validation is used to explain the method of analysing the performance of simulation and/or forecasting of models (Daniela *et al.*, 2012).

2.4.1 Sensitivity Analysis

Determination of the most sensitive parameters for a given watershed or sub-watershed is essential before going to the actual calibration and validation process in SWAT. The user determines which variables to adjust based on expert judgment or sensitivity analysis. Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs. It is necessary to identify the most sensitive parameters and the parameter precision required for calibration. Sensitivity analysis thus helps to identify and rank parameters that have significant impact on specific model outputs of interest (Saltelli *et al.*, 2000).

There are mainly two types of sensitivity analysis: local, by changing values one at a time (van Griensven *et al.*, 2006), and global, by allowing all parameter values to change. The two analyses, however, may yield different results. Sensitivity of one parameter often depends on the value of other related parameters; hence, the problem with one-at-a-time analysis is that the correct values of other parameters that are fixed are never known.

In the global sensitivity analysis, all parameters are allowed to vary by certain percentage or are simultaneously perturbed, allowing investigation of parameter interactions and their impacts on model outputs. The disadvantage of the global sensitivity analysis is that it needs a large number of simulations. Both procedures, however, provide insight into the sensitivity of the parameters and are necessary steps in model calibration. The modelled stream flow may also show varying sensitivity of parameters in different climatic settings (Cibin *et al*., 2010).

2.4.2 Calibration and Validation

The second step is the calibration process. Calibration is an effort to better parameterize a model to a given set of local conditions, thereby reducing the prediction uncertainty. Model calibration is performed by carefully selecting values for model input parameters (within their respective uncertainty ranges) by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions.

The final step is validation for the component of interest (streamflow, sediment yields, etc.). Model validation is the process of demonstrating that a given site-specific model is capable of making sufficiently accurate simulations, although "sufficiently accurate" can vary based on project goals. Validation involves running a model using parameters that were determined during the calibration process, and comparing the predictions to observed data not used in the calibration. In general, a good model calibration and validation should involve:

1. Observed data that include wet, average, and dry years
2. Multiple evaluation techniques
3. Calibrating all constituents to be evaluated; and
4. Verification that other important model outputs are reasonable.

In general, graphical and statistical methods with some form of objective statistical criteria are used to determine whether the model has been calibrated and validated properly. Calibration can be accomplished manually or using auto-calibration tools in SWAT or SWAT-CUP.

Calibration and validation are typically performed by splitting the available observed data into two datasets, one for calibration, and another for validation. Data are most frequently split by time periods, carefully ensuring that the climate data used for both calibration and validation are not substantially different, i.e., wet, moderate, and dry years occur in both periods.

2.4.3 Calibration using SWAT Calibration and Uncertainty Procedures (SWAT-CUP)

The calibration of large scale distributed models has become difficult due to large model uncertainty, input uncertainty, and parameter non-uniqueness (Abbaspour, 2007). SWAT-CUP is an interface developed for SWAT which makes the calibration procedure easy and provides a faster way to do the time consuming calibration operations (Singh, 2013). It provides capabilities in the complex calibration, validation and sensitivity analysis of SWAT models (Gorgan *et al*., 2012). The program is written in C# programming platform. It involves several methods such as Particle Swarm Optimization (PSO), Sequential Uncertainty Fitting (SUFI-2), Generalized Likelihood Uncertainty Estimation (GLUE), Parameter solution (Parasol) (van Griensven and Meixner, 2006) and MCMC. The program accesses the SWAT input files and runs the SWAT simulations by modifying the given parameters. A schematic diagram of the linkage between SWAT and the optimisation programs is shown in Fig. 2.2.

SWAT parameters for were estimated using the SUFI-2 program (Abbaspour *et al*., 2007). The major objectives of SWAT-CUP are to

1. Integrate various calibration/uncertainty analysis procedures for SWAT in a single user interface

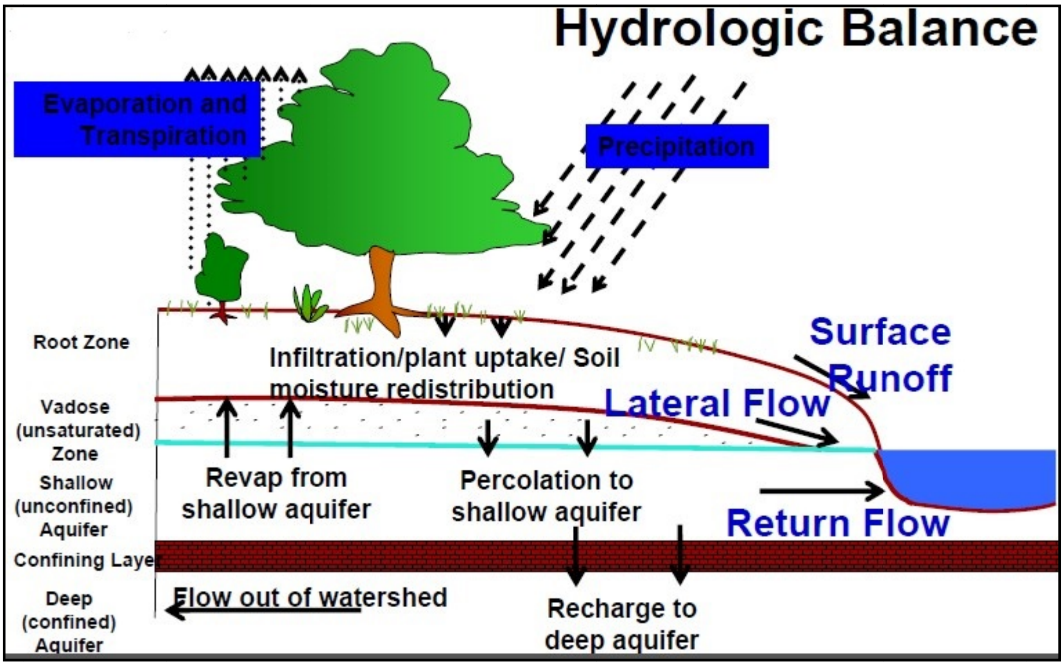

Fig. 2.1 Schematic representation of the hydrologic cycle in SWAT

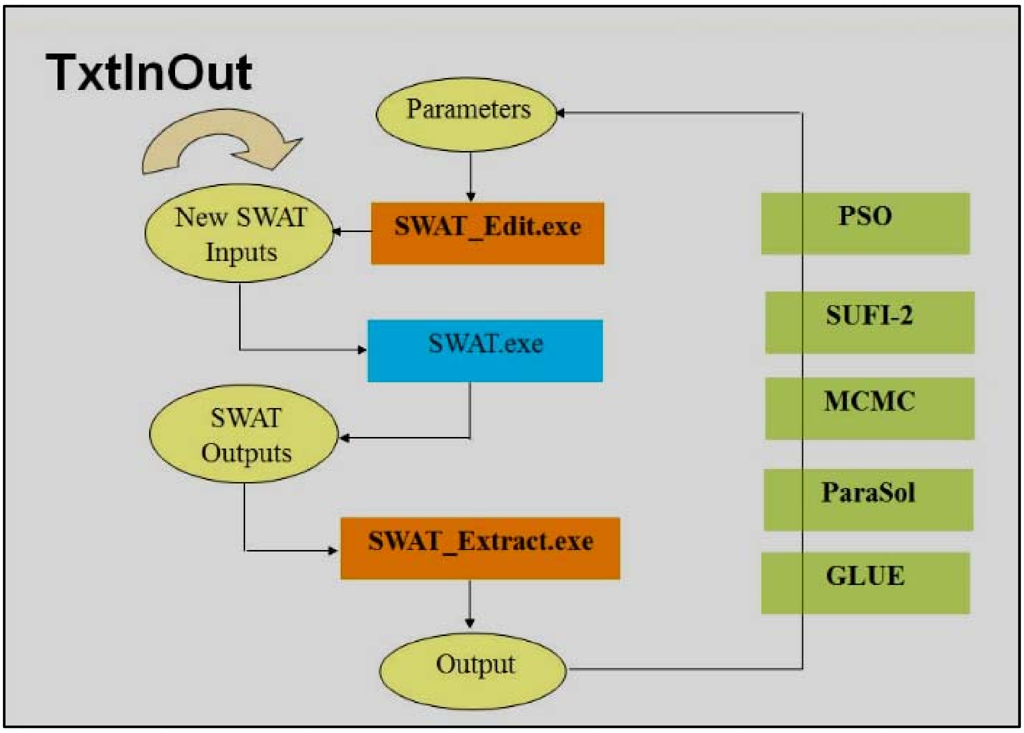

Fig. 2.2 Linkage between SWAT and optimisation programs

2. Make the calibrating procedure easy to use and make the learning of the programs easier

3. Provide a faster way to do the time consuming calibration operations and standardize calibration steps and

4. Add extra functionalities to calibration operations such as creating graphs of calibrated results, data comparison, etc.

The discrepancy between the observed and simulated variables is accounted by the uncertainty. The calibration and uncertainty analysis is combined here to find parameter uncertainties while calculating smallest possible prediction uncertainty band. All sources of uncertainty are reflected during the calibration, i.e. conceptual model, forcing inputs (e.g., temperature) and the parameters considered.

The degree to which the uncertainties are accounted is quantified by a measure referred to as the *p-factor*, which is the percentage of measured data bracketed by the 95 percent prediction uncertainty (95PPU). The 95PPU is calculated at the 2.5 percent and 97.5 percent levels of the cumulative distribution of an output variable obtained through Latin hypercube sampling. Another measure *d-factor*, which is the average thickness of the 95PPU band divided by the standard deviation of the measured data is useful in quantifying the strength of a calibration/uncertainty analysis. SUFI-2, hence seeks to bracket most of the measured data with the smallest possible *d-factor*. The SUFI-2 (Abbaspour *et al*., 2007) is easy to handle, requires minimum runs, gives comparably good results and is able to describe all kinds of uncertainty sources.

2.4.4 Multi-variable and Multi-site Calibration

Multi-variable and multi-site approach to calibration and validation of SWAT for the calibration of complex watersheds has gained popularity (White and Chaubey, 2005; Zhang *et al*., 2008). In the case of using multi-site data, the parameters were calibrated on the basis of data from multiple sites (van Liew and Garbrecht, 2003; Bekele and Nicklow, 2007).

For multi-site automatic calibration, two types of calibration methods are usually used. The first calibration method aggregates the different objective function values calculated at each monitoring site into one integrated value, and then applies the single-objective optimization algorithms for parameter estimation (e.g., van Griensven and Bauwens, 2003). The second calibration method uses multi-objective evolutionary algorithms to optimize the different objective functions calculated at multiple sites simultaneously (Bekele and Nicklow, 2007). When applied with multi-site data, the single-objective method can identify better parameter solutions in the calibration period (Zhang *et al.*, 2008).

2.5 MODEL EFFICIENCY CRITERIA

Some of the common efficiency criteria used to evaluate hydrologic models are Nash-Sutcliffe efficiency, Co-efficient of determination, Index of agreement and Percent Bias.

2.5.1 Nash-Sutcliffe Efficiency (NSE)

Nash-Sutcliffe efficiency was proposed by Nash and Sutcliffe (1970) and is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation and is given by the equation,

$$\text{NSE}=1-\frac{\sum_{i=1}^{n}[O_i-P_i]^2}{\sum_{i=1}^{n}[O_i-\bar{O}]^2},$$

Where, O_i is the observed value, P_i is the simulated value, $\bar{O}$ is the average of the observed values and n is the number of simulations. The range of NSE lies between 1.0 (perfect fit) and $-\infty$. The major disadvantage of NSE is that larger values in a time series are strongly overestimated whereas lower values are neglected (Legates and McCabe, 1999).

2.5.2 Coefficient of Determination

The coefficient of determination (r^2) is defined as the squared value of the coefficient of correlation according to Bravais Pearson. It is used to analyse how differences in one variable can be explained by a difference in a second variable.

$$r^2 = \left\{ \frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}} \right\}^2$$

The value of r^2 range between 0 and 1 with the value of zero meaning no correlation whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation. The major drawback of using this coefficient alone is that only the dispersion is quantified.

2.5.3 Index of Agreement

The index of agreement (d) is a standardized measure of the degree of model prediction error and varies between 0 and 1. The value of 'd' equal to 1 indicates a perfect agreement between the measured and predicted values, and 0 indicates no agreement (Willmott, 1981). The index of agreement is the ratio of the mean square error and the potential error (PE) multiplied by N (no. of observation) and then subtracted from one (Willmott, 1984).

$$d = 1 - \frac{\sum_{i=1}^{N}[O_i - P_i]^2}{\sum_{i=1}^{N}[\,|P_i - \bar{O}| + |O_i - \bar{O}|]^2} = 1\text{-N}\left(\frac{MSE}{PE}\right)$$

Legates and McCabe (1999) suggested a modified index of agreement (d_1) that is less sensitive to high extreme values because errors and differences are given appropriate weightage by using the absolute value of the difference instead of using the squared differences.

2.5.4 Percent Bias (PBIAS)

Percent bias (PBIAS) is a measure of the average tendency of the simulated data to be larger or smaller than the corresponding observed data (Gupta *et al*., 1999). Low values close to zero indicate accurate model simulation, with the optimum value as zero. Positive values indicate model under estimation bias, and negative values indicate model over estimation bias (Gupta *et al*., 1999).

PBIAS is calculated using the equation

$$\text{PBIAS} = \frac{\sum_{i=1}^{n}(O_i - P_i)\text{x}100}{\sum_{i=1}^{n} O_i}$$

Where PBIAS is the deviation of data being evaluated, expressed as a percentage.

2.6 CLIMATE SCENARIOS AND MODELS

Climate change is recognized as one of the most serious challenges mankind is facing today. Future greenhouse gas (GHG) emissions are the product of very complex dynamic systems, determined by driving forces such as demographic development, socio-economic development, and technological change. Different approaches are used to predict the future changes in climate. It is highly uncertain how the driving forces may influence future emission outcomes. General Circulation Models (GCM's) are the only reliable source for simulating future climate scenarios.

2.6.1 Causes of Climate Change

Anthropogenic greenhouse gas emissions since the pre-industrial era have driven large increases in the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Their effects, together with those of other anthropogenic drivers, have been identified as the dominant cause of the observed warming since the mid 20th century. A total annual anthropogenic GHG emission by gases during 1970–2010 is shown in Fig. 2.3. The graph also shows 2010 emissions, using alternative CO_2 equivalent emission weightings based on IPCC Second Assessment Report (SAR) and Fifth Assessment Report (AR5). Total anthropogenic GHG emissions have continued to increase over 1970 to 2010 with larger absolute increases between 2000 and 2010, despite a growing number of climate change mitigation policies. The most important drivers of increase in CO_2 emissions are due to fossil fuel combustion, occurring mainly because of the economic and population growth. Using the most recent 100 year Global Warming Potential (GWP_{100}) values from the AR5, it is seen that higher total annual GHG emissions (52 $GtCO_2$-eq/yr) occur due to increased contribution of methane, but does not change the long term trend significantly.

2.6.2 General Circulation Models

General Circulation Models provide us with projections of how the climate of the earth will change in the future and gives useful results to the international community to take decisions on climate change mitigation. Climate change occur at local scales, but presently models used for projecting climate change due to future greenhouse gas emissions have high average global climate model resolution. Most of the hydrologic models cannot use the GCMs directly since the spatial resolution of these models (150-300 km by 150-300 km) is very coarse (Wang, 2013). Regional Climate Downscaling (RCD) has an important role to play providing projections with much greater detail. Downscaling is done to get the data at a fine resolution which is compatible for use in impact assessments.

The greenhouse gas scenarios are periodically updated as the science of climate change advances. The most recent projections for the 21st century given by IPCC, 2013 align with the earlier projections in IPCC, 2007. The new greenhouse gas scenarios range from an extremely low emission scenario to a high "business as usual" scenario. Most of these new scenarios have close analogy to the scenarios used in previous assessments (Fig. 2.4 and Table 2.1).

The previous greenhouse gas scenarios used in 2007 IPCC reports are described in the Special Report of Emission Scenarios (SRES; Nakicenovic *et al.*, 2000). With the Fifth Assessment Report of IPCC a set of four new scenarios, denoted as Representative Concentration Pathways (RCP's) were identified (van Vuuren *et al.*, 2011). For the Coupled Model Inter-comparison Project Phase 5 (CMIP5) results, these values are indicative only, as the climate forcing resulting from all drivers varies between models due to specific model characteristics. These four RCPs include one mitigation scenario leading to a very low forcing level (RCP2.6), two stabilization scenarios (RCP4.5 and RCP6), and one scenario with very high greenhouse gas emissions (RCP8.5). The RCP's can thus represent a range of 21stcentury climate policies, as compared with the no-climate policy of the Special Report on Emissions Scenarios (SRES) used in the Third Assessment Report and the Fourth Assessment Reports.

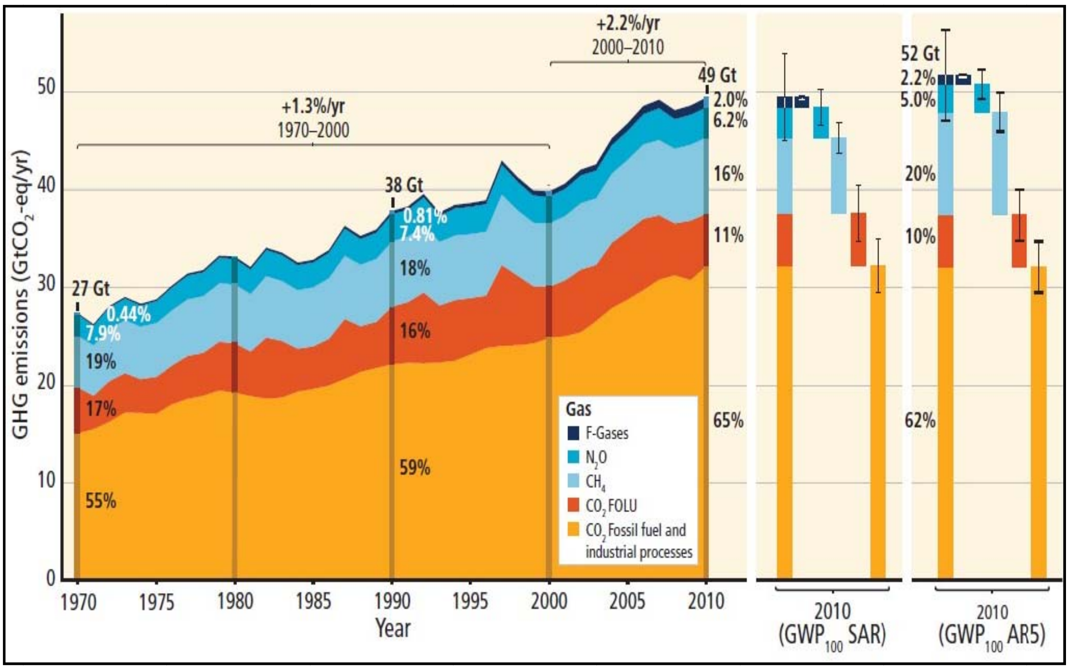

Fig. 2.3 Total annual anthropogenic GHG emissions by gases 1970–2010

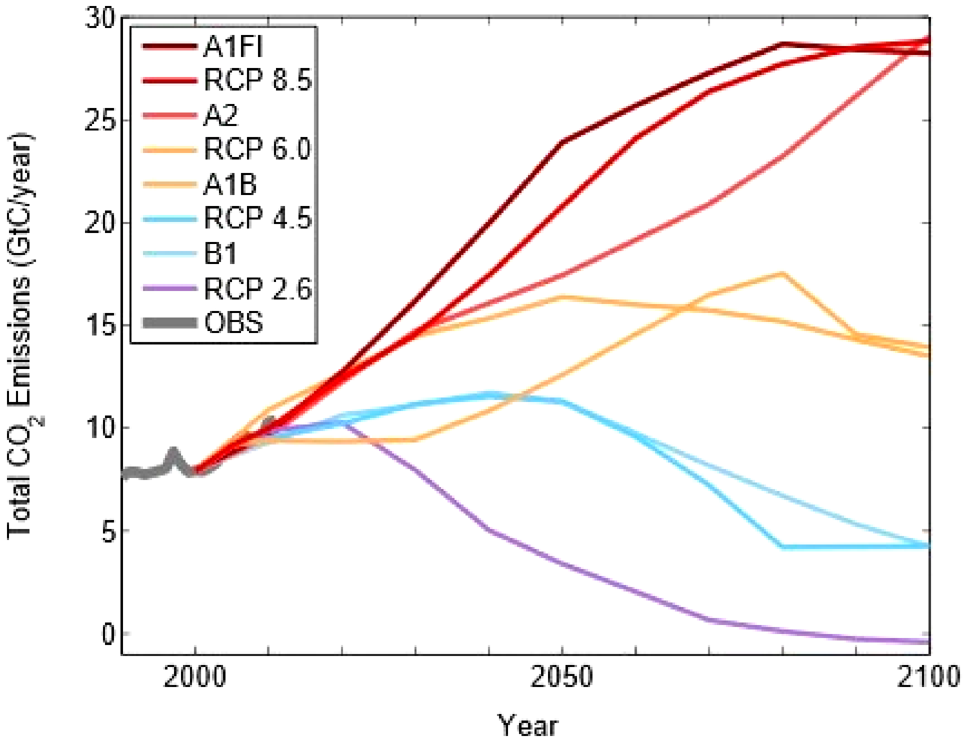

Fig. 2.4 Analogy between the old scenario (SRES) and the new scenario

Table 2.1 Characteristics of new climate scenarios

New scenarios	Characteristics of scenarios	Comparison to old scenarios
RCP 2.6	An extremely low scenario that reflects aggressive greenhouse gas reduction and sequestration efforts. Its radiative forcing level first reaches a value around 3.1 W/m^2 mid-century, returning to 2.6 W/m^2 by 2100.	No analogue to previous scenarios
RCP 4.5	A low scenario in which greenhouse gas emissions stabilise by mid-century and fall sharply thereafter. Stabilization is achieved by employing a range of technologies and strategies for reducing greenhouse gas emissions	Very close to B1 by 2100, but higher emissions at mid-century
RCP 6.0	A medium scenario in which greenhouse gas emissions increase gradually until stabilising in the final decades of the 21st century. Stabilization is achieved by employing a range of technologies and strategies for reducing greenhouse gas emissions.	Similar to A1B by 2100, but closer to B1 at mid-century
RCP 8.5	A high scenario that assumes continued increases in greenhouse gas emissions until the end of the 21st century. It is characterized by increasing greenhouse gas emissions over time representative of scenarios in the literature leading to high greenhouse gas concentration levels.	Nearly identical to A1F1

For RCP6.0 and RCP8.5, radiative forcing does not peak by year 2100; for RCP2.6 it peaks and declines; and for RCP4.5 it stabilizes by 2100 models

(Chaturvedi *et al*., 2012). Each RCP provides spatially resolved data sets of land use change and sector-based emissions of air pollutants, and it specifies annual greenhouse gas concentrations and anthropogenic emissions up to 2100. RCPs are based on a combination of integrated assessment, simple climate models, atmospheric chemistry and global carbon cycle models. While the RCPs span a wide range of total forcing values, they do not cover the full range of emissions in the literature, particularly for aerosols.

2.6.3 CORDEX - Impact of Changing Climate at Regional Scales

The Coordinated Regional Climate Downscaling Experiment (CORDEX) was launched by the World Climate Research Programme (WCRP) to create a framework for evaluating and comparing various RCD techniques that are in use all over the world. This project is the latest ensemble experiments involving many research centres throughout the word which aims to produce high resolution climate change scenarios at regional level for climate change impact studies and to characterize associated uncertainties (van der Linden and Mitchell, 2009; Nikulin *et al*., 2012; Sarr *et al*., 2015)

2.6.4 Regional Climate Models (RCM's)

Modelling of climate change and earth systems in the regional scale is essential for projecting the impact of climate change on the hydrology and other natural resources (Mondal and Mujumdar, 2015). Thus RCM can simply be defined as "Climate model for regional purposes". The nested regional climate modelling technique consists of using initial conditions, time dependent lateral meteorological conditions and surface boundary conditions to drive high-resolution RCMs. The driving data is derived from GCMs (or analyses of observations) and can include GHG and aerosol forcing. A variation of this technique is also to force the large-scale component of the RCM solution throughout the entire domain (IPCC, 2013).

2.6.5 Climate Projections for the Fifth Assessment Report of IPCC

The projections are made using the newly developed representative concentration pathways (RCPs) under the Coupled Model Inter comparison Project 5 (CMIP5). Multi model and multi scenario climate projections for the Indian region for the period 1860-2099 are available based on the new climate data.

Climate projections in the past relied on the CMIP3 multi model data (Kumar *et al*., 2006; Kumar *et al*., 2010), but with the development of the CMIP5 data and new RCPs, more accurate projections of temperature and precipitation is possible. Chathurvedi *et al*. (2012) compared different individual models and ensemble mean with the observed climate data and found that the CMIP5 ensemble mean climate is closer to observed climate than any individual model. Among the individual models, GFDL-CM3 was found to the best performing one, followed closely by several others.

2.6.6 Downscaling Techniques

Downscaling is the method of obtaining high resolution climate or climate change information from relatively coarse resolution global climate models (GCMs). The necessity of RCM data for impact studies is already discussed and hence downscaling techniques need to be employed to scale up the mismatch between the GCM outputs and regional hydrologic variables (Wilby and Dawson 2013). The two main approaches to downscaling climate information are statistical downscaling and dynamic downscaling.

2.6.6.1 Statistical Downscaling

A statistical relationship is established from observations between large scale variables, like atmospheric surface pressure, and a local variable, like the wind speed at a particular site. The relationship is then subsequently used on the GCM data to obtain the local variables from the GCM output. Statistical downscaling is a two step process consisting of i) the development of statistical relationships between local climate variables (e.g., surface air temperature and precipitation) and large-scale predictors (e.g., pressure fields), and ii) the application of such relationships to the output of global climate model experiments to simulate local climate characteristics in the future.

2.6.6.2 Dynamic Downscaling

In dynamic downscaling, the output from the GCM is used to drive a regional, numerical model in higher spatial resolution, which therefore is able to simulate local conditions in greater detail. Dynamical downscaling requires running high resolution climate models on a regional sub domain, using observed data or low resolution climate model output as a boundary condition. These models use physical principles to reproduce local climates, but are computationally intensive.

Dynamic downscaling can resolve atmospheric processes, guarantees consistency with the driving GCM and generates internally consistent output variables (Wilby *et al*., 2002). The requirement of powerful computing capacities and the dependency on initial and boundary conditions are the major drawbacks.

2.7 UNCERTAINTY IN PROJECTED DATA AND BIAS CORRECTION

Uncertainties or errors are inherent in all projections of the future. In climate change, uncertainties are related to future path of emissions and limitation in climate models. Uncertainties must be taken into account when assessing the impacts, vulnerability and adaptation options. Bias is defined as the time independent component of the error (Frei *et al*., 2003). Bias arises because of several reasons and has a high spatial component as well. Also, the biases in the output subsequently influence other hydrologic processes like evapotranspiration, runoff, snow accumulation and melt.

While using the regional climate model output directly for hydrologic modelling, the problem is that there is significant variation between the computed precipitation and temperature (Frei *et al*., 2003). Some form of pre processing is necessary to remove biases present in the computed climate output fields before they can be used for impact assessment studies. Biases (errors) present in the computed climate output fields must be removed before they can be used for impact assessment studies (Leander and Buishand, 2007; Christensen *et al*., 2008; Raneesh and Thampi, 2013). Even RCM simulations of temperature and precipitation are often considerably biased (Christensen *et al*., 2008; Teutschbein and Seibert, 2010).

The COordinated Regional climate Downscaling Experiment-South Asia (CORDEX-SA) data was introduced in 2012, and the RCM data has become available only recently. Even then, the climate projections show bias in the magnitude and distribution and bias correction is essential (Chaturvedi *et al*., 2012; Pechlivanidis *et al*., 2015). One possibility to reduce the error is the use of multiple RCM's (Giorgi, 2006; Teutschbein and Seibert, 2010; Ehret *et al*., 2012). For temperature predictions, this will give reasonably good simulations, but in the case of precipitation, the predictions often deviate from observations and are not able to capture the variability in the observations. Hence it is essential to do bias correction before using RCM data in hydrologic impact studies.

Hydrological modelling depends on the choice of a bias correction method and the location of a watershed. This is very much important because the errors in the bias corrected data are usually amplified in the modelled runoff. Moreover, distribution based methods are consistently better than mean based methods.

2.8 CLIMATE TREND ANALYSIS

To assess and simulate potential hydrological climate change impacts, hydrologic models require reliable meteorological variables for current and future climate conditions (Teutschbein *et al*., 2011). Agricultural production and water resources availability are affected by changes in rainfall and temperature. Several researchers have studied the variability and trends in temperature and rainfall to understand the severity of climate change (Marengo 2004; Longobardi and Villani 2010; Mondal *et al*., 2012; Dash *et al.,* 2011) and have contributed significant results. Study of the temperature regimes and changes in the general rainfall pattern at local level is needed for understanding the regional scenarios.

Agriculture and other related sectors of India and especially Kerala depends mainly on the monsoon rainfall, viz., South-West (June to September) and the North-East (October to November). Though Kerala, the southernmost state of India is blessed with an annual average rainfall of 3107 mm (India-WRIS, 2015), the flow in the rivers during summer is very less. Hence, slight variations in the temperature and rainfall pattern in the future will affect the agricultural scenario of the state.

Trend analysis of mean annual temperatures with time from various parts of India showed linear increasing trends (Rao, P.G. 1993; Arora *et al*., 2005; Bhutiyani *et al*., 2007; Thomas *et al*., 2015). Rao *et al*. (2009) reported that there was an increase of 0.44°C in mean annual surface air temperature over a period of 49 years (1956 to 2004) in Kerala and similar warming was noticed in the entire West Coast of India.

Analysis of climatological data for 140 years (1871-2007) over Kerala in the humid tropics of India indicated cyclic trend in annual rainfall (Krishnakumar *et al*., 2009; Rao *et al*., 2008), whereas during the past 60 years (1950-2010) there was a decreasing trend in annual and southwest monsoon rainfall (Rao *et al*., 2009). Increase in extreme rainfall events have been reported from various parts of the country (Goswami *et al.*,2006; Rajeevan *et al.,* 2008; Thomas *et al*., 2015), whereas varying trends in different seasons for the same area was also reported (Krishnakumar *et al*., 2009; Manikandan and Tamilmani 2012).

2.8.1 Occurrence of Drought

Drought is an extreme hydrological event occurring in an area which can affect the socio economic status of the people. The probability of occurrence of drought if predicted can help in adopting certain precautionary measures which can reduce the adverse consequences to a significant extent. Rainfall deficit occurring in a region for a period of time could lead to various degrees of drought conditions. The concept of drought may vary from place to place since the rainfall varies significantly among different regions.

2.8.2 Types of Drought

Droughts can be classified into four major types:

2.8.2.1 Meteorological Drought

It describes a situation where there is a reduction in rainfall for a specific period (days, months, seasons or year) below a specific amount (long term average for a specific time). The Indian Meteorological Department (IMD) has defined drought as a situation occurring in any area when the mean annual rainfall is reduced by 25 percent of the normal rainfall.

2.8.2.2 Hydrological Drought

A meteorological drought often leads to hydrological drought which is associated with deficiency of water on surface or subsurface due to shortfall in precipitation. Hydrological drought is mainly concerned about the way in which the deficiency in rainfall affects different components of the hydrological cycle. Hydrological droughts are of two types (i) surface water drought (ii) groundwater drought, based on whether it affects the surface water or groundwater resources.

2.8.2.3 Agricultural Drought

This links various characteristics of meteorological or hydrological drought to agricultural impacts. When soil moisture and rainfall conditions are not adequate enough to support a healthy crop growth to maturity thereby causing extreme moisture stress and wilting of major crop area, it leads to agricultural drought.

2.8.2.4 Socio-economic Drought

The availability of food and income loss on account of crop failures which may affect the food and social security of the people is called Socio-economic drought. It is associated with the demand and supply aspect of economic goods together with elements of meteorological, hydrological and agricultural drought.

2.8.3 Standardised Precipitation Index

A simple and statistically relevant index was introduced by the World Meteorological Organization (WMO) to monitor the severity of drought events. SPI has temporal flexibility which allows its application for water resources on all timescales. SPI will have a standard normal distribution with an expected value of zero and a variance of one. SPI allocates a single numeric value varying between -3 and +3 to the precipitation, which can be compared across different climatic regions (Mckee *et al.*, 1993). SPI is based on precipitation alone and its fundamental strength is that it can be calculated for a variety of timescales. So it can be used to monitor short term water supplies such as soil moisture to long term water resources such as groundwater supplies, streamflow, and lake and reservoir levels.

SPI was demonstrated as a tool that could be used operationally as part of a state, regional, or national drought watch system in United States (Hayes *et al.*, 1999). The drought prediction by SPI was much better than the Palmer Drought Severity Index (PDSI) and the timeliness of prediction is invaluable for improving mitigation and response actions. Thomas *et al.* (2015) used the SPI index to predict drought in Narmada Basin in Central India for the periods 1951–1970 and 1989–2008. The results indicate that the entire basin has experienced drought during the past two decades (1989–2008) and that proper mitigation measures need to be adopted in future especially in the middle zone of the basin which is more susceptible to drought.

2.9 SWAT APPLICATIONS AND IMPACT STUDIES

SWAT model has been extensively used since 1993, by researchers, mainly hydrologists, for long term simulations of watershed hydrology. The integration of Remote Sensing, GIS and SWAT model can be a powerful tool in watershed management and protection (Jeark and Ariel, 2012).

2.9.1 Application on Water Resources Systems

Mehta *et al*. (2013) used SWAT model to predict runoff from Tungabhadra catchment in India. Proper calibration and parameterization was done to get good simulation results for daily and monthly flows. The statistical parameters used for comparison, viz. R^2, NS and bR^2 showed good correlation between the simulated and observed stream flows. Hydrological simulations were conducted recently in different parts of the world using SWAT model: in Koshi River Basin, Nepal (Devkota and Gyawali, 2014), Yellow river basin, China (Yao *et al*., 2014), Galo creek watershed in Espírito Santo State, South east Brazil (Pereira *et al*., 2014) etc. Major studies conducted in Kerala using SWAT were in the Meenachil river basin (George and James, 2013), Karuvannur river basin (Sandra and Sathian, 2016), Kunthipuzha sub basin of Bharathapuzha river basin (Sathian and Syamala, 2009) and in Chaliyar river basin (Raneesh and Thampi, 2011).

2.9.2 Application of SWAT in Sediment Control

Rainfall in India depends mainly on the South-West and North-East monsoon and shows high spatial and temporal variation. Due to this large spatial and temporal variation in rainfall, the heavy monsoon rainfall leads to floods and severe erosion of top soil (Thapliyal, 1997). Mishra *et al.* (2007) used SWAT model for assessing the sediment transport within a watershed, and to prioritize the sediment control structures within a watershed so as to get maximum reduction of sediment losses. Van Liew *et al*. (2003) simulated the effect of flood retarding structures successfully in the Little Washita River watershed in southwest Oklahoma using SWAT model. Kirsch *et al*. (2002) estimated the sediment and phosphorus load delivered to the streams and surface water bodies in the Rock River basin on an average annual basis. The results indicate that implementation of improved tillage practices (predominantly conservation tillage) can reduce sediment yields by about 20 percent. Checkdams installed in upland watershed areas control peak discharge rates by storing a portion of the surface runoff and help in removing relatively good quantity of coarse and medium size sediment and help in the settling of fine sediments (Stovin *et al.*, 2002)

2.9.3 Climate Change and its Impact on Water Resources

Climate change refers to a long term change in the state of climate, that can be identified in the mean and/or changes in the variability. Climate change affects the water availability and agriculture of an area (Anupama, 2014). More than 60 percent of the cropped area in India still depends solely on monsoon rainfall (Central Statistical Organization, 1998). The effects of changes due to climatic variability on hydrological responses have been extensively studied at watershed and river basin scales (Jha *et al*., 2004; Githui *et al*., 2009; Hurkmans *et al*., 2010; Terrink *et al*., 2010; Raneesh and Thampi, 2011; Teng *et al*., 2015). A few studies reported expected increase in stream flows (Jha *et al*., 2004; Githui *et al*., 2009; Li-chi and Yuan, 2015), whereas, most of the studies predicted decreased stream flows in the future (Ghosh and Mujumdar, 2009; Raneesh and Thampi, 2011; Wagner *et al*., 2012; Morán-Tejeda *et al*., 2014).

The attempt to assess the adaptation of climate change on water resources in India began in 2003 by Gosain et al., 2003. Later, the impact of climate change on two river basins of India, viz. Godavari and Tapi was studied by Gosain and Rao, (2007). RCM data of HadRM2 (Hadley Centre for Climate Prediction, United Kingdom was used for the study. It was predicted that in the greenhouse gas scenario, severity of droughts and intensity of floods may get strengthened.

An attempt was done by Gosain *et al.* (2011) to study the effect of climate change on the water resources of India using SWAT model. The study was based on A1B scenario of PRECIS for the near term, 2021-2050 (MC) and long term or end century, 2071-2098 (EC) climate scenarios. It was predicted that the river systems except Brahmaputra, Cauvery and Pennar show increase in precipitation at the basin level and corresponding increase in runoff. In EC scenario, all the rivers showed increase in precipitation and associated increase in water yield. In both conditions, most of the river systems showed an increase in sediment load except some areas of Krishna, Pennar and Brahmaputra under EC scenario.

Predictions of changes in ET and water yield were done based on variations in precipitation and temperature in Beijing river basin in China (Lirong and Jianyun, 2012). Different combinations of (15 sets) percentage changes in precipitation and temperature were selected to assess the impact of climate change on ET and watershed runoff. When temperature was kept invariable and precipitation increased, evaporation and water yield increased. When precipitation was kept invariable and temperature increased to simulate runoff, the average annual ET increased and the water yield decreased.

SWAT model was used to predict the impact of changes in land management practices under present and future climate scenarios on hydrologic regimes of Cauvery basin in India (Singh and Gosain. 2011). The data generated by the Hadley Centre for Climate Prediction, UK (Had RM2) was used in the study. Intensification of hydrologic cycle is predicted in the future climate scenario, which was more significant on an annual basis.

Thampi *et al*. (2010) studied the impact of climate change on streamflow in the Chaliyar basin of Kerala using the hydrologic model SWAT. Calibration was performed using the data for the period 1987 to 1991 and validation using the data from 1999 to 2003. Goodness of fit measures such as the Nash-Sutcliffe efficiency and coefficient of correlation were evaluated to assess the performance of the model. These values were high, suggesting that the model performance is good. Results of the study indicate that hydrology of the basin is very sensitive to projected climate changes. Thus climate change is likely to add stress to the water systems in the developing countries.

The SWAT model was used to predict the trends in streamflow using the changes in climate predicted under different scenarios. Many researchers have reported that the results obtained by simulations using SWAT model is highly promising in different physiographic conditions for impact studies (Cibin *et al*., 2010; Thampi *et al*., 2010; Baker and Miller, 2013; Fukunaga *et al*., 2015). The hydrologic changes in a catchment can be understood from the trend of streamflow. Changes in climate, landuse and catchment characteristics have been taken into consideration by analysing trends in streamflow with respect to these changes (Zhang *et al*., 2010; Pechlivanidis *et al*., 2015). At the same time, it is difficult to assess the relative contributions of multiple drivers of change from the streamflow alone, and it is essential to analyse the different components of flow for studying this effect.

2.9.4 Impact of Climate Change on Agriculture

Climate change can affect Agriculture through direct effects like changes in temperature or carbon dioxide, precipitation etc. and also due to indirect effects from changes in the hydrologic cycle (Agarwal, 2007). Direct impacts also occurs due to increased variability in weather, extreme weather conditions, sea level rise, ruining coastal agricultural lands and CO_2 fertilization (Bates *et al*., 2008; FAO, 2003). Indirect impacts also occur due to changes in crop-weed competition dynamics, varietal changes of pests and pathogens and decreased biodiversity in natural ecosystems (Patterson *et al*., 1999; FAO, 2003; IPCC, 2008).

Agriculture and fisheries are highly dependent on specific changes in climatic conditions. It is difficult to understand the overall effect of climate change on Agriculture. The predictions are that the effect of climate change in future will be mixed (USDA, 1935).

Considering the Indian scenario, high temperatures, increased evapo-transpiration and decreased winter precipitation may bring about more droughts. The severity of flooding in many Indian river basins, especially those of the Godavari and Mahanadi is expected to increase (Gosain *et al*., 2006). This may result in biodiversity loss and the living conditions of the people may get affected.

Climate change has considerable impacts on Agriculture and hence on food security and farmers livelihood. Certain adaptation strategies need to be adopted so that the food systems are not affected. These adaptations should aim at sustainable development of agriculture and can be at the level of individual farmer, society, farm, village, and watershed or at national level. Also, approaches which help in the mitigation of greenhouse gas emissions from agriculture need to be adopted.

2.9.5 SWAT Application in Groundwater and Recharge Studies

SWAT groundwater aquifer systems has two components: a shallow, unconfined aquifer which contributes return flow to streams within the watershed and a deep, confined aquifer which contributes no return flow to streams inside the watershed. Estimation of groundwater level and recharge rates is complicated since it depends on many factors such as land use changes, urbanization, climate change etc. The watershed model SWAT need to be integrated with other groundwater models for predicting groundwater levels during hydrologic modelling. SWAT was integrated with the fully-distributed groundwater model, MODFLOW to apply for the Musimcheon Basin in Korea and predict the spatio-temporal distribution of groundwater recharge rates, aquifer evapotranspiration and groundwater levels (Kim *et al*., 2008). Groundwater table depth is not usually computed by SWAT model, but a procedure to compute perched groundwater table depth using SWAT outputs is proposed, in order to expand SWAT's capabilities (Vazquez-Amabile and Engel, 2005).

A scientific method was proposed by Thampi and Raneesh (2012) to predict the impact of climate change on groundwater recharge. Two climate change scenarios A2 and B2 of PRECIS (Providing Regional Climates for Impact Studies) were considered in the study. The groundwater recharge model developed can be used for assessing the groundwater potential and can also be used by the planners for devising strategies for efficient use of the available water resources.

2.9.6 Impact of Land use Changes on Watershed Hydrology

Land use/cover change is one of the most sensitive factors that show the interactions between human activities and the ecological environment. Land use changes affect the water resources in a big way, but quantifying the impact is more challenging (Stonestrom *et al*., 2009). For the reason of increasing water scarcity, the impact of changes in land use on the hydrological cycle at the basin scale has become an important research issue among the hydrologists. Landuse directly influences the splitting up of precipitation into runoff, evapotranspiration, and infiltration (Foley *et al*., 2005). The SWAT model can be used for understanding the watershed response to land use changes (Baker and Miller, 2013; Peng *et al*., 2013; Ghaffari *et al*., 2010).

Mango *et al*. (2011) predicted the impact of land use cover change on the discharge of Nyangores river using SWAT. Three land use change scenarios were tried with partial deforestation, complete deforestation and partial conversion of forests to agricultural land. They found that conversion of forest land to agriculture land and grasslands increased the peak flows and reduced the dry season flow or base flow.

The wide range of SWAT applications in different watersheds with various climatic and land cover conditions (Githui *et al*., 2009; Li *et al*., 2009; Peng *et al*., 2013; Wagner *et al*., 2013; Pervez and Henebry, 2014) highlights that SWAT is a very flexible and robust tool that can be used to simulate a variety of land management problems. In general, an increase of agricultural area leads to an aggravation of the imbalance of water availability and demand in dry season due to increased consumption of irrigation water, whereas urbanization results in more runoff during rainy season due to the increase of paved surface area (Wagner *et al*., 2013). Thus in areas depending on monsoon rains, urbanization and increase in agricultural areas worsen the imbalance between seasonal water availability and water demand. The impact of urbanization on annual runoff is less compared to its impact on floods and in particular, smaller floods are more influenced than larger floods by an increase of impervious area.

In a study conducted in Australia to assess the impact of climate and land use changes on floods in an urban catchment, it was seen that the future flood magnitudes are unlikely to increase for large flood events in the urban catchment (Chen. and Nagayanagi, 2012). SWAT model is thus a useful tool for modeling the impact of land use changes in various small and large watersheds. Several researchers across the globe have thus proved that SWAT is an effective tool for assessing the impact of land use/land cover change on the hydrological status of the river basins (Memarian *et al*., 2013).

2.9.7 Watershed Interventions and its Impact on Hydrologic Processes

Runoff decreases as water demand and withdrawal from rivers increase (Foley *et al*., 2005). Water stored by the water retention structures is utilised for irrigation and as the irrigated area increases, water withdrawal increases, evapotranspiration increases and runoff decreases. The artificial water storage and diversion structures through watershed development activities will further reduce the flow through the rivers (George *et al.*, 2011).

A modelling framework to evaluate climate change and watershed development impacts on water security was developed by George *et al.* (2011). The framework involves the integration of biophysical and hydrological modelling coupled with socio economic modelling to provide a quantitative hydro economic evaluation of the performance associated with each scenario-response combination. The impact of watershed development on hydrology was also analysed using this modelling framework within a river basin.

Zhan *et al*. (2014) identified climate change and human activities as the two main reasons for the change in runoff. An integrated approach which combined the elasticity coefficient approach and the hydrological modelling approach were used to understand the factors causing runoff change. The contribution of climate change and human activities to runoff change was 34.1-47.3 and 52.7-65.9 percent, respectively. The study gives insight to the causes of change in runoff and provides information to water resource management

Watershed development has been identified as a cause of change in runoff in a few river basins of India (Nune *et al*., 2014). They studied the reasons for change in stream flow in the Himayat Sagar Catchment (HSC), India. The reasons identified were the increase in surface water storage capacity of small watershed development structures and increase in evapotranspiration associated with irrigation development. It was also concluded that most of the anthropogenic activities studied were interrelated, which makes separation difficult.

While quantifying the impact of climate variability and human activities on stream flow in the middle reaches of the Yellow river basin in China, it was seen that climate change has a greater effect on stream flow reduction in a few tributaries, where as human activities including soil and water conservation structures, dams and reservoirs and water consumption are the dominant factors responsible for the decrease in runoff in all the other tributaries (Yao *et al*., 2014).

Construction of dams and its impact on natural ecosystems, particularly on rivers, is found to be intense and profound and has far-reaching consequences (WCD, 2000). Changes in water quality of rivers due to the construction of dams have also been documented in many research reports (Petts, 1984; Hart *et al*., 1991). The hydrologic systems will be affected by changes in precipitation and temperature which in turn may affect the regional water resources.

2.10 ASSESSMENTS AND RESEARCH NEED

Many studies have been reported giving insight into the land use changes in river basins, but only a very few have taken into account of the watershed activities happening in the catchment areas. From the literatures reviewed and discussed so far it is clear that no studies have been reported from South India assessing the impact of climate change on river basin hydrology using the CORDEX-SA data. The future projection run which includes both natural and anthropogenic forcing is based on the IPCC AR5 climate scenarios. These data are more reliable and hence was used in the study.

The influence of Bharathapuzha river valley on the cultural formation of the people of the state is invaluable (George, 2007). The river flow has decreased and is now meandering through some portions of the river bed (Dinesan, 2012). The greed of mankind exploiting the natural resources is the major cause of this severe situation. Due to the spatial distribution of topography, soil characteristics, vegetation, land use/land cover, rainfall and evaporation, the physically based distributed model SWAT was found to be the suitable tool for simulation of the hydrological processes and to study the impact of climate change and watershed interventions on river flow of Bharathapuzha and hence the study was undertaken.

Materials and Methods

CHAPTER III

MATERIALS AND METHODS

This chapter covers the study area, analysis of different climate scenarios, hydrological model used and the methodology adopted to achieve the objectives of the study. Based on the review of different models to estimate runoff, SWAT model was used for the study. The study is concerned mainly about the impact of climate change and watershed interventions on the hydrology of Bharathapuzha river. The methodology used for bias correction of the climate change data and the procedures adopted for sensitivity analysis, calibration and validation of the model are also detailed.

3.1 DESCRIPTION OF THE STUDY AREA

Bharathapuzha is the second longest river in Kerala, India which lies between 10°25' - 11°25' N and 75°50' - 76°55'E having a length of around 209 km (Bijukumar *et al*., 2013). The river has a total drainage area of 5,988 km^2 (Magesh *et al*., 2013) which lies in the two states of India, namely Kerala and Tamil Nadu with about 71 percent of the catchment area in Kerala and 29 percent in Tamil Nadu. It originates from the Anamalai hills in Western Ghats near Pollachi in Tamil Nadu and discharges into the Arabian sea at Ponnani. The river consists of four main tributaries, viz., Gayathripuzha, Chitturpuzha, Kalpathipuzha and Thuthapuzha (Magesh *et al*., 2013). The river basin consists of a well-developed flood plain and fluvial terrace of recent origin. An outline map of Bharathapuzha river basin with geographical location is shown in Fig. 3.1.

The climate of the basin is humid tropical (Guhathakurta and Rajeevan, 2007). The river is the major source of water for three districts of Thrissur, Palakkad and Malappuram in Kerala and two districts Coimbatore and Tiruppur in Tamil Nadu. Average annual discharge of the river is around 3.94 km^3 (Raj and Azeez, 2009) and the geology of the area is characterized by archaean crystalline formation (gneiss, schist, charnockite), tertiary formations, sub recent laterite and recent riverine alluvium (CGWB 2007). Major drainage pattern of the area is dendritic in nature and is highly influenced by the topography. Most of the area experiences high humidity during the monsoon months from June to October.

One of the major social issues leading to environmental consequences in the region is sand mining. Very lean flows, low levels of watertables on either side, acute shortage of water in summer season, salinity intrusion in the coastal regions, stream bank erosion, forest degradation and unsustainable exploitation of natural resources are other problems encountered in the region. Today the river is like a trickle in the summer months and flows rapidly with muddy water for a couple of weeks when there is heavy rains. Sand mining has caused fall in the river bottom level and consequently the groundwater levels. Due to the decrease in wetted perimeter and increase in hydraulic gradient, the velocity of the water flow increases, making it violent during monsoons. The lean flow in the river also causes saline water back flow into the river channel. Apart from the dams constructed across the river in 1970’s and 80’s, a number of check dams have been constructed across its tributaries for retaining water for irrigation and drinking purpose. From the climate studies done in the basin, it is seen that the temperature in the area is having an increasing trend (Raj and Azeez, 2010) and at the same time the precipitation is decreasing (Raj and Azeez, 2010; Jagadeesh and Anupama, 2013) in major part of the basin.

Due to the above explicated reasons, it was felt that the impact of watershed development activities as well as future climate change on the hydrology of Bharathapuzha river basin need to be assessed. SWAT hydrologic model was used to simulate the transport of water through the river basin.

3.1.1 Physiography of the Area

Physiographically, Kerala is divided into three categories- the low land, the midland and the high ranges depending upon the elevation from the mean sea level. The river begins its flow from the highlands, flows through the mid land and low land areas before merging to the Arabian sea. The summer view of Bharathapuzha river at Kuttippuram and the area where Kunthipuzha joins the main river are shown in Plates 1 and 2 respectively. General elevation of the area

Plate 1 Summer view of Bharathapuzha river at Kuttippuram

Plate 2 Kunthipuzha joining the main river

ranges from 75 m to 2238 m in the upper region, 10 m to 75 m in the middle region and less than 10 m in the lower region. The slope of basin varies from 0^o to 70^o and the slope variation is chiefly controlled by the local geology and erosion cycles (Magesh *et al*., 2013).

3.1.2 Climate of the region

The State of Kerala is popularly known as the "Gateway of summer monsoon" over India (Krishnakumar *et al*., 2009). The State is like a narrow strip of land with length in the North-South direction, with the Arabian sea in the west and the Western Ghats along the eastern boundary. Uncertainties in monsoon variability and rainfall distribution over Kerala are noticed in recent times.

The mean annual temperature of the Bharathapuzha basin during the period 1965-2005 was 24.30°C, with a standard deviation of 0.3°C (Raj and Azeez, 2011). The water year is divided into four seasons: South-West monsoon (June–September), North-East monsoon (October - December), Post-monsoon (January–March), and Pre-monsoon (April–May). Around 65-70 percent of the annual rainfall in the basin is received during the South-West monsoon, 15-20 percent during the North-East monsoon period and the rest during the pre and post monsoon periods (Krishnakumar *et al*., 2009).

3.2 METEOROLOGICAL DATA

Required climate data are rainfall, maximum and minimum air temperature, wind speed, relative humidity and solar radiation on daily basis.

3.2.1 Rainfall

Daily rainfall data from ten raingauge stations viz., Pattambi, Malampuzha, Mannarkkad, Angadippuram, Kollengode, Ottappalam, Thrithala, Mangalam, Ponnani and Chittur were used for the model simulations. The average annual rainfall of the area is 2,924.4 mm (Magesh *et al*., 2013).

3.2.1.1 Observed data

Observed rainfall data was collected from IMD, Water Resources Department, Government of Kerala and Kerala Agricultural University. Daily rainfall for the period 1971-2013 was collected from different stations.

3.2.1.2 Gridded data

Gridded data of rainfall and temperature prepared by the Indian Meteorological Department (IMD) for the Indian region have been used in the study. The gridded data on rainfall was prepared based on 1803 raingauge stations with a minimum data availability of 90 percent for the period 1951-2008. Shepard (1968) method was used for data interpolation. The weighted sum of the observations at the surrounding raingauge stations falling within the predefined radius of influence is considered. The entire data of Indian region has been interpolated into 32 x 32 grid cells.

The daily gridded interpolated rainfall data for the area was taken from the data of the Indian region. The data from IMD is available in Network Common Data Format (NetCDF). This format is a set of interfaces for array oriented data access. NetCDF libraries support a machine independent format for representing the scientific data. The add-in called netcdf4excel was downloaded and installed to access the data in the NetCDF. Using this add-on, the data was imported to excel. It was compared with the direct observation for the grid where raingauge data was available for the period 1976-97.

The comparison of observed data and gridded data was done based on the coefficient of determination (R^2) between the gridded and observed data. The range of R^2 values obtained was 0.53-0.99 which showed moderate to very strong correlation between the data. Rainfall analysis was carried out for all the seasons as well as the whole year separately for each station. The statistical parameters mean, maximum, minimum, standard deviation and coefficient of variation for rainfall data have been computed for seasonal and annual periods. Gridded data of mean temperature and maximum temperature after comparison with the observed data was also used to study the temperature trend of the area.

3.2.2 Hydro-meteorological data

The daily meteorological data other than rainfall such as temperature, wind speed, relative humidity, sunshine hours and evapotranspiration for the period

1989 to 2013 were obtained from Regional Agricultural Research Station (RARS), Pattambi, Kerala Agricultural University. Daily rainfall data of different stations was obtained from Regional Agricultural Research Station (RARS), Pattambi, Kerala Agricultural University, IMD and Water Resources Department, Government of Kerala. Streamflow data of different gauging stations in the area were collected from CWC and Water Resources Department. The location of the raingauge stations and river gauge stations is shown in Fig. 3.2.

3.3 TREND ANALYSIS

The magnitudes of trend of rainfall and temperature were determined using regression analysis (parametric test) and using Mann-Kendall test (non-parametric method). Both these methods assume a linear trend in the time series. Time is taken as the independent variable and rainfall/temperature as the dependent variable for the regression analysis. The linear trend value represented by the slope of the simple least-square regression line provided the rate of increase/decrease in the variable. The trend analysis was carried out for the temperature (mean, maximum and minimum) and rainfall data using the Mann-Kendall and the t-test.

3.3.1 Mann-Kendall Trend Test

The Mann-Kendall (MK) test is a non-parametric statistical procedure which is well suited for identifying trends in data over long time periods (Mann 1945; Kendall 1975; Burn *et al.*, 2004; Thomas *et al.*, 2015). The Mann-Kendall statistic S measures the trend in the data and is given mathematically as

$$S = \sum_{k=1}^{n-1} \sum_{j=i+1}^{n} sgn(xj - xk) \qquad \text{---------- (1)}$$

The positive values of S indicate an increasing trend, whereas negative values indicate a decrease in value over time. There are n data points and xi, xj, xk represents data points at time i, j and k respectively. The strength of trend is proportional to the magnitude of S (i.e., larger the S value, stronger the trend). The sign of the difference between the consecutive sample sets is given by the following equations.

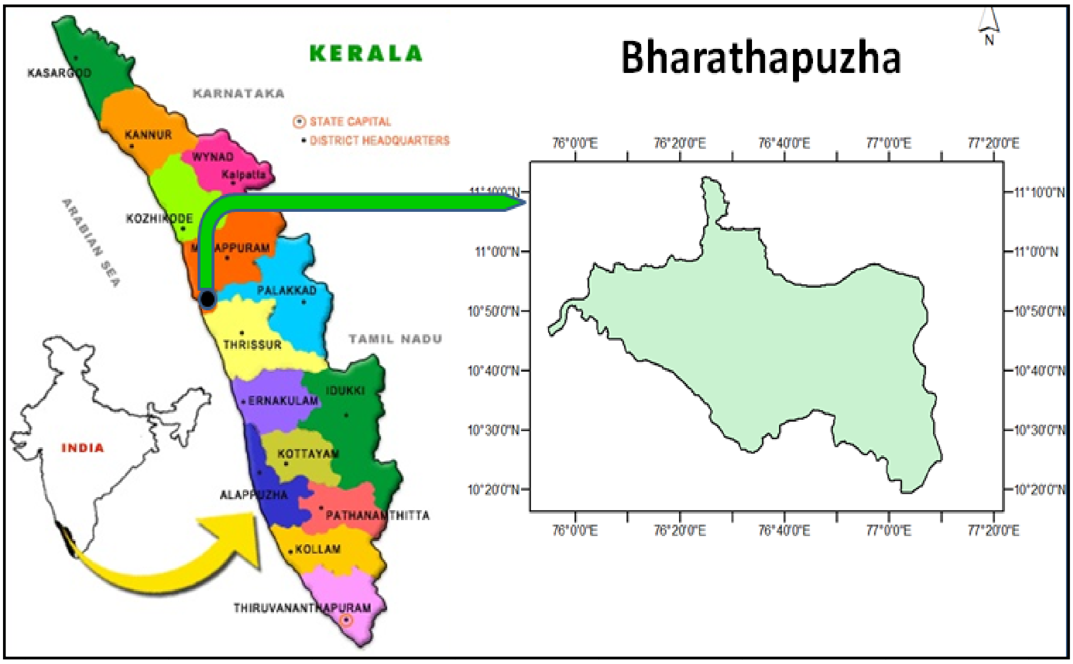

Fig. 3.1 Location of Bharathapuzha river basin

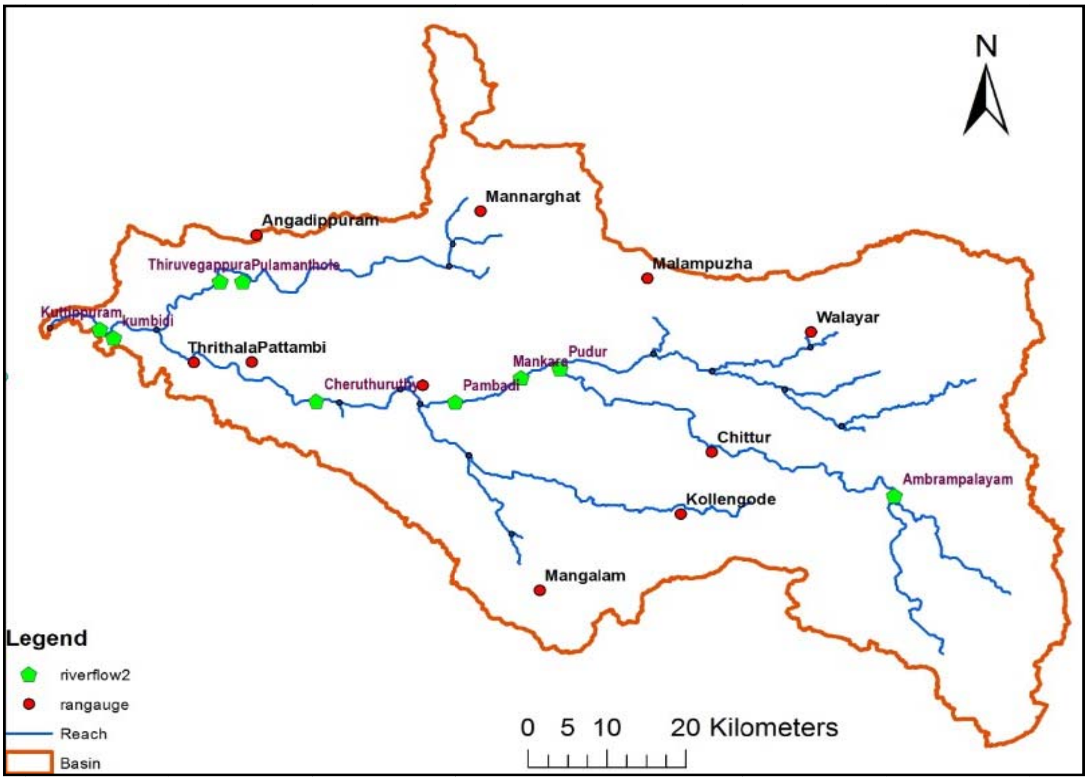

Fig. 3.2 Location of raingauge and streamgauge stations in Bharathapuzha

$Sgn(x_j-x_k) = 1$ if $x_j-x_k>0$ -----------(2)

$Sgn(x_j-x_k) = 0$ if $x_j-x_k=0$ -----------(3)

$Sgn(x_j-x_k) = -1$ if $x_j-x_k<0$ -----------(4)

$Sgn(x_j-x_k)$ is an indicator function that results in the values 1, 0, -1 according to the sign of x_j-x_k where j>k.

The null hypothesis is that there is no trend (H_0) in the time series. Using the Kendall probability table and by assessing the S result along with the number of samples ‘n’ we get the probability of rejecting the null hypothesis for a given level of significance, z which is given as

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} \text{for } S > 0 \\ 0 \qquad S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} \text{for } S < 0 \end{cases} \qquad \text{----------- (5)}$$

Z follows a normal distribution and if the Z value is positive and the computed probability is greater than the level of significance, there is an increasing trend. If the Z value is negative and the computed probability is greater than the level of significance, there is a decreasing trend.

The purpose of the Mann-Kendall test is to statistically assess if there is a monotonic upward or downward trend of the variable of interest over time. A monotonic upward (downward) trend means that the variable consistently increases (decreases) through time, but the trend may or may not be linear. The MK test can be used in place of a parametric linear regression analysis, which can be used to test if the slope of the estimated linear regression line is different from zero. The regression analysis requires that the residuals from the fitted regression line be normally distributed; an assumption not required by the MK test, the test being non-parametric.

3.3.2 Standardised Precipitation Index

Rainfall deficit occurring in a region for a period of time could lead to various degrees of drought conditions. The concept of drought may vary from place to place since the rainfall varies significantly among different regions. Hence, a simple and statistically relevant index was introduced by the World Meteorological Organization (WMO) to monitor the severity of drought events. SPI will have a standard normal distribution with an expected value of zero and a variance of one. SPI allocates a single numeric value varying between -3 and +3 to the precipitation, which can be compared across different climatic regions (Mckee *et al.*, 1993).

The Z or SPI value is obtained computationally using an approximation provided by Abramowitz and Stegun (1965) that converts cumulative probability to the standard normal random variable Z:

$$Z = SPI = -\left[t - \frac{C_0 - C_1 t - C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right] \text{ for } 0<H(x)\leq 0.5$$

$$Z = SPI = +\left[t - \frac{C_0 - C_1 t - C_2\ t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right] \text{ for } 0.5<H(x)\leq 1.0$$

$$t = \sqrt{\ln\left\{\frac{1}{H(x)^2}\right\}} \qquad \text{for } 0<H(x)\leq 0.5$$

$$t = \sqrt{\ln\left\{\frac{1}{1-H(x)^2}\right\}} \qquad \text{for } 0.5<H(x)\leq 1.0$$

Where c_0= 2.51552, c_1=0.80285, c_2=0.01033, d_1=1.43279, d_2=0.18927, d_3=0.00131 and H(x) is the cumulative probability. Drought impact for different time scales (1, 3, 6, 12, 24 or 48 months) can be calculated. Since the SPI is normalized, wetter and drier climates can be represented in the same way. Based on the classification, a drought event occurs any time if the SPI is continuously negative and reaches an intensity of -1.0 or less (Mckee *et al.*, 1993).

3.4 SOFTWARES AND TOOLS USED

The study was conducted utilising the different models, softwares and tools available for effective analysis of data and prediction of trends and impact analysis. A brief description of the models and tools used in the study is given below.

3.4.1 ArcGIS 10.3

ArcGIS is a proprietary Geographic Information System (GIS) software for working with maps and geographic data. It is mainly used for creating and using maps, compiling geographic data, analysing mapped information, sharing and discovering geographic information in a range of applications and managing geographic information in a database. The developer of ArcGIS is Environmental Systems Research Institute (ESRI) and was initially released in 1999 at New York. ArcGIS 10.3, which was released in 2014, was used for this study. The system provides an infrastructure for making maps and geographic information, available in an organization, across a community and openly on the Web.

ArcGIS for Desktop consists of several integrated applications, including ArcCatalog, ArcMap, ArcToolbox, and ArcGlobe. ArcCatalog is the data management application, used to browse datasets and files on the computer, database, or other sources. In addition to showing what data is available, ArcCatalog also allows users to preview the data on a map. It also provides the ability to view and manage metadata for spatial datasets. ArcMap is the application used to view, edit and query geospatial data, and create new maps. The ArcMap interface has two main sections, including a table of contents on the left and the data frame(s) which display the map. Items in the table of contents correspond with layers on the map. ArcToolbox contains geoprocessing, data conversion, and analysis tools, along with many functions in Arc Info. It is also possible to use batch processing with ArcToolbox for frequently repeated tasks.

In this study, ArcGIS 10.3 is used for setting projection for all the SWAT inputs such as DEM, landuse and soil map. Georeferencing of soil map and the toposheets required for the study area has been carried out using this tool. Digitization and the preparation of soil map for the study area has also been done with this software.

3.4.2 ERDAS IMAGINE 2015

ERDAS IMAGINE is an image processing high end software with raster graphics editor abilities designed by ERDAS for geospatial applications. The latest version, ERDAS IMAGINE 2015 is used in this study. The software is aimed primarily at geospatial raster data processing and allows the user to prepare, display and enhance digital images for mapping use in GIS or in computer aided design (CAD) software. It consists of a set of tools allowing the user to perform numerous operations on multispectral images and generate an answer to specific geographical queries. In this study, land use map of the Tamil Nadu region of the study area has been prepared using the ERDAS software. Supervised classification of the false colour composite has yielded the land use.

3.4.3 Soil Plant Atmosphere Water (SPAW) Hydrologic Budget Model

Soil Plant Atmosphere Water (SPAW) hydrologic budget model was developed by Keith Saxton, United States Department of Agriculture (USDA) Agricultural Research Service (ARS). SPAW is a daily hydrologic budget model used for calculating the characteristics of soil. The model estimates the daily content and movement of water and nutrients for farm fields and their soil, plus daily water budgets for agricultural wetlands, ponds and reservoirs. Soil Water Characteristics (SWC) is the program which estimates soil water tension, conductivity and water holding capability based on the soil texture, organic matter, gravel content, salinity and compaction. Soil hydraulic conductivity, electrical conductivity and bulk density were obtained using this model. SPAW model interface is shown in Fig. 3.3.

3.4.4 SWAT-CUP

SWAT-CUP is a calibration/uncertainty or sensitivity program interface for SWAT. SWAT-CUP 2012 version 5.1.6 was used for the study. The program links SUFI-2, PSO, GLUE, ParaSol, and MCMC procedures to SWAT. It helps in sensitivity analysis, calibration, validation and uncertainty analysis of SWAT models. It is a public domain program and uses an advanced user friendly interface (Fig. 3.4). Each SWAT-CUP project contains one calibration method and allows user to run the procedure many times until convergence is reached. In the study SUFI-2 program was used for calibration.

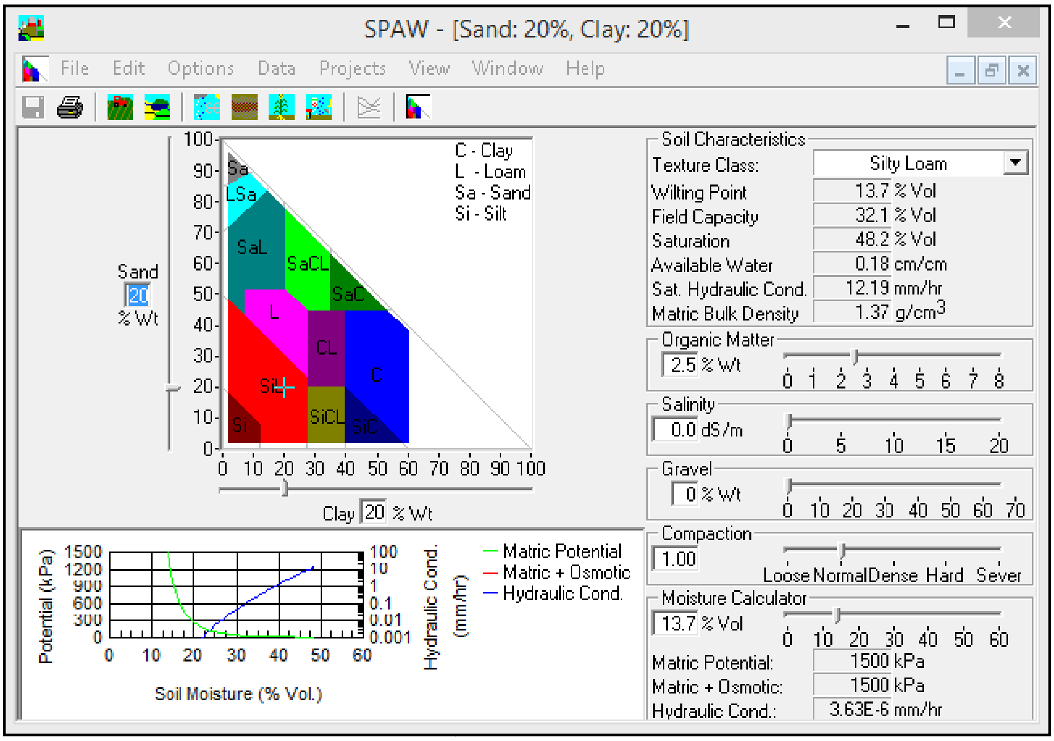

Fig. 3.3 SPAW model interface

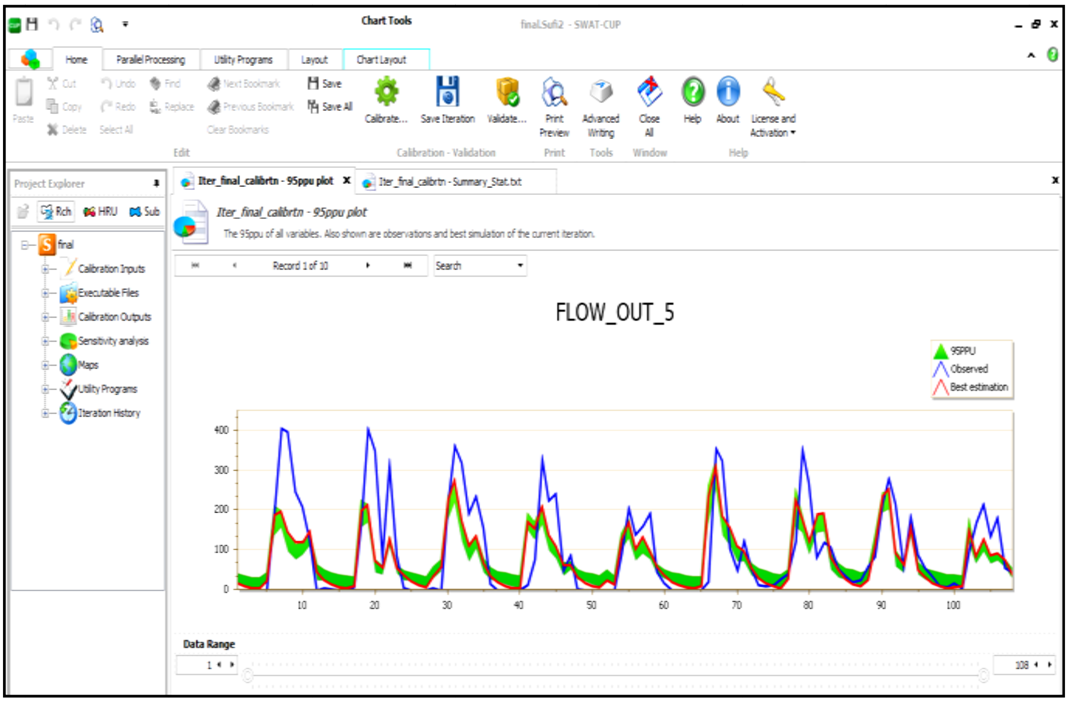

Fig. 3.4 SWAT-CUP interface

In SUFI-2, parameter uncertainty accounts for all sources of uncertainties such as uncertainty in driving variables (e.g., rainfall), conceptual model, parameters, and measured data. Uncertainties are accounted using the *p*-factor and d-*factor*. *P-factor* is the percentage of measured data bracketed by the 95 percent prediction uncertainty (95PPU), d-factor corresponds to the average thickness of the 95PPU band divided by the standard deviation of the measured data. SUFI-2, hence seeks to bracket most of the measured data with the smallest possible *d-factor*. A *p-factor* of about 100 percent and a *d-factor* near zero can be considered as an ideal solution. When acceptable values of *d-factor* and *p-factor* are reached, then the parameter uncertainties are the desired parameter ranges. Nash-Sutcliff (NS) coefficient and coefficient of determination (R^2) can be used to assess further goodness of fit between the observations and the final best simulation. The calibration iterations are saved in the iteration history for further use.

3.4.5 TREND

TREND is a product from the Climate Research Center for Catchment Hydrology's (CRCCH) Climate Variability Program. The scientific development and testing was carried out by Francis Chiew and Lionel Siriwardena and the software was developed by Sylvain Arene and Joel Rahman. TREND is designed to facilitate statistical testing for trend, change and randomness in hydrological and other time series data. It has 12 statistical tests, based on the World Meteorological Organisation (WMO)/ The United Nations Educational, Scientific and Cultural Organization (UNESCO) Expert Workshop on Trend/Change Detection and on the Cooperative Research Centre (CRC) for Catchment Hydrology publication Hydrological Recipes.

The TREND software was used for doing the Mann-Kendall (non-parametric test for trend), students' t-test and the Linear Regression (parametric test for trend).

3.4.6 Standardized Precipitation Index (SPI) Program

The basic SPI program was developed by National Drought Mitigation Centre (NDMC), University of Nebraska, Lincoln, United States. The

Standardized Precipitation Index (SPI), developed by T.B. McKee, N.J. Doesken, and J. Kleist in 1993, is based only on precipitation. One unique feature of SPI is that it can be used to monitor drought conditions at different time scales. This temporal flexibility allows SPI to be useful in both short-term agricultural and long-term hydrological applications.

Analysis of drought events has been carried out for two time periods, 1971-1987 and 1988-2005. Five time scales were considered for the analysis, 1-month SPI which is indicative of meteorological drought, 3-month SPI for agricultural drought which is indicative of soil moisture conditions, 6-month SPI that represents surface water availability and 12-month SPI for hydrological drought considering long term storages. The user interface of SPI program is shown in Fig. 3.5 and the sample output screen is shown in Fig. 3.6.

3.5 SWAT MODEL DESCRIPTION

Soil and Water Assessment Tool (SWAT) was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds. It is a physically based, semi-distributed and computationally efficient model which can be used to assess long term impacts. It also allows simulating a number of physical processes in the watershed. The watershed can be partitioned into subbasins in situations where the land use, soil and slope are dissimilar enough in properties to affect the hydrology. Lumped land areas in a subbasin that are composed of unique land cover, soil and management conditions are called Hydrologic Response Units (HRU's).

Land phase and the routing phase are the two major components of the watershed hydrology. The land phase controls the quantity of water, sediments, nutrients and pesticide loadings to the main stream in each subbasin and the routing phase controls the movement of water, sediments etc. through the channel network to the watershed outlet (Arnold *et al.*, 2012). Major soil water processes occurring in the watershed include infiltration, evaporation, plant uptake, lateral flow and percolation to lower layers.

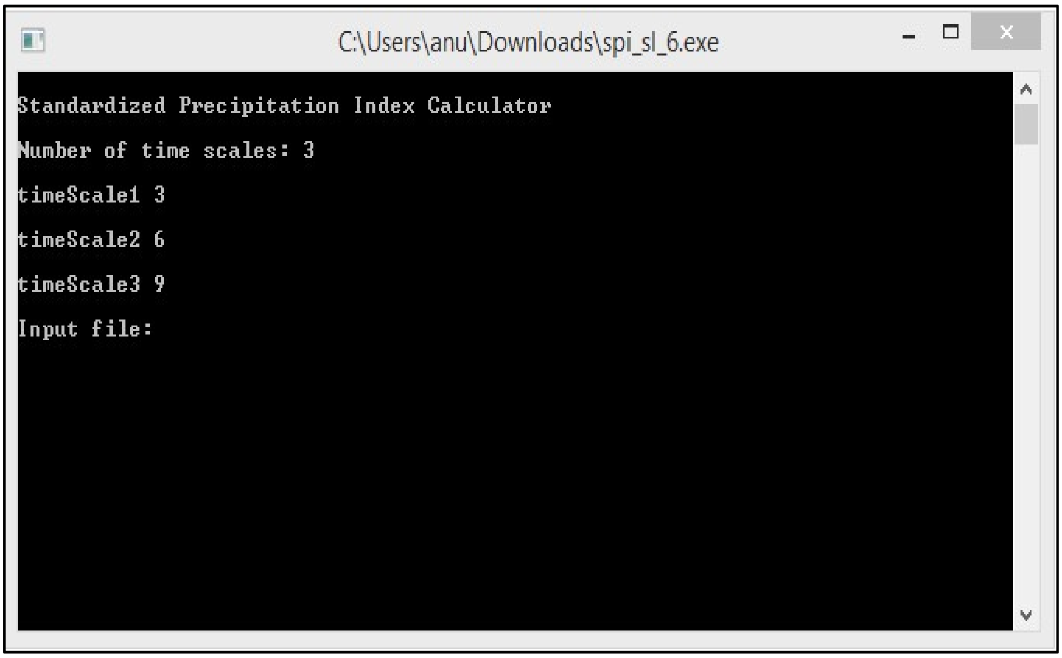

Fig. 3.5 View of the SPI program window

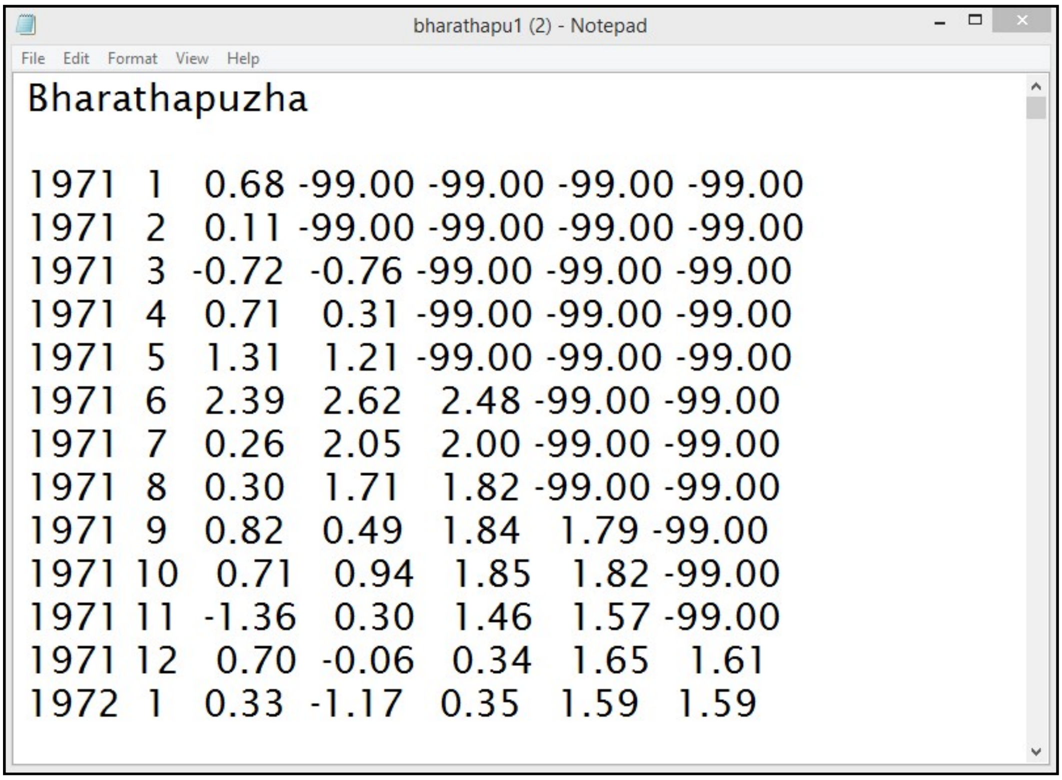

Fig. 3.6 View of the SPI program output window

Water balance is the major driving force in the SWAT simulations (Neitsch *et al.*, 2011). Hydrologic simulation of SWAT is based on the water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad \text{------------- (1)}$$

where: SW_t is the final soil water content (mm), SW_0 is the initial soil water content on day i (mm), *t* is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} is the amount of return flow on day i (mm).

3.5.1 Estimation of Surface Runoff

The Soil Conservation Service (SCS) curve number procedure was used in the estimation of runoff volume. It is an empirical model which provides a consistent basis for estimating runoff in different land use and soil type.

SCS curve number equation is: $Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)}$ -------------------- (2)

Where, Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), I_a is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm), and S is the retention parameter (mm). The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content.

The retention parameter depends on soil, land use, management and slope and temporally due to changes in soil water content. The retention parameter is defined as:

$$S = 25.4(\frac{100}{CN} - 10) \quad \text{---------------- (3)}$$

where, CN is the SCS curve number for the day.

The initial abstractions, I_a, is commonly approximated as 0.2S. This is an empirical model that estimates the amounts of runoff under varying land use and soil types. The curve number is a function of the soil permeability, land use and antecedent soil water conditions.

3.5.1.1 Estimation of Peak Runoff Rate

The peak runoff rate is an indicative of the erosive power of rainfall and is used to predict sediment loss. SWAT calculates peak runoff rate using the modified rational formula.

$$Q_p = \frac{CIA}{3.6} \quad \text{--------------------- (4)}$$

Where Q_p is the peak runoff rate (m^3/s), C is the runoff coefficient, I is the rainfall intensity (mm/h), A is the subbasin area in km^2 and 3.6 is a unit conversion factor.

3.5.1.2 Time of Concentration

Time of concentration is the amount of time from the beginning of a rainfall event until the entire subbasin is contributing to flow at the outlet. The time of concentration is calculated by summing the overland flow time and the channel flow time.

$$t_c = t_{ov} + t_{ch} \quad \text{--------------------(5)}$$

where t_c is the time of concentration for the subbasin (h), t_{ov} is the time of concentration of overland flow (h), t_{ch} is the time of concentration for channel flow (h).

3.5.2 Evapotranspiration

Evapotranspiration is a collective term that indicates all the processes by which water at the earth's surface is converted to water vapour. It includes evaporation from the plant canopy, evaporation from rivers and lakes, transpiration, sublimation and evaporation from the soil. Evapotranspiration is the primary mechanism by which water is removed from a watershed. The model computes evaporation from soils and plants separately. Potential soil water evaporation is estimated as a function of potential evapotranspiration and leaf area index (area of plant leaves relative to the area of the HRU).

3.5.2.1 Potential Evapotranspiration

Potential evapotranspiration (PET) is the rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation that has access to an unlimited supply of soil water. There are three options in the model for estimating potential evapotranspiration: Hargreaves (Hargreaves *et al*., 1985), Priestley-Taylor (Priestley and Taylor 1972), and Penman-Monteith (Monteith 1965). The Penman-Monteith method is used in the study to estimate PET. It combines components that account for energy needed to sustain evaporation, the strength of mechanism required to remove the water vapour and aerodynamic and surface resistance terms. Actual soil water evaporation is estimated by using exponential functions of soil depth and water content. Plant transpiration is simulated as a linear function of potential evapotranspiration and leaf area index.

3.5.3 Soil Water

The water that enters the soil may be removed from the soil by plant uptake or evaporation. It can also percolate past the bottom of the soil profile and ultimately become aquifer recharge. A final option is that water may move laterally in the profile and contribute to streamflow. Out of these different pathways, plant uptake of water removes the majority of water that enters the soil profile.

Water in the soil can flow under saturated and unsaturated conditions. In saturated soils, flow is driven by gravity and usually occurs in the downward direction whereas in unsaturated soils the flow is caused by gradients.

3.5.3.1 Percolation

Percolation is calculated for each soil layer in the profile. Water is allowed to percolate if the water content exceeds the field capacity water content for that layer and the layer below is not saturated. Water that percolates out of the lowest soil layer enters the vadose zone. The vadose zone is the unsaturated zone between the bottom of the soil profile and the top of the aquifer.

3.5.3.2 Lateral flow

Lateral flow will be significant in areas with soils having high hydraulic conductivities in surface layers and an impermeable or semi-permeable layer at a shallow depth. In such a system, rainfall will percolate vertically until it encounters the impermeable layer and the water then ponds above the impermeable layer forming a saturated zone of water, i.e., a perched water table. This saturated zone is the source of water for lateral subsurface flow.

Lateral flow is determined by the equation,

$$Q_{lat} = 0.024 \frac{2SSCsin\propto}{\theta_d L}$$

where, Q_{lat} = lateral flow (mm/ day), S = drainable volume of soil water per unit area of saturated thickness (mm/day), SC = saturated hydraulic conductivity (mm/h), L = flow length (m), α = slope of the land, θ_d = drainable porosity.

3.5.4 Groundwater

Groundwater is the water in the saturated zone of earth materials under pressure greater than atmospheric, i.e., positive pressure. The groundwater table is the depth at which the pressure between water and the surrounding matrix is equal to atmospheric pressure. Although recharge by seepage from surface water bodies may occur, water enters groundwater storage primarily by infiltration/percolation. Water leaves groundwater storage primarily by discharge into rivers or lakes, but it is also possible for water to move upward from the water table into the capillary fringe, a zone above the groundwater table that is saturated.

3.5.4.1 Base flow

The steady state response of base flow to recharge is given as:

$$Q_{gw} = \frac{800 * K * h}{L_{gw}^2}$$

where Q_{gw} is the groundwater flow or basin flow into the main channel on the day I mm, K is the saturated hydraulic conductivity of the aquifer in mm/h, L_{gw} is the distance from the ridge or subbasin divide for the groundwater system to the main channel in m, and h is the water table height in m.

3.5.4.2 REVAP

Water may move from the shallow aquifer into the overlying unsaturated zone. SWAT models the movement of water into overlying unsaturated zones as a function of water demand for evapotranspiration. To avoid confusion with soil evaporation and transpiration, this process has been termed as "revap". This process is significant in watersheds where the saturated zone is not very far below the surface or where deep rooted plants are growing.

3.6 INPUT DATA

SWAT model requires the data on terrain, landuse, soil and weather for assessment of water resource availability at various locations of the drainage basin. These data at 1:50000 scale for the river basin was used in the model. The following sections provide the details of the data used and the pre-processing done before inputting the data to the model.

3.6.1 Topography/Digital Elevation Model

Digital Elevation Model (DEM) represents a topographic surface in terms of a set of elevation values measured at a finite number of points. One of the essential prerequisites for a hydrological model is the DEM (Wagner *et al*., 2011). Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) provided by the Consultative group for International Agriculture Research Consortium for Spatial Information (CGIAR-CSI) with a spatial resolution of 30 m was downloaded from Earthexplorer.usgs.gov. SRTM 1 Arc-Second Global elevation data offer worldwide coverage of void filled data at a resolution of 1 arc-second (30 m) and provide open distribution of this high-resolution global data set. The U.S. Geological Survey (USGS) Earth Explorer (EE) tool provides users the ability to query, search, and order satellite images, aerial photographs and cartographic products from several sources. The DEM in the WGS_1984_UTM_Zone_43N coordinate system was used in ArcSWAT for watershed delineation.

3.6.2 Land use Map

Land use map of Bharathapuzha (Kerala region) was prepared through supervised classification in consultation with Kerala State Remote Sensing and Environment Centre using LISS III imagery of IRS P6 of 2008. Visual interpretation and ground truthing was employed to assist supervised classification process. To get the land use of Tamil Nadu region, imagery of the area was downloaded and supervised classification was done using ERDAS Imagine 2015 developed by Intergraph, USA.

Supervised classification is strictly controlled by the user. In the classification process, the pixels that represent the land cover features were recognised and identified with the help of other sources like aerial photos, google imagery and ground truth data. The patterns are identified and instructions are given to the computer to identify pixels with similar characteristics. The classified land use map of Tamil Nadu region was joined to the land use map of Kerala region in ArcGIS to get the landuse map of the river basin.

3.6.3 Soil Map

Soil map is the important map layer that is to be supplied to the SWAT model for HRU analysis. The morphological characteristics of the soil and soil map needed for the SWAT model were collected from the Directorate of Soil Survey & Soil Conservation of Kerala State. The soil map was digitized and converted to grid file using ArcGIS 10.3 for use in the SWAT model. The soil properties which were not available from the data collected from soil survey were computed using SPAW software.

3.7 FUTURE CLIMATE SCENARIOS

A high resolution regional model simulation has been developed by the World Climate Research Programme (WCRP) and is made available to the scientific community, through the CORDEX (Co-ordinated Regional Downscaling Experiment) program (Giorgi *et al*., 2009). The simulations over South Asian region (CORDEX-SA) are available for different models and are available at the data portal of Centre for Climate Change Research of Indian Institute of Tropical Meteorology (IITM), Pune, India (Patwardhan *et al*., 2014). These models are of approximately 50 km × 50 km horizontal resolution and have been derived using the lateral boundary conditions from Coupled Model Intercomparison Project Phase 5 (CMIP5). CORDEX-SA provides the multi-model outputs for different scenario conditions and gives a range of uncertainty of model simulations. These multi-model simulations are used in the present study.

Population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy are the major anthropogenic factors which drive the greenhouse gas emissions. Four different Representative Concentration Pathways (RCPs) which describe 21st century emissions have been defined (IPCC, 2014). The four scenarios are a low emission so-called peak-and-decay scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one with very high emissions scenario (RCP8.5). RCP 4.5 represents a stabilisation scenario, where the total radiative forcing is stabilised before 2100 and RCP 8.5 is characterised by increasing greenhouse gas emissions over time.

3.7.1 Climate Change Data

Climate change data is used to study the future prediction of climate change. Global climate models are the best models to understand and project the changes in climate. Rainfall and temperature data was downscaled and bias corrected before it is used in the hydrologic model SWAT to forecast hydrologic scenarios of future. Climate change data was downloaded from CORDEX-South Asia Multi Models Output site (http://cccr.tropmet.res.in/cordex/files/downloads.jsp). The models under IPCC AR4 have been used widely for prediction of climate data earlier, but with the introduction of IPCC AR5, new models have come up, the data of which was used for the impact analysis. These include projected changes in daily rainfall (mm) and Temperature (°C) using

Representative Concentration Pathway (RCP) 4.5 scenario and 8.5 scenario, for the historical period as well as for the future period. Future climate change data for RCP 4.5 and RCP 8.5 for the two periods 2041-70 and 2071-99 were downloaded. RCP 4.5 is a scenario of long term global emissions of greenhouse gases (GHGs), short lived species and land use, land cover which stabilizes Radiative Forcing at 4.5 W/m^2 (approximately 650 ppm CO_2 equivalent in the year 2100 without ever exceeding the value) and RCP 8.5 is characterised by increasing greenhouse gas emissions over time.

3.7.2 Comparison of Different Models

The comparison of output of five different climate models and the selection of an appropriate model was done. Observed data of Bharathapuzha river basin on precipitation and temperature during the reference period (1989 to 2005) and historical data from experiments RCA4, CCAM (CCSM4), CCAM(CNRM), CCAM(GFDL-CM3) and CCAM(MPI) were compared. These data sets were derived from the GCM's EC-EARTH, CCSM4, CNRM-CM5, GFDL-CM3 and MPI-ESM-LR respectively. The details of the climate models used are given in Table 3.1.

3.7.3 Selection of Model Data

The similarity of the data sets with the observed data was evaluated on the basis of four statistical parameters (Standard deviation, correlation coefficient, coefficient of variation and centred root mean square difference). Two emission scenario pathways selected for the study, RCP4.5 and RCP8.5 roughly corresponds to the Special Report on Emission Scenarios (SRES) B1 and A1F1 respectively by 2100. The model with highest correlation with the observed data was then selected for further analysis.

3.7.4 Bias Correction

Precipitation and temperature are the key drivers for the hydrological regimes and hence both were bias corrected.

Table 3.1 Details of climate models used

Model	Modelling centre (or group)
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory
CCSM4	National Centre for Atmospheric Research, USA
EC-EARTH	EC-EARTH Consortium
MPI-ESM-LR	The Max Planck Institute for Meteorology, Germany
CNRM-CM5	National Centre for Meteorological Research

In the simplest formulations of bias correction, only the changes in a specific statistical aspect (mean value or the variance) of the computed field are used. Leander and Buishand (2007) found that a relatively simple non-linear correction, adjusting both the biases in the mean and its variability, leads to better reproduction of observed extreme daily and multi-daily precipitation amounts than the commonly used linear scaling correction. This power law transformation method which corrects for the coefficient of variation (CV) and the mean of the precipitation values was used in this study to correct for bias in precipitation data. The most important statistics (coefficient of variation, mean and standard deviation of the model data) were matched with corresponding quantities computed from the observed values. The daily precipitation P is transformed to a corrected value P^* using

$$P^* = aP^b \qquad (1)$$

where a and b are constants.

Correction for temperature involves shifting and scaling to adjust the mean and the variance. The corrected daily temperature T* is given by:

$$T^* = \bar{T}_{obs} + \frac{\sigma(T_{obs})}{\sigma(T_{mod})}(T_{mod} - \bar{T}_{obs}) + (\bar{T}_{obs} - \bar{T}_{mod}) \qquad (2)$$

Where T_{mod} is the uncorrected daily temperature from GFDL-CM3 model and T_{obs} is the observed daily temperature. The average over the considered period is denoted by an overbar in the equation and σ the standard deviation. The bias corrected data for both scenarios and the two future scenario periods were compared with the observed data.

3.8 MODEL DEVELOPMENT

The study determines the present water availability in time and space under various components of the hydrologic cycle. The same framework is then used to predict the impact of climate change on the availability of water resources for future by using the predicted data of the selected model with the assumption that the other management practices remain the same. The model set up is done mainly in four steps: Watershed delineation, HRU analysis, writing input tables and editing of SWAT input.

3.8.1 Delineation of the River Basin

The basic spatial datasets needed for SWAT are Digital Elevation Model (DEM), land use map and the soil map. The DEM can either be prepared from contour map, or can be downloaded from different websites where they are available. SRTM 1 Arc-Second (30 m) high-resolution global data set was used in the study for the delineation of the watershed. While using DEM alone, the areas with less slope change will not be delineated with accuracy. Hence, the drainage shape file of the area prepared in ArcGIS was also used in the burn in option available in the model, so that additional accuracy in the delineation can be achieved. Automatic delineation of the river basin was done by using DEM as input and the final outflow point of the river basin as the final pour/drainage point. The river basin is further divided into subbasins depending on the selection of the threshold value. The SWAT interface for watershed delineation is shown in Fig.3.7.

The Watershed Delineator menu in ArcSWAT comprises of two commands that are required to perform subbasin delineation and evaluate the results. The Automatic Delineation command accesses the dialog box used to import topographic maps and delineate the watershed. The Watershed Reports command provides access to the topographic report generated by the interface.

Area elevation data (hypsometric information) of the watershed can be prepared using this data.

Subwatershed outlets are added at points in the drainage network of a subwatershed where streamflow exits the subwatershed area. Adding outlets at the location of monitoring stations is useful for comparison of measured and predicted flows and sediment concentrations. Subbasin outlets are manually added where river gauging data is available. This was done for comparison of measured and predicted flows and sediment concentrations. Subbasin outlets were added at Mankara, Cheruthuruthy, Pulamanthole and Kumbidi, where river gauging stations are available.

When a portion of the watershed area cannot be directly modelled with SWAT, the inlet of draining watershed option can be used so that the inflow to the modelled area can be given as input. This point is also selected so that it coincides with a gauging station. Ambrampalayam gauging station of Central Water Commission was selected as input point for inputting the river flow from the area draining to that point.

To study the variation of elevation with percentage area above the particular elevation, hypsometric curves are plotted. A hypsometric curve is an empirical cumulative distribution function of elevations in a catchment or it is a curve showing the relationship of area to elevation for a specified terrain. A hypsometric curve is plotted on a graph on which the x-axis represents elevation (m) and the y axis represents percentage area above elevation.

3.8.2 HRU Analysis

The steps involved in HRU analysis is the loading of the soil layer, land use layer and the slope map to the SWAT model and the classification of the area to HRU's. The HRU Analysis menu contains three commands that perform the land use, soils, and slope analysis used to generate SWAT HRUs. Land uses that cover a percentage (or area) of the subbasin area less than the threshold level are eliminated and the area of the remaining land uses are reapportioned so that 100 percent of the land area in the subbasin is modelled. As with the land use areas, minor slope classes and soil areas less than threshold are eliminated, and the area of remaining classes is reapportioned so that 100 percent of the soil area is modelled. A land use look up table is used to specify the SWAT land cover/plant code or SWAT urban land type code to be modelled for each category in the land use map grid. The land use and soil look up table is used to specify the SWAT land cover or plant code and the type of soil to be modelled for each category in the soil map grid respectively. Both the table must be formatted in dBase format.

The Land Use/Soils/Slope Definition command accesses the dialog box used to import land use and soil maps, link the maps to SWAT databases and perform an overlay. Land use classes are reclassified into SWAT defined classes. The HRU Analysis Reports is also available to study the details of the different HRUs in the subbasins. SWAT interface for HRU analysis is shown in Fig. 3.8.

3.8.3 Attribute Data Preparation

In case of data preparation for precipitation, two type of tables are needed; precipitation gauge location table and the precipitation data table. The precipitation gauge location table is used to specify the location of rain gauges. The precipitation gauge location table should have .txt (.text) extension. The precipitation data table is used to store the daily precipitation for an individual raingauge. This table is needed if the raingauge option is chosen for rainfall in the weather data dialog box. There will be one precipitation data table for every location listed in the raingauge location table. Daily precipitation data table must be formatted only as an ASCII text file. The individual precipitation gauge data files must be located within the same folder as the precipitation gauge location table.

The temperature gauge location table should also have txt extension. Daily maximum and minimum temperature data table must be formatted only as an ASCII text file. Other weather parameters like solar radiation, wind velocity and relative humidity are also prepared in the same format. The daily records must be listed in sequential order. In the case of climate change data also, it must be in the same text file format to run in the SWAT.

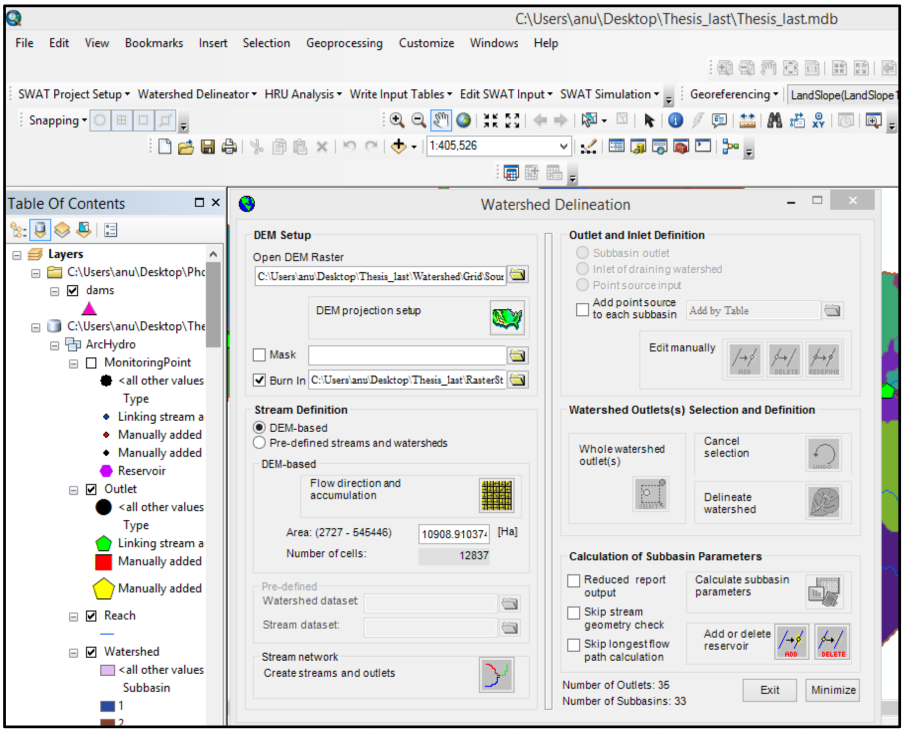

Fig.3.7 SWAT interface for watershed delineation

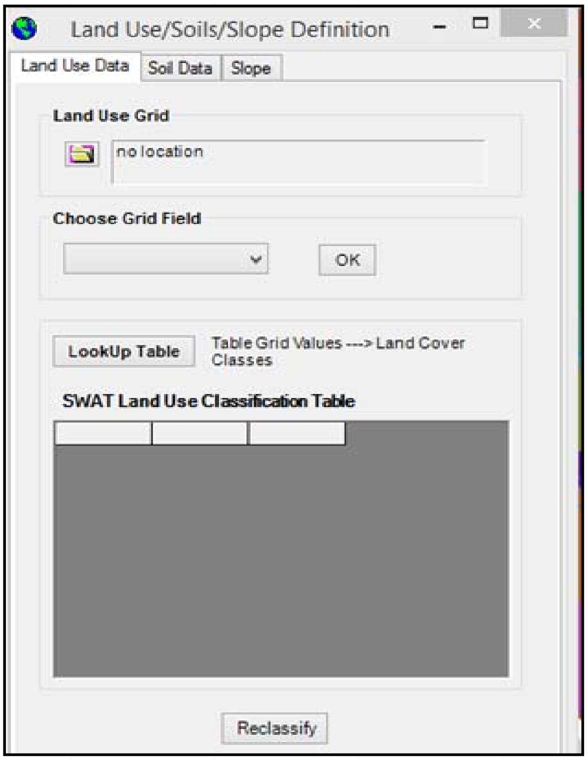

Fig.3.8 SWAT interface for HRU analysis

3.8.4 Writing Input Tables

The Input menu contains the commands which generate the ArcSWAT geo-database files used by the interface to store input values for the SWAT model. The Weather Stations command loads weather station locations and data for use. The Write SWAT Input Tables command opens up an interface to manage the creation of ArcSWAT geodatabase tables that store values for SWAT input parameters. Initial SWAT ASCII input files are also generated.

3.8.5 Editing SWAT Input

The Edit SWAT Input menu allows the user to edit the SWAT model databases and the watershed database files containing the current inputs for the SWAT model. Seven items are listed on the Edit Input menu which can be used for editing of different databases.

3.8.5.1 Databases

The Databases command allows the user to access the SWAT model databases from within a project. SWAT databases may be edited at any time during the development of a SWAT project. The SWAT databases must be edited to their desired content prior to writing the SWAT input tables in order to be reflected in the model input files.

3.8.5.2 Point Source Discharges

The Point Source Discharges command allows the user to access/define the point source loadings for all subbasins with point source discharges. Edits made to point source discharges using the ArcSWAT interface are reflected only in the current SWAT project.

3.8.5.3 Inlet Discharges

The Inlet Discharges command allows the user to access/define loadings for upstream sections of the watershed not directly modelled in the current project. In case of inlet discharges also the edits done using the ArcSWAT interface are reflected only in the current SWAT project.

Bharathapuzha river basin is intricate in the sense that there is transfer of water between the basin and nearby basins and it is dammed widely. The Parambikulam Aliyar Project (PAP) agreement was signed between Kerala and Tamil Nadu for interlinking of rivers and to divert a part of the waters of Aliyar and Palar rivers which are tributaries of Bharathapuzha to Tamil Nadu. It is practically difficult to simulate this part of the river basin coming under the PAP agreement. Ambrampalayam gauging station is the only station that comes in Tamil Nadu State and is located in the lower reach of the river Aliyar. Hence the input to the river from that area through the Ambrampalayam gauging station of CWC was taken into consideration and based on that, simulation of the rest of the basin was done. The flow passing this station was used as inlet discharge to the model.

3.8.5.4 Reservoirs

The Reservoirs command allows the user to access/edit input parameters for any reservoirs located within the watershed. The reservoir input file (*.res) contains input data to simulate water and sediment processes. The outflow of the reservoir can be given either as average annual release rate, measured daily outflow, measured monthly outflow or simulated controlled outflow. The reservoir file is a free format file and the data was entered in the specified format.

3.8.5.5 Subbasins Data

The Subbasins data command allows the user to access/edit input parameters for land areas, channels, ponds/wetlands and groundwater systems within the watershed. Edits made to subbasin data using the ArcSWAT interface are reflected only in the current SWAT project.

3.8.5.6 Watershed Data

The Watershed data command allows the user to access/edit input parameters that are applied to the watershed as a whole. Edits made to watershed using the ArcSWAT interface are reflected only in the current SWAT project.

3.8.5.7 Re-Write SWAT Input Files

The Re-Write SWAT input files command allows users to re-write the ASCII SWAT input files (.sub, .mgt, .hru, etc.) after the SWAT geo database files have been edited.

3.8.6 SWAT Model Simulation and Output

The simulation menu allows finalizing the set up of input for the SWAT model and run the SWAT model; it reads the results of the simulation and builds dBASE tables. The starting and ending dates of the simulation are selected and SWAT simulation is done. The files that are to be imported to the database are selected and imported as output files and the simulation is saved with a proper name. Using the Run SWAT check option one can check whether any aspects of the results raise concern.

3.8.7 Sensitivity and Uncertainty Analysis

Sensitivity analysis facilitates in understanding the behaviour of the system being modelled and to evaluate the applicability of the model (van Griensven *et al*., 2006). The hydrologic simulation by SWAT is based on around 25 parameters that have to be calibrated and adjusted before actual simulations. While doing so, the calibration process becomes complex and computationally extensive. Sensitivity analysis is done to find out the most sensitive parameters and this parameter selection was done based on characteristics of the study area as well as on literature review.

The SWAT-CUP package has provision for doing the sensitivity analysis. For applying parameter identifiers, the changes made to the parameters should have physical meanings and should reflect physical factors such as soil, landuse, elevation, etc. Therefore, the following scheme is suggested:

x__<parname>.<ext>_<hydrogrp>_<soltext>_<landuse>_<subbsn>_<slope>

Where x__ Code to indicate the **type of change** to be applied to the parameter:

v__ means the existing parameter value is to be **replaced** by the given value,

a__ means the given value is **added** to the existing parameter value, r__ means the existing parameter value is **multiplied** by (1+ a given value).----

<parname> = SWAT parameter name.

<ext> = SWAT file extension code for the file containing the parameter.

<hydrogrp> = (optional) soil hydrological group ('A','B','C' or 'D')

<soltext> = (optional) soil texture

<landuse> = (optional) name of the landuse category

<subbsn> = (optional) subbasin number(s)

<slope> = (optional) slope

Any combination of the above factors can be used to describe a parameter identifier; hence, providing the opportunity for a detailed parameterization of the system. Omitting the identifiers <hydrogrp>, <soltext>, <landuse>, and <subbsn> allows global assignment of parameters.

The parameters were adjusted so that the simulated and observed values have a close relationship with each other. On the basis of sensitivity analysis, calibration and validation can be later done with the limited dominant parameters.

Uncertainty analysis is needed to perform the best estimation and uncertainty identification of hydrological models. The uncertainty test and analysis was done using SUFI-2 uncertainty analysis procedures. Uncertainty is defined as difference between observed and simulated variables in SUFI-2, where it is counted by variation between them. In SUFI-2, uncertainty of input parameters is depicted as a uniform distribution, while model output uncertainty is quantified at the 95 Percent Prediction of Uncertainty (PPU). The concept behind the uncertainty analysis of the SUFI-2 algorithm is depicted graphically in Fig. 3.9. The cumulative distribution of an output variable is obtained through Latin hypercube sampling. SUFI-2 starts by assuming a large parameter uncertainty within a physically meaningful range, so that the measured data initially fall within 95 PPU, then narrows this uncertainty in steps while monitoring p_factor and r_factor. Parameters are updated in such a way that the new ranges are always smaller than the previous ranges, and are centered around the best simulation (Abbaspour *et al*., 2007). The p_factor is the percentage of data bracketed by 95 PPU and r_factor is the ratio of average thickness of 95 PPU band to the standard deviation of the corresponding measured variable. A p-factor of 1 and r-factor of zero is a simulation that exactly corresponds to measured data.

Two types of sensitivity analysis can be performed in SWAT-CUP; Global sensitivity analysis and the one at a time sensitivity analysis.

3.8.7.1 Global Sensitivity Analysis

Global sensitivity analysis is the process of apportioning the uncertainty in outputs to the uncertainty in each input factor over their entire range of interest. A sensitivity analysis is considered to be global, when all the input factors are varied simultaneously and the sensitivity is evaluated over the entire range of each input factor. Global sensitivity analysis quantifies the importance of model inputs and their interactions with respect to model output. One of the most challenging issues for global sensitivity analysis is the intensive computation needed.

3.8.7.2 One-at–a-time Sensitivity Analysis

One-at-a-time sensitivity should be performed for one parameter at a time only. The main advantage of this method is that it is simple to implement and perform, computationally efficient and the sensitivity is clearly attributed to one model parameter. But the major disadvantage is that the sensitivity is only assessed locally.

To perform one-at-a-time sensitivity analysis, the sensitivity of one parameter is checked at a time and the values of the parameters that are to be kept constant are set to some reasonable values. The best simulation (simulation with the best objective function value) of the last iteration can be used for this.

Based on an initial one-at-a-time sensitivity analysis (sequentially varying one parameter while keeping all others constant) and then using global sensitivity analysis (varying all parameters simultaneously), the parameters to be included in the calibration of the model was decided. The global sensitivity analysis was done for the whole river basin for the simulation of streamflow with thirteen hydrologic parameters pertinent to river flow (Winchell et al., 2007).

3.8.8 Calibration of the Model

The model was calibrated using observed streamflow records for a 12-year period from January 1989 to December 2000. The model parameters were adjusted manually by trial and error based on certain statistical indicators and the characteristics of the study area. The statistical criteria used to evaluate the hydrological goodness of fit were the coefficient of determination (R^2) and the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970). Calibration was done for the monthly time series. Comparison of different components of hydrology was also done since it gives a better confidence of the model output than mere comparison of the total river flow. The interaction of SWAT and SWAT-CUP is shown in Fig. 3.10. The steps involved are:

1. The calibration program writes model parameters in model.in,

2. Swat_edit.exe edits the SWAT's input files with new parameter values,

3. The SWAT simulator is run, and

4. Swat_extract.exe program extracts the desired variables from SWAT's output files and write them to model out. The procedure continues as required by the calibration program.

3.8.9 Multi-site Calibration

Calibration was carried out using the average monthly observed flow at 4 river gauging stations Kumbidi, Pulamanthole, Mankara and Thiruvegappura.

The calibration was performed by changing the sensitive parameters sequentially for obtaining values of river flow which are closely matching with the observed values. This was monitored first in the subbasins coming in the upper reaches and then with the river basin as a whole at the Kumbidi gauging station.

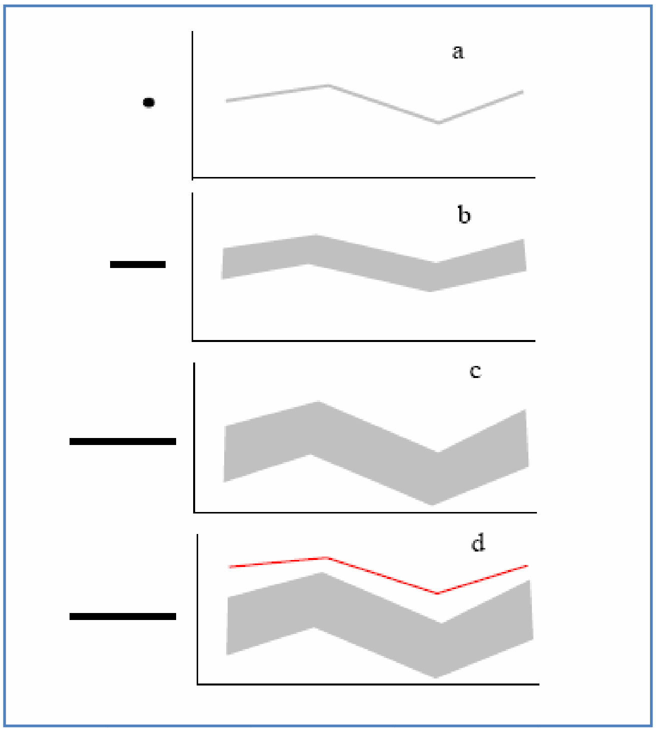

Fig. 3.9 Conceptual illustration of the relationship between parameter uncertainty and prediction uncertainty

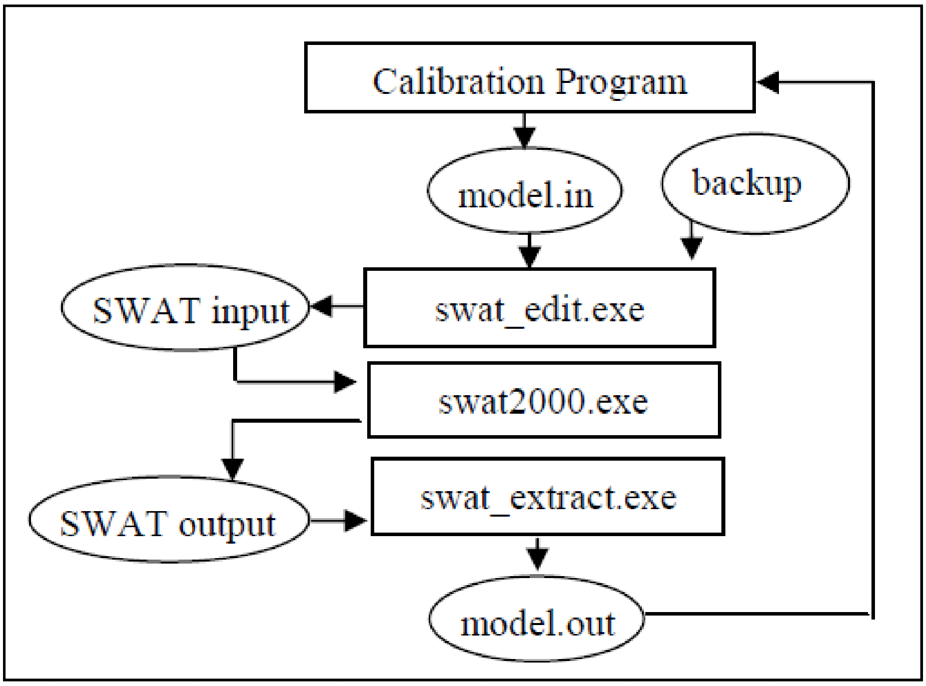

Fig. 3.10 Interaction of SWAT and SWAT-CUP

SUFI-2 program which utilizes a combined optimization-uncertainty analysis was used. SUFI-2 is a multi-site, semi-automated global search procedure. The objective function was formulated as the Nash-Sutcliff (*NS*) coefficient between the measured and simulated discharges.

3.8.10 Validation of the Model

Validation is the process of comparison of model results with an independent data set without further adjustments of model parameters. After calibrating the model, validation of the model was performed using data for another 9-year period from 2001 to 2009.

3.9 MODEL PERFORMANCE

Common efficiency criteria's used to evaluate hydrologic models are Nash-Sutcliffe efficiency, co-efficient of determination, percent bias (PBIAS) etc. The general performance ratings for the recommended statistics (Moraisi, 2007) are given in Table 3.2.

Table 3.2 General performance ratings for monthly statistics

Performance rating	**RSR**	**NSE**	**PBIAS (%)**	
			Streamflow	**Sediment**
Very good	0.0<RSR<0.5	0.75<NSE<1.0	PBIAS <±10	PBIAS <±15
Good	0.5<RSR <0.6	0.65<NSE <0.75	±10<PBIAS<±15	±15<PBIAS <±30
Satisfactory	0.6<RSR <0.7	0.50<NSE <0.65	±15<PBIAS<±25	±30 <PBIAS <±55
Unsatisfactory	RSR > 0.7	NSE <0.50	PBIAS >±25	PBIAS >±55

3.10 ANALYSIS OF IMPACT OF CLIMATE CHANGE

The flow chart explaining the steps involved in the methodology of the research programme is shown in Fig. 3.11. The bias corrected future climate change data of rainfall and temperature was used as input in the calibrated model to predict the hydrology of the river basin in future.

3.11 IMPACT OF WATERSHED DEVELOPMENT

To study the impact of watershed interventions on water resources, the change in the water storage in the basin during the period 2005-2011 was taken into consideration. This period was chosen for the change analysis because major watershed development activities including construction of check dams, percolation ponds and pits, Vented Cross Bars (VCB's) etc. have come up in the area during this period. Glimpses of the structures during field visit are shown in Plates 3 and 4. The change in the area under water bodies, especially, reservoirs, lakes and ponds during the period was studied from the Landuse/ land cover classes prepared and published in the NRSC website. These thematic maps were prepared as a part of the project on "National Land Use/ Land Cover Mapping on 1:50,000 scale using temporal Resourcesat-1 Linear Imaging Selfscanning Sensor (LISS) -III data" was carried out by NRSC, ISRO of Department of Space under Natural Resources Census (NRC) Project of National Natural Resources Repository (NRR) Programme. Based on the per cent change in the water bodies during the period under consideration, further analysis was done. Details of watershed interventions were collected from different government departments.

The watershed interventions that have come up in the area in terms of the hydrologic structures is represented in the SWAT model by aggregating them as a reservoir. SWAT accommodates a single reservoir at the outlet of each subbasin. The hydrologic structures or water storage structures in each subbasin were thus aggregated into a single structure and the storage area was calculated by aggregating the individual structures. The storage volume was also estimated on the basis of the data collected from the field survey.

The impact of watershed interventions on streamflow was analysed by running the calibrated model with and without the storage structures and comparing the streamflow in both cases. The increase in storage volume due to the structures was assumed constant throughout the simulation period.

Plate 3 Check dam at Varathurkayal thodu

Plate 4 Regulator cum bridge at Velliamkallu

Results and Discussion

CHAPTER IV

RESULTS AND DISCUSSION

The present study was conducted to analyse the impact of climate change and watershed development activities on the hydrology of Bharathapuzha river basin. The temporal changes of climate variables, trends in the historical climate change as well as future predicted changes were analysed. Hydrologic model SWAT was used to analyse the impact of climate change and watershed interventions. The results from the study are illustrated and discussed in this chapter.

4.1 STUDY AREA

The Bharathapuzha river basin (BRB) lies between the geographical limits of 10°25’-11°25’N and 75° 50’- 76°55’E. The BRB is the largest river basin among the west flowing 41 river basins in the Kerala state of India. The river basin area is shown in Fig. 4.1.

4.2 HISTORICAL CLIMATE OF THE REGION

The river basin experiences a pleasant climate during the past years, and at the same time, anomalies in the rainfall distribution (Raj and Azeez, 2009) and in surface temperature of the region have been reported. Before doing the hydrologic modelling of the basin, it is essential to understand the trend in the historical climate change of the region. Hence, the following preliminary studies were done.

4.2.1 Study of Observed Climate Data

Observed climate data (average minimum and maximum temperature and relative humidity) of the area were divided into two time periods, 1975-1990 and 1991-2013 and was analysed to know whether any changes have happened between the two periods. The monthly averages of the climatic parameters for the two periods are shown in Fig. 4.2 to 4.4 and the monthly averages for the entire period is given in Appendix I to III.

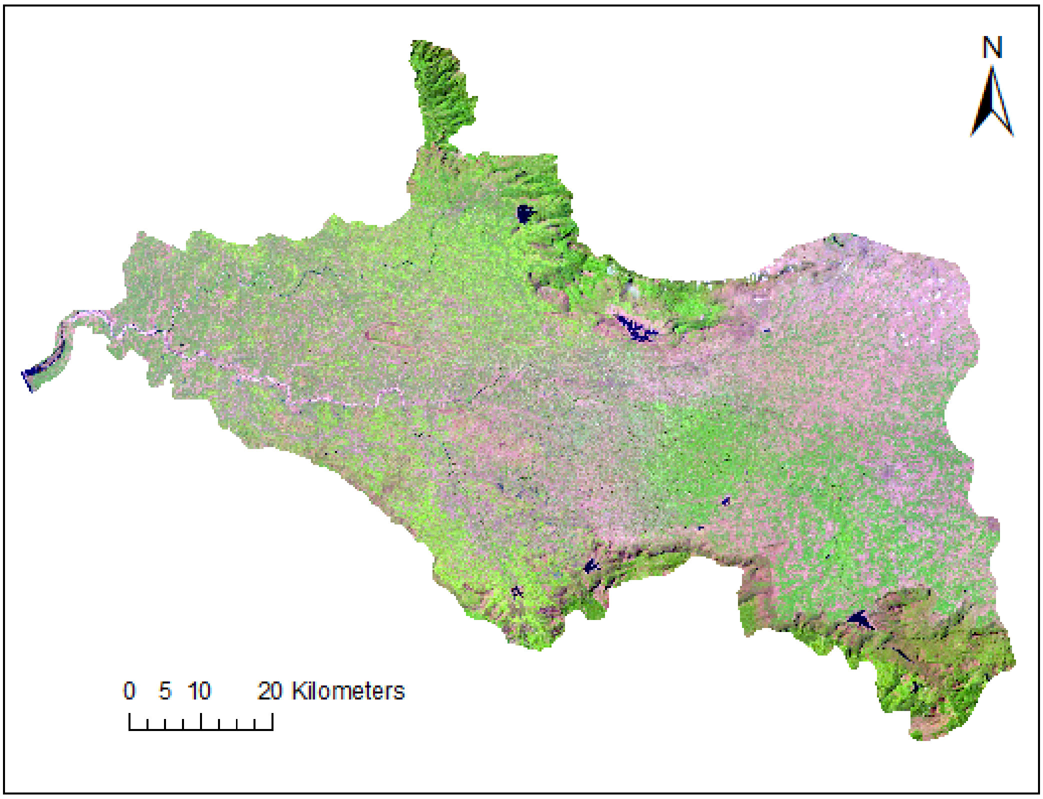

Fig. 4.1 Bharathpuzha river basin

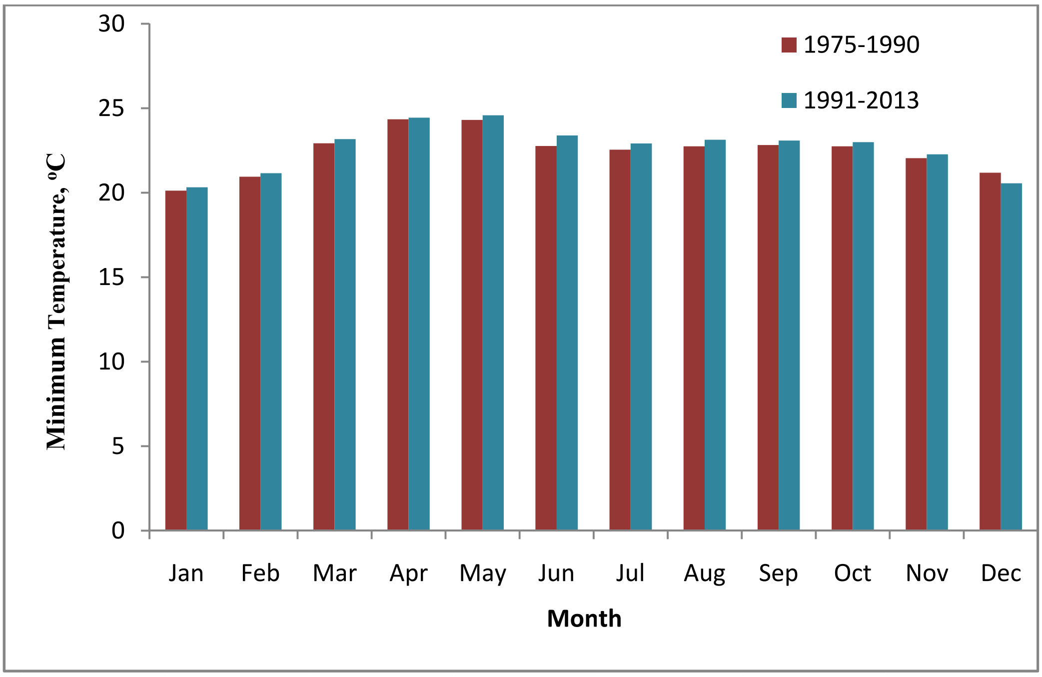

Fig. 4.2 Average minimum temperature of the study area

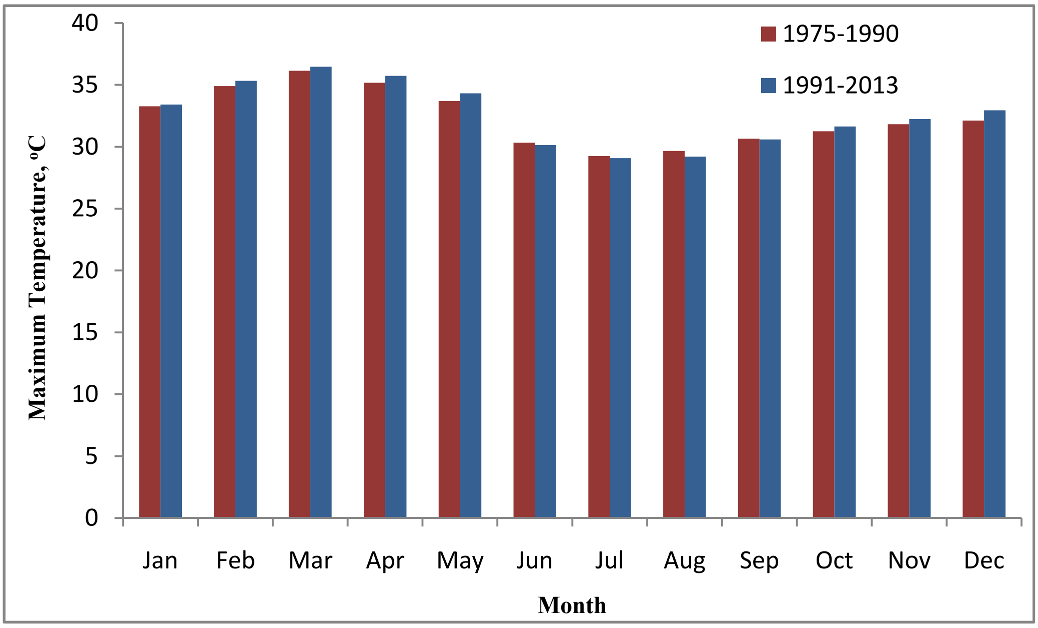

Fig. 4.3 Average maximum temperature of the study area

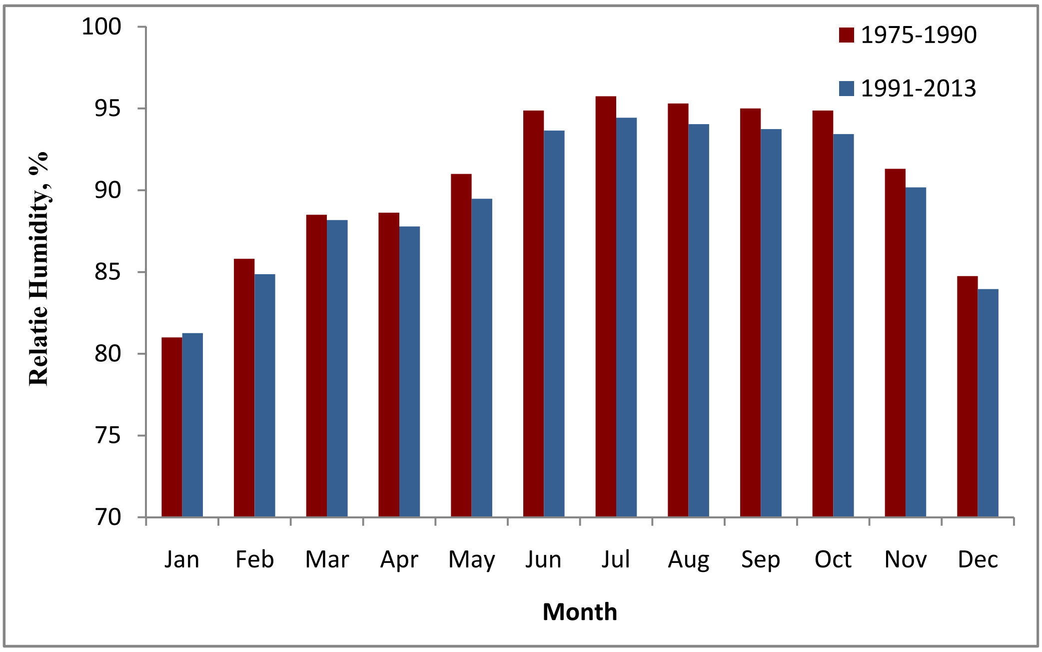

Fig. 4.4 Average relative humidity of the study area

The monthly averages of minimum temperature of the area ranged from 20.1 to 24.6°C during 1975 to 2013. The average temperatures during the period 1991-2013 were higher than the previous period in all months except for December. This shows that the temperature in the basin has increased during the two decades 1990 to 2010. A similar increasing trend was seen in case of maximum temperature also. The monthly averages of maximum temperature ranged from 29.1 to 36.5°C during 1975 to 2013. The temperatures during the period 1991-2013 were slightly higher than the previous period in the months except January, and June to September.

The monthly average relative humidity ranged from 81 per cent in January to 95.8 per cent in July during 1975-1990 and from 81.2 per cent to 94.4 per cent during 1991-2013 (Fig. 4.4). The values were found to decrease during 1991-2013, compared to the previous period of 1975-90 for all months with the exception of January. Monthly average of daily evaporation in the region during the period 1975-2013 is maximum during March (6.03 mm) and minimum (2.78 mm) during July (Fig. 4.5). The monthly average of wind speed was minimum during October, and maximum during January with values 2.4 to 5.56 km/h respectively. The monthly average values of daily evaporation and daily wind speed for the period 1975-2013 are given in Appendix IV and V respectively.

4.2.2 Temporal Trends in Temperature Based on Gridded Data

To understand the long term trends in climate of the region, gridded data (1°x 1°) of temperature for a longer period (1951-2011) was collected from IMD. The monthly estimated gridded temperature data obtained from IMD was first compared with the observed data, and the coefficient of determination (R^2) values was satisfactory. The R^2 values showed moderate to very strong correlation between the two data sets and it varies from 0.53 to 0.82 for maximum temperature and 0.27 to 0.90 for minimum temperature. The statistical characteristics (Mean, standard deviation (SD) and coefficient of deviation (CD)) of the maximum, minimum and mean annual temperature of the Bharathapuzha basin obtained from the gridded data of IMD for the period 1951-2013 are presented in Table 4.1.

The changes in temperature affect the hydrologic cycle and hence in the climate change studies of river basins, the trend in temperature is important. Month-wise variation of mean temperature using the gridded data is plotted in Fig. 4.6. Mean monthly maximum temperature is during the month of April (31.4^{o}C) and minimum temperature during the month of January (16.7^{o}C). Month-wise variation of minimum and maximum temperature is given in Fig. 4.7. The region experiences maximum temperature during March-April and minimum during December-January.

Table 4.1 Statistical summary of average temperature during 1951-2013

	Maximum temperature (^{o}C)			**Mean temperature (^{o}C)**			**Minimum temperature (^{o}C)**		
	Mean	**SD**	**CV(%)**	**Mean**	**SD**	**CV(%)**	**Mean**	**SD**	**CV(%)**
January	28.0	0.54	1.92	22.4	0.60	2.68	16.7	0.66	3.92
February	29.4	0.59	2.00	23.6	0.51	2.18	17.8	0.68	3.80
March	31.1	0.85	2.74	25.3	0.61	2.41	19.5	0.50	2.55
April	31.4	0.92	2.92	26.2	0.86	3.29	21.0	0.47	2.25
May	30.4	0.91	3.00	25.8	1.21	4.68	21.0	0.51	2.44
June	27.7	0.75	2.71	24.0	1.06	4.40	20.1	0.41	2.02
July	26.6	0.72	2.69	23.2	0.68	2.95	19.6	0.28	1.40
August	26.7	0.51	1.92	23.3	0.53	2.29	19.7	0.29	1.47
September	27.6	0.60	2.17	23.7	0.47	1.99	19.7	0.27	1.38
October	27.6	0.58	2.10	23.6	0.46	1.96	19.5	0.35	1.79
November	27.2	0.50	1.85	23.0	0.34	1.46	18.8	0.55	2.93
December	27.3	0.57	2.07	22.4	0.47	2.10	17.6	0.69	3.93

The temporal variation of mean temperature during 1951-2013 using IMD gridded data is shown in Fig. 4.8. There is an increasing linear trend which implies that there is a positive linear relationship between annual averages of mean temperature and time. This warming up is at the rate of 0.069^{o}C/decade. Similar increasing trend in mean annual temperatures have been reported from various parts of India (Rao, P.G. 1993; Arora *et al*., 2005; Bhutiyani *et al.*, 2007; Thomas *et al.*, 2015).

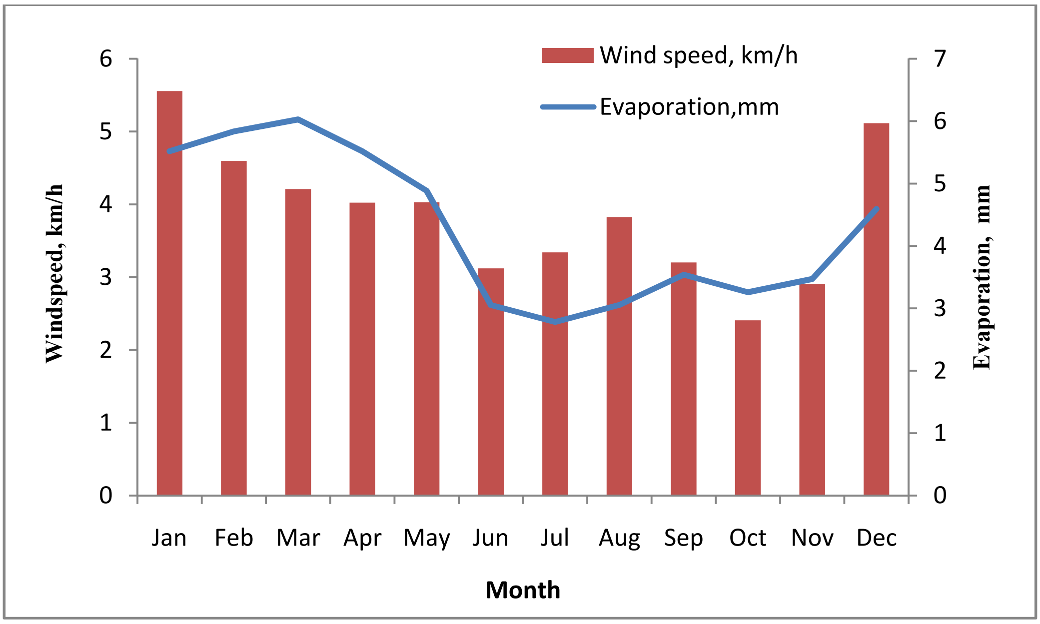

Fig. 4.5 Average daily evaporation and wind speed during 1975-2013

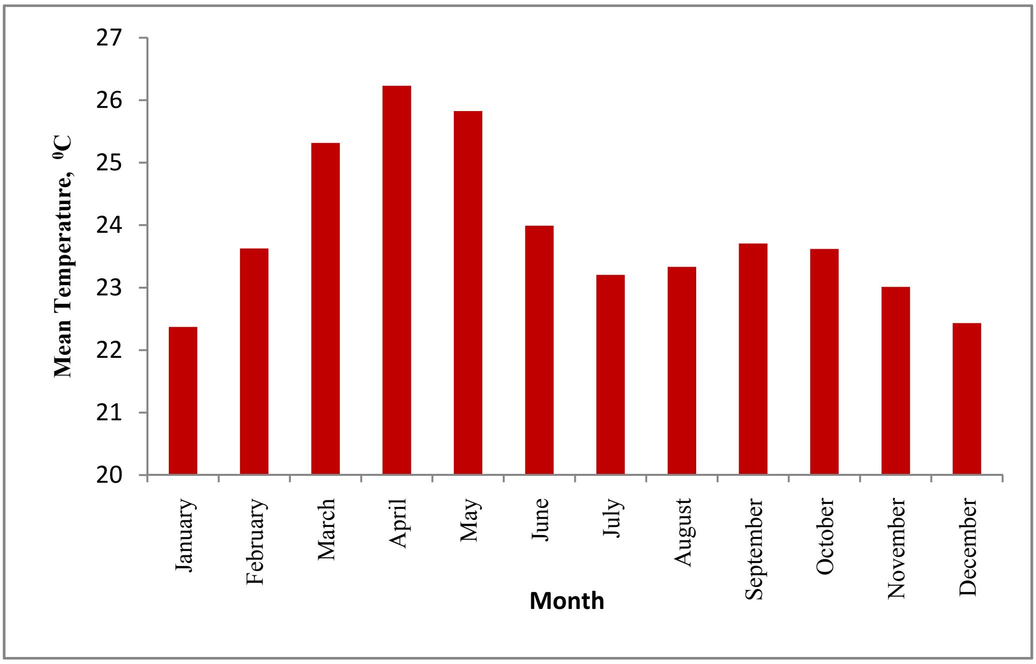

Fig. 4.6 Month-wise variation of mean temperature during 1951-2013

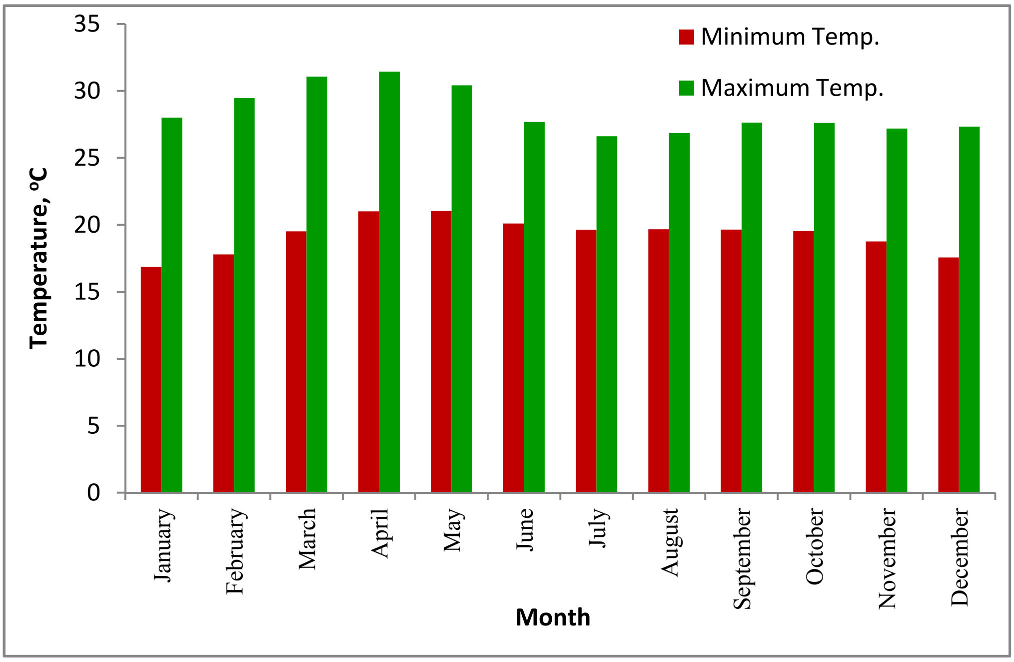

Fig. 4.7 Month-wise variation of minimum and maximum temperature during 1951-2013

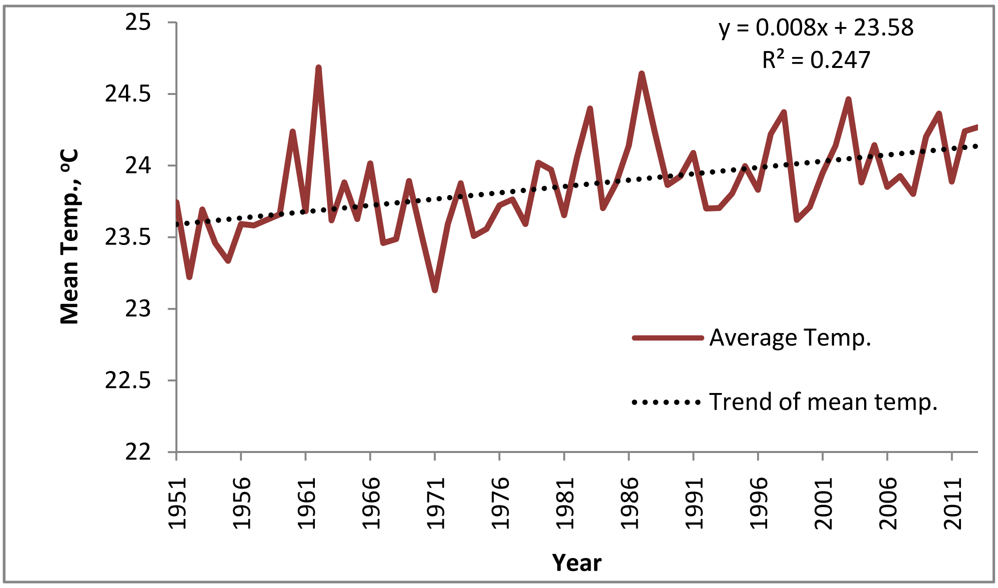

Fig. 4.8 Temporal variation of mean temperature

Rao *et al*. (2009) reported that there was an increase of 0.44°C in mean annual surface air temperature over a period of 49 years (1956 to 2004) in Kerala and similar warming was noticed in the entire west coast of India.

The temporal variation of mean maximum temperature with time was also studied by plotting trend lines and using the Mann-Kendall and t-test. Variation of maximum and minimum temperature with time during the period 1951-2013 is plotted in Fig. 4.9 and 4.10 respectively.

The trend is shown by the linear regression line whose equation and R^2 values are also given in the figure. There is an increasing trend in maximum temperature with an increase of 0.14°C/decade and there is an increase of 0.68°C during the period 1951-2013. Studies conducted by Kothawale *et al*. (2010) also revealed that the annual mean, maximum and minimum temperatures showed significant warming trends of 0.51, 0.72 and 0.27°C respectively over 100 years during 1901–2007.

The results of the Mann-Kendall test and the t-test (Tables 4.2 and 4.3) also confirmed the results obtained from the linear regression analysis. At an annual scale, the Mann-Kendall test of maximum temperature resulted in an increasing trend at 1 per cent level of significance. The data set is divided into two (1951-1981 & 1982-2013) and t-test was conducted to test the significance of these two data sets. The mean of maximum temperature for the periods 1951-1981 and 1982-2013 were estimated as 28.17°C and 28.71°C and the t-test results showed that the two data sets are significantly different 1 per cent level of significance. Similar analysis was conducted for mean temperature and minimum temperature and the means were found statistically different at the same level of significance.

Table 4.2 Mann-Kendall test results for temperature

Variable	S-value	Z-value	Result
Maximum temperature	931	5.52	Statistically significant trend (at a<0.01)
Mean Temperature	782	4.63	Statistically significant trend (at a<0.01)
Minimum temperature	121	3.63	Statistically significant trend (at a=0.01)

Such an increase in temperature over the basin has implications to basin hydrology since it can alter the hydrologic cycle mainly due to increased ET.

Table 4.3. Results of t-test on gridded data for temperature

	1951-1981	1982-2013	Results
Mean of Max. Temp.	28.17	28.72	Mean of 1951-81 and 1982-2013 is significantly different at a<0.01
Mean of Avg. Temp.	23.74	24.03	Mean of 1951-81 and 1982-2013 is significantly different at a<0.01
Mean of Mini. Temp.	19.15	19.37	Mean of 1951-81 and 1982-2013 is significantly different at a<0.01

4.2.3 Analysis of Temporal Trends in Rainfall Based on Gridded Data

The gridded data of IMD available at a resolution of 0.5°x0.5° was compared with the observed data for the period 1971-2005 and R^2 values ranged between 0.53 and 0.99 implying moderate to very strong correlation between the data sets (Table 4.4). Hence the gridded data was used for analyzing the temporal and seasonal changes in rainfall.

Table 4.4 Comparison of gridded data and observed data

Mean Rainfall (1971-2005)			
	Gridded	**Observed**	R^2
January	3.14	4.6	0.99
February	2.52	1.4	0.67
March	14.96	15.9	0.65
April	72.6	77.8	0.95
May	128.78	115.4	0.73
June	435.19	378.3	0.93
July	510.88	457.5	0.63
August	362.42	306.7	0.53
September	183.95	177.7	0.82
October	192.28	184.2	0.91
November	160.54	133.4	0.80
December	26.11	25.3	0.95

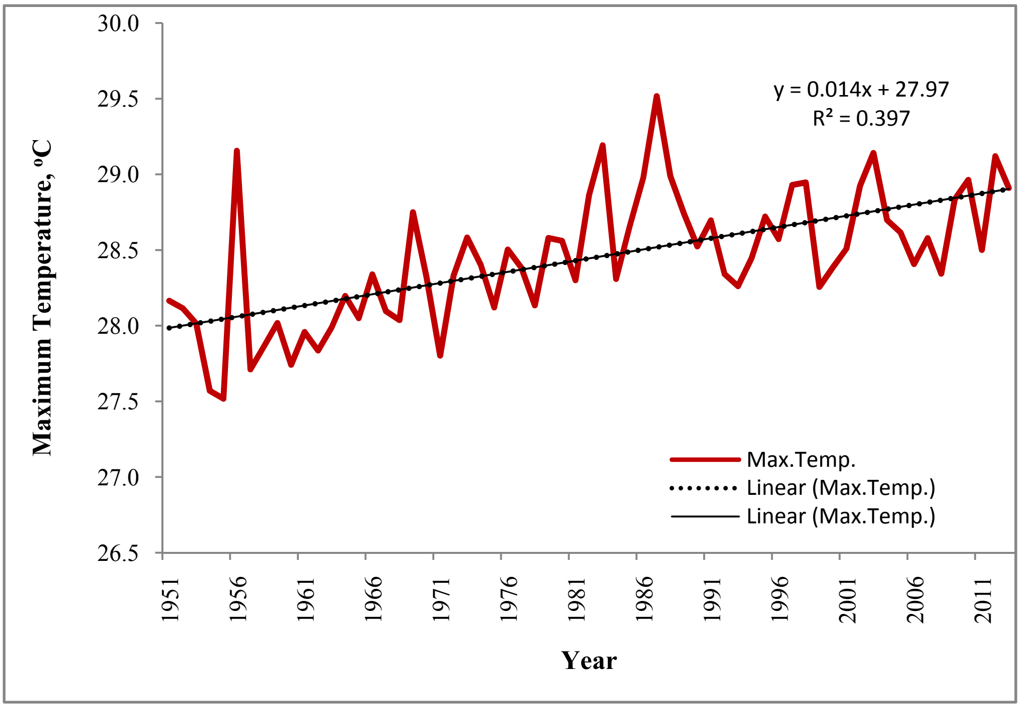

Fig. 4.9 Temporal variation of maximum temperature

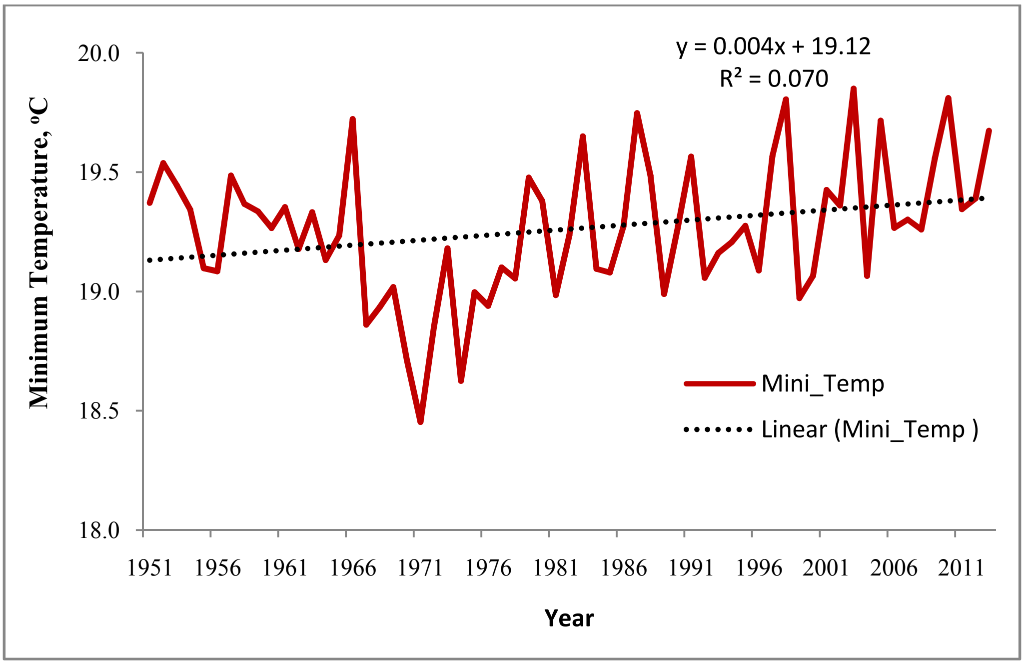

Fig. 4.10 Temporal variation of minimum temperature

About 60 per cent of rainfall occurs in the months of June, July and August. Maximum average monthly rainfall was received during July and minimum was recorded in January. The temporal variation of annual rainfall during 1971-2005 is shown in Fig.4.11. The trend line is fitted with a linear equation and has a decreasing trend in annual rainfall with a decrease of 15 mm/year is noted during this period. The results of the Mann-Kendall test and linear regression analysis (Table 4.5) also showed a statistically significant decline in rainfall at 99 per cent and 95 per cent confidence level.

Table 4.5 Mann-Kendall and linear regression test results for annual rainfall

	Test statistic	Critical values			Result
		(Statistical Table)			
		a=0.1	a=0.05	a=0.01	
Mann-Kendall	-1.70	1.65	1.96	2.58	Statistically significant decreasing trend at a=0.1
Linear regression	-2.11	1.69	2.04	2.74	Statistically significant decreasing trend at a=0.05

Raj and Azeez (2010) earlier examined the general trend of rainfall in the Palakkad plains of Kerala using rainfall data collected from four rain gauge stations in the area and reported a significant declining trend. Analysis of climatological data for 140 years (1871-2007) over Kerala (Krishnakumar *et al.*, 2009; Rao *et al.*, 2008) in the humid tropics of India indicated cyclic trend in annual rainfall, whereas during the past 60 years (1950-2010) there was a decreasing trend in annual and southwest monsoon rainfall (Rao *et al.*, 2009) except in certain locations where the rainfall trends were uncertain.

4.2.4 Seasonal Trend in Rainfall

Fig. 4.12 shows the average monthly variation of rainfall during the period 1971 to 2005 in Bharathapuzha basin on the basis of gridded data. Maximum rainfall occurred during the month of July (515.5 mm) and minimum during January (2.5 mm). Around 60 per cent of the average annual rainfall occurred during the months of June, July and August.

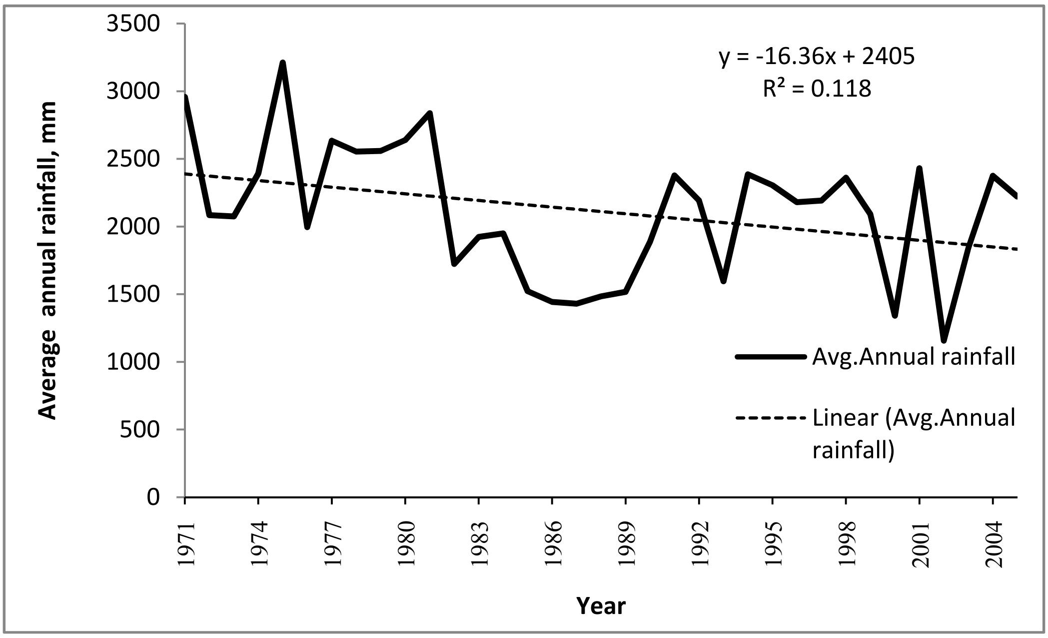

Fig. 4.11 Temporal variation of rainfall

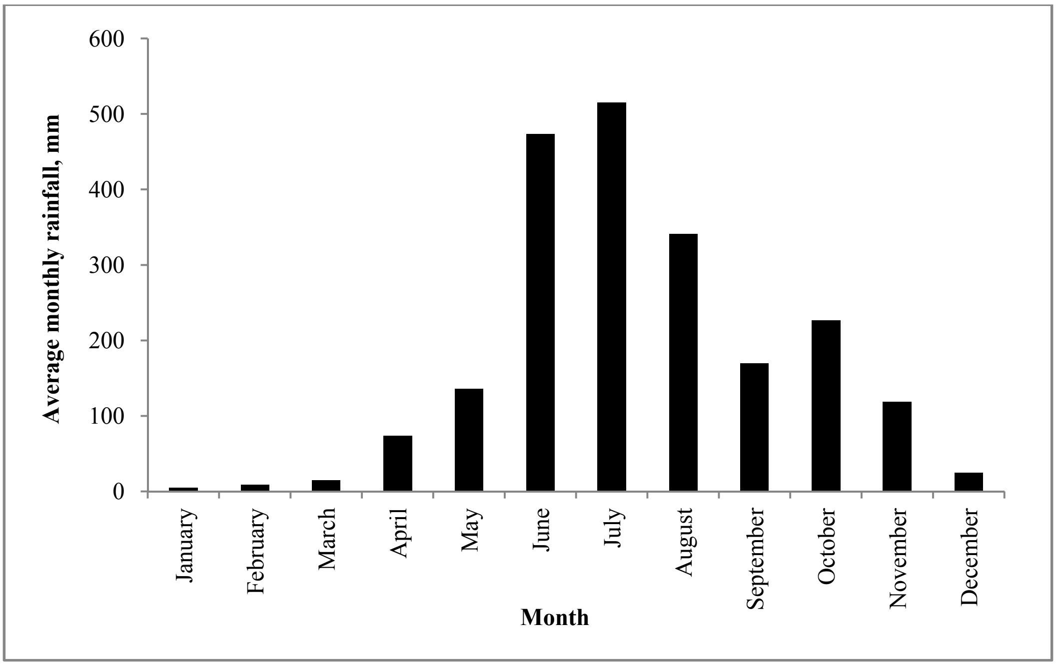

Fig. 4.12 Monthly variation of rainfall during 1971-2005

For assessing the trend of rainfall during four major rainy seasons (Ananthakrishnan *et al.*, 1979), annual rainfall was divided into south-west monsoon (June–September), north-east monsoon (October–November), pre-monsoon months or summer rains (March–May), and winter rains (December–February). Rainfall trend during the four seasons is shown in Fig. 4.13 and the seasonal averages of rainfall during the period are given in Appendix VI.

Mann-Kendall test performed to test the trend of seasonal rainfall (Table 4.6) indicated that there is a significant decreasing trend (at a=0.1) in case of south-west monsoon in the region during 1971-2005. In all the other seasons (North-East, summer and winter) there is no significant trend in rainfall. Krishnakumar *et al.* (2009) analysed the seasonal trend of rainfall in Kerala state during the period 1871 to 2005 and found that there was significant decreasing trend in the south-west monsoon and increase in post monsoon season whereas rainfall during summer and winter had insignificant decreasing trend. A better understanding of the trends or variations in temperature and rainfall of an area will thus be helpful for evaluating the uncertainties associated with the management of water resources.

Table 4.6 Mann-Kendall test results of seasonal variation of rainfall

	Mean (mm)	S.D.	C.V.	S-value	Z-value	Result
South-West	1445.3	610.3	181.3	-125.0	-1.82	Significant decreasing trend at a=0.1
North-East	392.1	218.9	122.0	-33.0	-1.15	NS
Winter	37.2	70.2	620.5	-32.0	-0.16	NS
Summer	235.7	166.0	261.6	-19.0	-0.47	NS

The regional scale variations in rainfall over India have been studied by many researchers with the analysis of annual and seasonal series of rainfall. Rathore *et al.* (2013) reported that spatially coherent increasing trends were observed in monthly rainfall for the months of February, May and June while in January, March, July and September there was decreasing trends in most states of India. Increase in extreme rainfall events have been reported from various parts of the country (Thomas *et al*., 2015, Rajeevan *et al*., 2008), whereas varying trends in different seasons for the same area was also reported (Krishnakumar *et al*., 2009; Manikandan and Tamilmani, 2012; Thomas *et al*., 2015).

4.2.5 Analysis of Drought Based on Standardised Precipitation Index (SPI)

Analysis of drought events has been carried out for two time periods, 1971-1987 and 1988-2005. The time scales considered for the analysis were: 1-month SPI (representing meteorological drought), 3-month SPI (for agricultural drought which indicates soil moisture conditions), 6-month SPI (indicates surface water availability) and 12-month SPI (indicating hydrological drought). SPI values computed for different time scales (1, 3, 6 and 12 months) using the station rainfall data were not significantly different from the SPI values obtained from the gridded data. Hence, further analysis of drought was done based on the gridded rainfall data only.

Comparison of the drought duration for the periods 1971-87 and 1988-2005 was done (Fig. 4.14) on the basis of SPI values. It is seen that more droughts are being experienced during the recent years, compared to the past. Hence drought occurrence increases with increasing trend in temperature (mean and maximum) and decrease in rainfall trend. In the case of 1-month and 3-month SPI, the frequency of drought events has remained almost same during both the periods. The frequency of drought events is more pronounced during the recent years when compared to the past with 6-month and 12-month SPI. In the case of 6-month SPI, drought events have occurred 4 times during 1971-87 while it occurred 7 times during 1988-2005. Similarly while considering the 12-month SPI, drought event has occurred twice during 1971-87, while it occurred 4 times during 1988-2005. The 6-month and 12-month SPI values of the two periods thus indicate that the chance of seasonal droughts is increasing.

4.3 PROJECTED FUTURE CLIMATE OF THE BASIN

IPCC reports a significant change in the worldwide air temperatures amid the 21st century (IPCC, 2013), and that it is going to have an immediate effect on the season and intensity of rainfall across the globe.

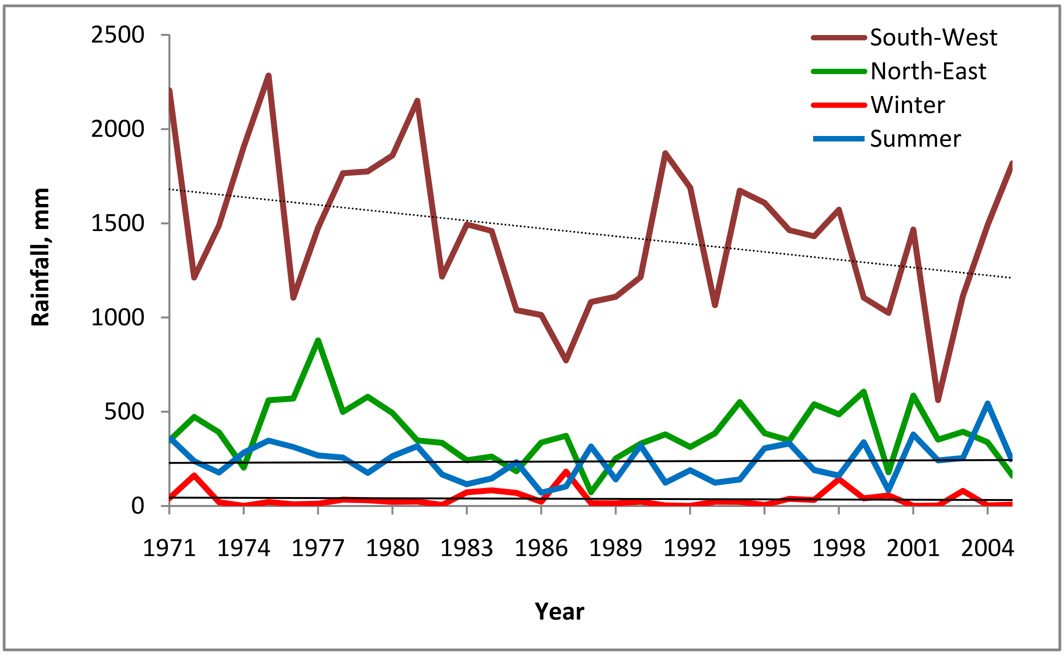

Fig. 4.13 Seasonal trend of rainfall

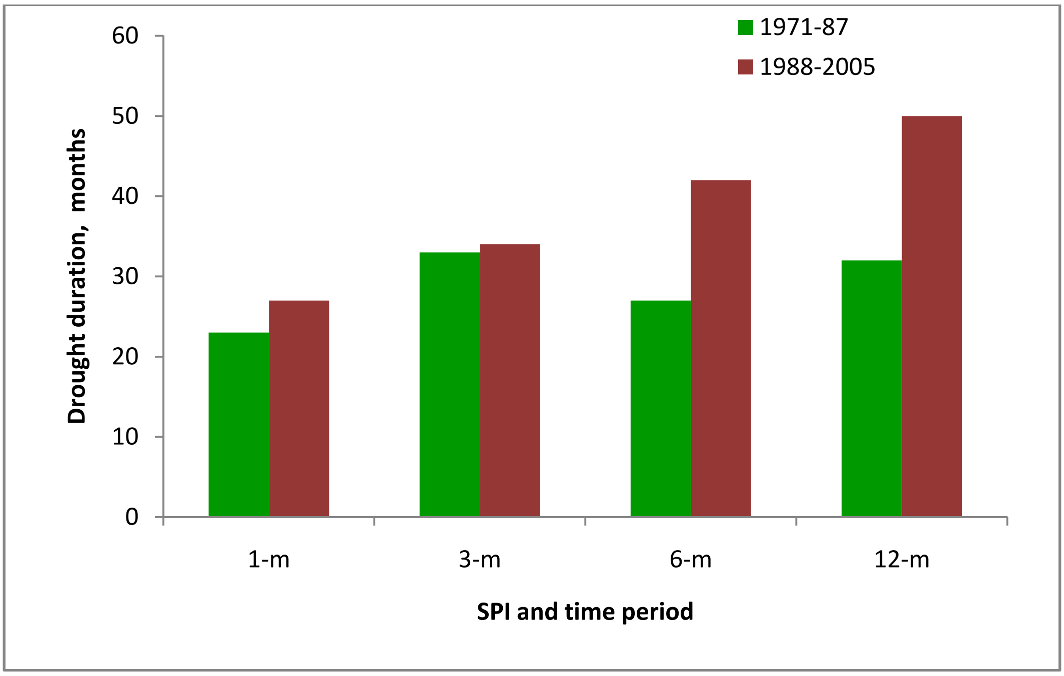

Fig. 4.14 Duration of droughts during different time periods

Prediction of future climate is essential for doing the climate change impact analysis in the Bharathapuzha basin. So, for getting reliable future climate data of the region based on the latest CMIP5 dataset, the following procedures were adopted.

4.3.1 Prediction and Downscaling of Future Climate Data

A historical run forced by observed atmospheric composition changes, cover much of the industrial period (from the mid-nineteenth century to near present), and also referred to as "twentieth century" simulations was used for comparing with the observed data to assess the reliability of the model.

4.3.2 Comparison of Predicted Data to Observed Data

Observed data of Bharathapuzha river basin on precipitation and temperature during the reference period, and historical data from the 5 regional climate models for the period 1989 to 2005 were compared initially on the basis of graphical representation (Fig. 4.15, 4.16 and 4.17). Statistical comparison was also done to ascertain the results of graphical comparison. The results of comparison on the basis of the four statistical parameters (Standard deviation, Correlation coefficient, coefficient of variation and centred root mean square difference) are given in Table 4.7. The GFDL-CM3 model was found to be the best on the basis of the statistical analysis done since it showed close correlation with the observed data. Jena *et al*., 2016 have reported that GFDL-CM3 is one of the best models in the CMIP5 dataset which can capture the pattern of Indian rainfall.

Table 4.7. Statistical comparison of model estimates with observed data

	EC-Earth	CCSM4	CNRM-CM5	GFDL-CM3	MPI	Observed
Precipitation						
Standard deviation	49.69	56.50	58.52	73.43	56.87	181.46
Correlation coefficient	0.24	0.68	0.74	0.76	0.78	
Coeff. of variation	0.44	0.58	0.62	0.66	0.59	1.03
Centered RMSE	3.86	1.75	1.88	1.57	1.71	

Maximum Temperature						
Standard deviation	2.92	2.47	2.62	2.32	2. 50	2.39
Correlation coefficient	-0.14	0.72	0.69	0.76	0.73	
Coeff. of variation	0.10	0.09	0.10	0.09	0.09	0.07
Centered RMSE	3.86	1.75	1.88	1.57	1.71	
Minimum Temperature						
Standard deviation	1.52	1.72	1.82	1.71	1.82	1.09
Correlation coefficient	0.49	0.77	0.78	0.82	0.81	
Coeff. of variation	0.09	0.08	0.09	0.08	0.09	0.05
Centered RMSE	1.31	1.07	1.13	0.99	1.08	

4.3.3 Bias Correction of Predicted Data

Even though the model GFDL-CM3 showed a good ability to simulate the present climate over the basin, the presence of uncertainties on the future climate because of systematic bias needs to be corrected. The method reported by Leander and Buishand (2007) was used for bias correction of future data. The constants a and b in the equation used was found out by the following procedure.

Determination of the parameter 'b' was done iteratively, so that the coefficient of variation of the daily precipitation values predicted by the model matches the coefficient of variation of the observed daily precipitation. After evaluating the parameter 'b', the transformed intermediate daily precipitation values were calculated and based on that the parameter a was determined such that the mean of the transformed daily values of precipitation matched with the observed mean. The parameter 'a' depends on 'b', but parameter b depends only on the coefficient of variation and is independent of the value of parameter 'a'. The bias correction coefficients 'a' and 'b' obtained for different months are plotted in Fig. 4.18 and the values of the coefficients are given in Appendix VII. Correction for temperature involves shifting and scaling to adjust the mean and the variance. The rainfall data of the best performing model, GFDL-CM3 was compared with the bias corrected data and found to have an almost perfect match with the observed data (Fig. 4.19).

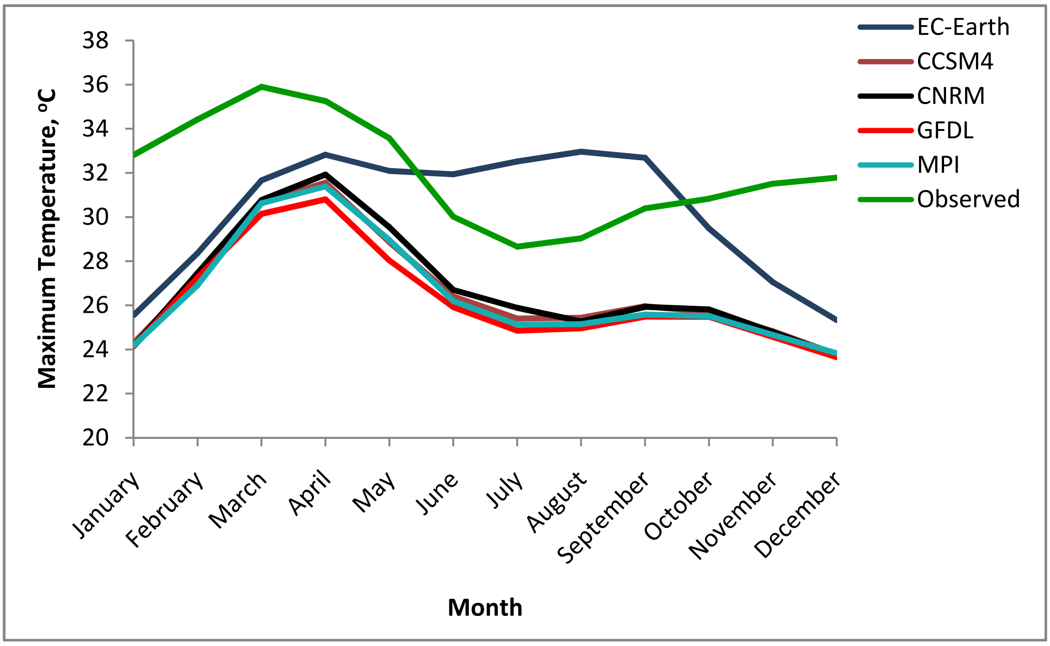

Fig. 4.15 Comparison of maximum temperature of different models with observed data

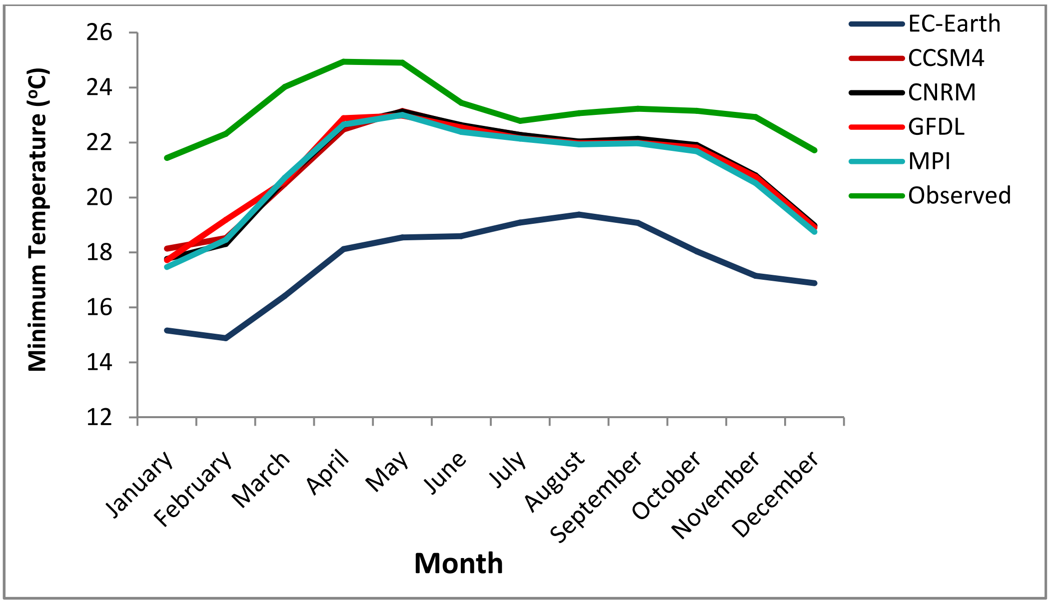

Fig. 4.16 Comparison of minimum temperature of different models with observed data

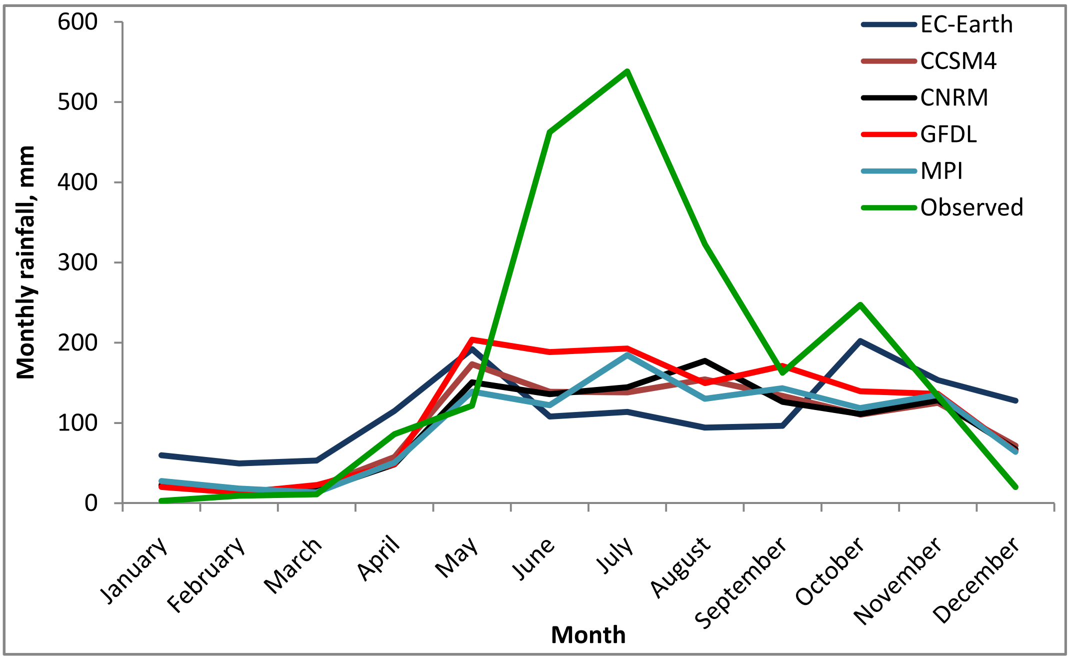

Fig. 4.17 Comparison of monthly rainfall of models with observed data

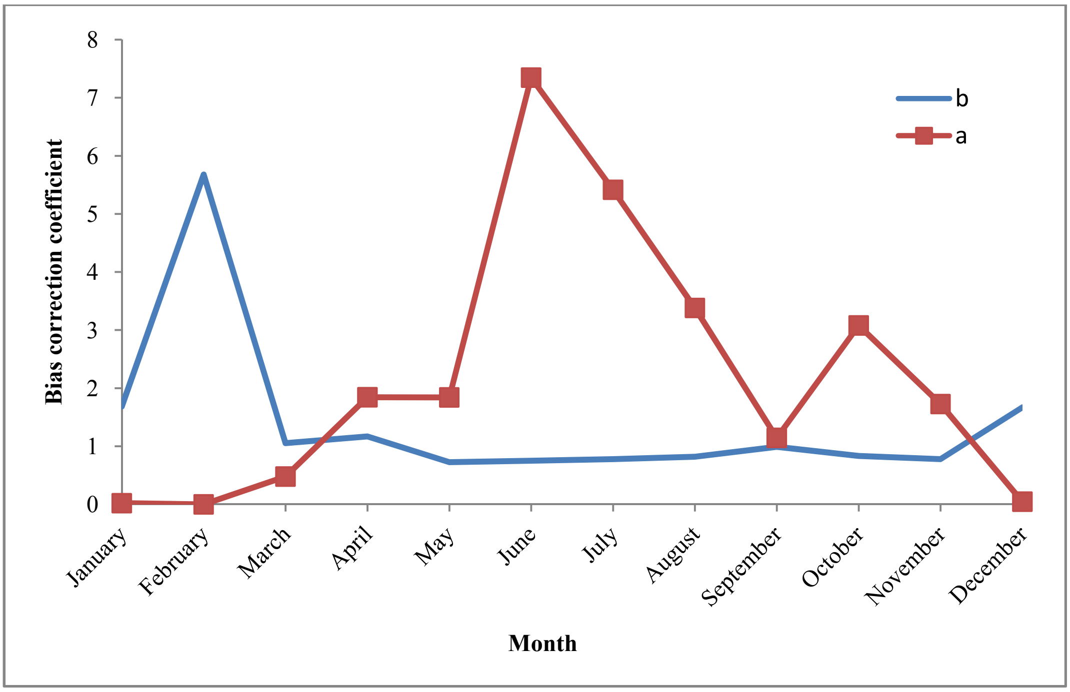

Fig. 4.18 Comparison of monthly transformation coefficients

A marked improvement was achieved with nonlinear transformation, adjusting the mean and coefficient of variation of daily precipitation. The coefficient values determined by this method for each month were used to correct the precipitation and temperature data for the future periods also. The model data for the two emission scenarios RCP4.5 and RCP8.5 and two scenario periods 2041-70 and 2071-99 were selected for the study based on the availability of data and so as to get a long term trend of the impact studies. The downscaled data on precipitation and temperature (maximum and minimum) was bias corrected using the above explained methods.

4.3.4 Predicted Future Precipitation of the Basin for Different Scenarios

Two future projection simulations forced with specified concentrations (RCPs), consistent with a high emissions scenario (RCP8.5) and a midrange mitigation emissions scenario (RCP4.5) was selected for the study. The monthly variation of the bias corrected data of precipitation for the two emission scenarios RCP4.5 and RCP8.5 for the periods 2041-70 and 2071-99 is shown in Fig. 4.20 and the average monthly precipitation values for different scenarios is given in Appendix VIII. There is a consistent decrease in rainfall during majority of the months except May, August, September, November and December for the two emission scenarios and for both future periods. After studying the rainfall trend during the southwest monsoon, it was observed that the rainfall during the months of June and July showed a decrease, whereas there was an increase in rainfall during August and September. A seasonal shift in the rainfall pattern was observed with a significant decrease in southwest monsoon (June to September) rainfall and an increase in rainfall during the northeast (October to November) monsoon period.

Based on the predictions, there may be a decrease of 4 per cent and 11 per cent in average annual rainfall in the basin during 2041-70 under RCP4.5 and RCP8.5 respectively. A decrease of up to 8 per cent and 15 per cent in annual rainfall during 2071-99 is also predicted for RCP4.5 and RCP8.5 respectively along with the seasonal shift.

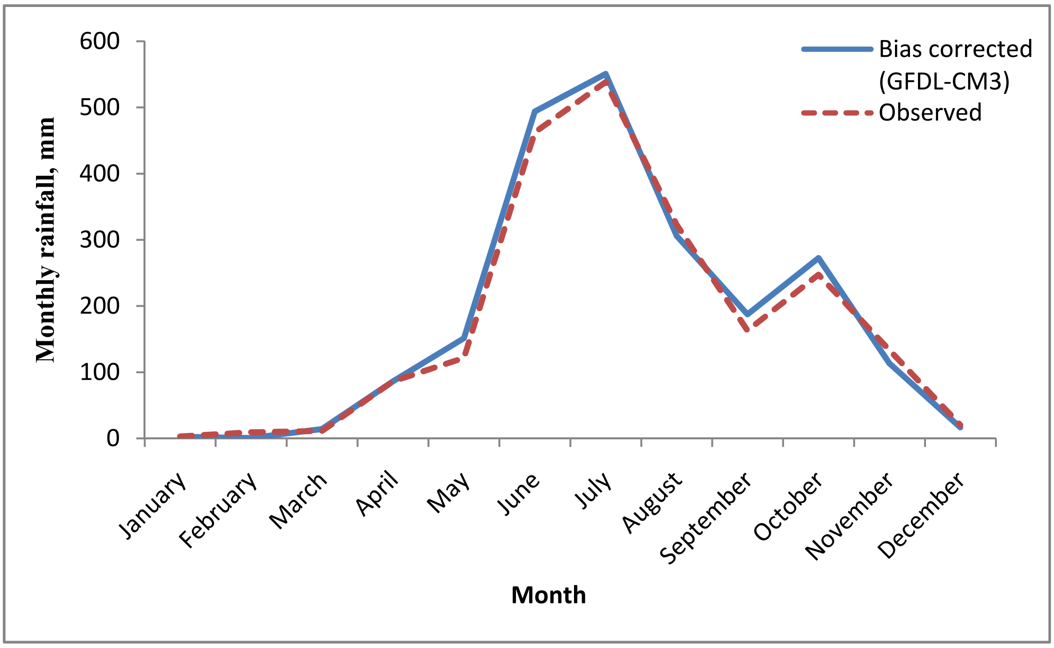

Fig. 4.19 Comparison of observed and bias corrected monthly precipitation

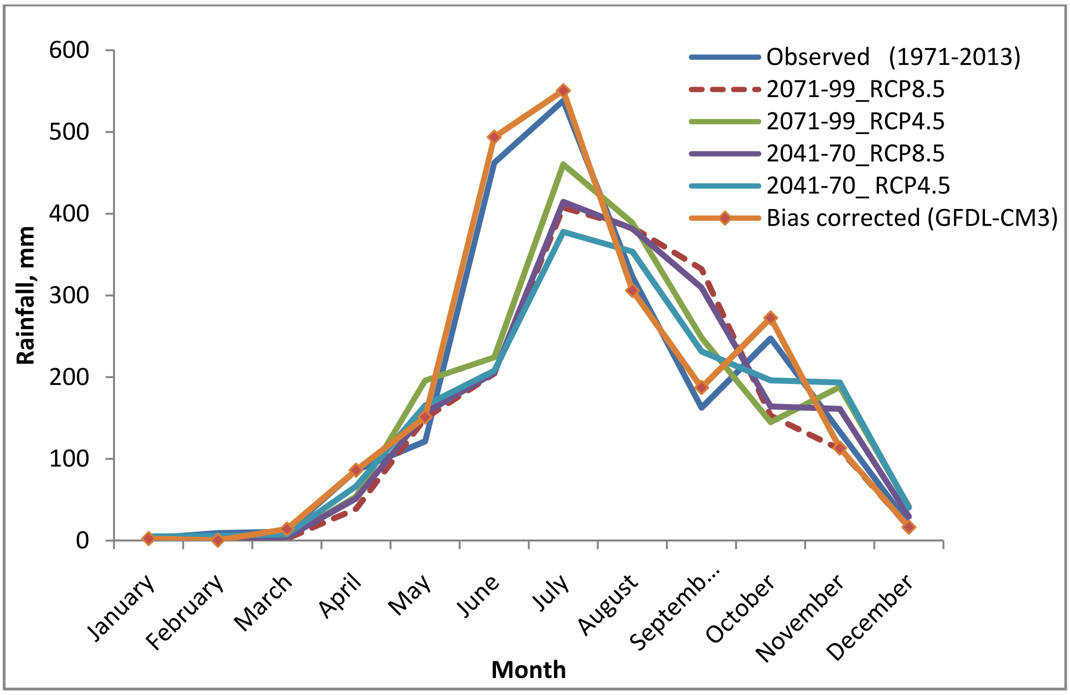

Fig. 4.20 Comparison of present and bias corrected future precipitation

Rainfall decline is more predominant in June and July, but it is increasing in August and September. This decreasing trend in southwest monsoon rainfall in Kerala has been reported by other researchers (Guhathakurta and Rajeevan, 2007; Raneesh and Thampi, 2013; Patwardhan *et al*., 2014).

To analyse the variation of rainfall during different months, it is better to analyse the change in terms of the per cent change in different scenarios from the observed monthly values. The per cent change in monthly rainfall from the observed monthly values is plotted in Fig. 4.21. From the graph, it is clear that the monthly average of rainfall decreases in most of the months except in May, August, September, November and December. The changes in monthly rainfall and seasonal shift in the rainfall pattern need to be taken into account during planning of agricultural activities.

Out of an estimated 140.3 Mha net cultivated area in India, 79.44 Mha (57 per cent) is rainfed, contributing 44 per cent of the total food grain production (Sharma, 2011). As far as Kerala is concerned, one of the major rice belts is in Palakkad district, with 41.5 per cent of total paddy area in the state, producing around 42 per cent of the total paddy production of the state (Agricultural statistics, 2013-14). Around 80 per cent of Palakkad district comes under Bharathapuzha basin, and this decrease in rainfall during June, July and October and increase during August and September will adversely affect the Kharif/Viruppu crop cultivation during the South-West monsoon period.

4.3.5 Predicted Future Temperature of the Basin for Different Scenarios

The monthly variation of the bias corrected data of maximum temperature and minimum temperature for the two emission scenarios RCP4.5 and RCP8.5 for the periods 2041-70 and 2071-99 is shown in Fig. 4.22 and 4.23 respectively and the average monthly values are given in Appendix IX and X respectively. The annual maximum temperature in the basin during 2041-70 under both scenarios may increase by 3-5^{o}C with an increase of 8 to 9 per cent over the present temperature.

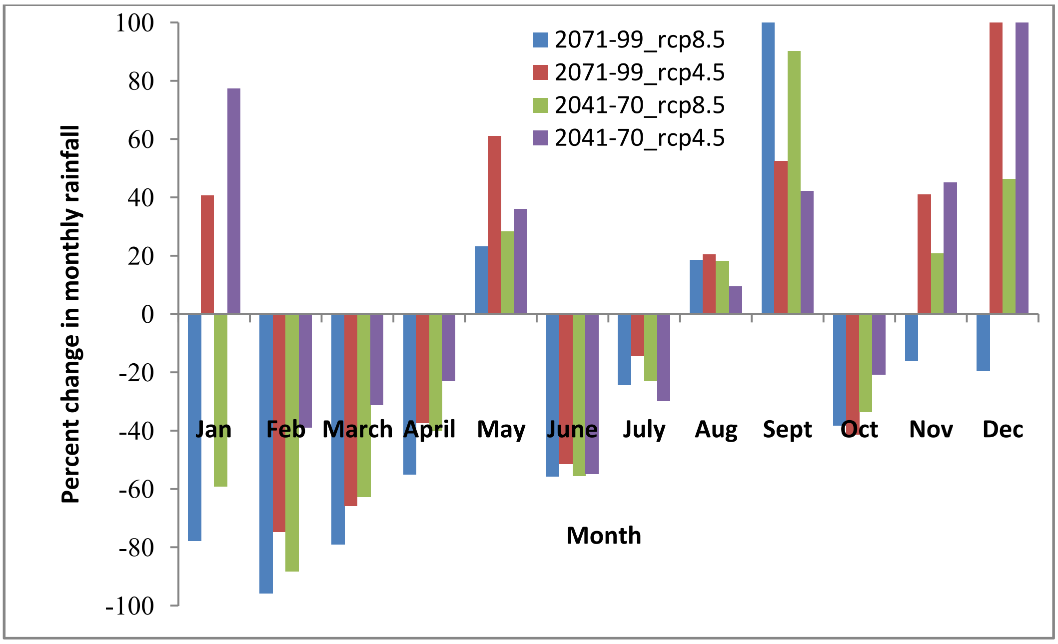

Fig. 4.21 Percent change in monthly rainfall from observed data

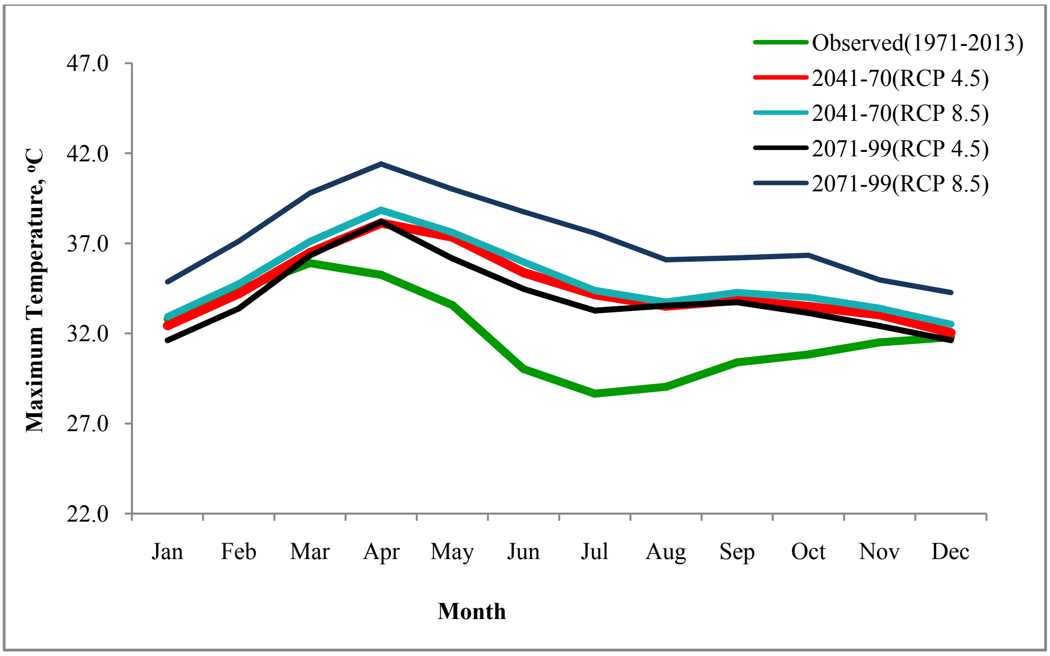

Fig. 4.22 Comparison of present and bias corrected future scenario maximum temperature

The increase in temperature under RCP4.5 during 2071-99 is almost to the same range, where as in the RCP8.5 scenario the increase over the present temperature was to the range of 4-8^{o}C (8 to 15 per cent) in the years 2071-99.

A similar increasing trend in temperature was also noted in the case of minimum temperature and the annual minimum temperature may increase by 5 to 8 per cent during 2041-70 under both RCPs, whereas the increase during 2071-99 under RCP8.5 may be up to 15 per cent. These results were used for assessing the impact of climate change in the area using the hydrologic model SWAT.

4.4 PREPARATION OF DATA INPUTS FOR SWAT

The spatial datasets needed for SWAT are Digital elevation model, land use map and the soil map.

4.4.1 Digital Elevation Model

Watershed boundary corresponding to the lowest point of the basin was delineated using Soil and Water Assessment Tool (SWAT) model in ArcGIS platform. SRTM DEM of 30 m spatial resolution was used for the delineation. Datum and projection used were WGS_1984 and UTM_Zone 43 respectively. The river basin area or watershed delineated from the DEM is shown in Fig. 4.24.

4.4.2 Land use Map

The land use map prepared in ERDAS and reclassified in ArcGIS is shown in Fig. 4.25. In SWAT, all the spatial data sets are to be in the same projection, and hence the land use map was also projected to the WGS_1984 and UTM_Zone43 projection. A land use look up table in dbase format was also prepared to relate the actual land uses to the land use SWAT code.

4.4.3 Soil Map

The soil map of the basin was also prepared in the same projected co-ordinate system. It was prepared in polygon feature class vector format and was later converted to raster format before inputting to SWAT (Fig. 4.26). The major soil series of the study area are Mannur-Sreekrishnapuram, Bhavajinagar, Karinganthodu-Kinnasseri, and Kozhinjampara.

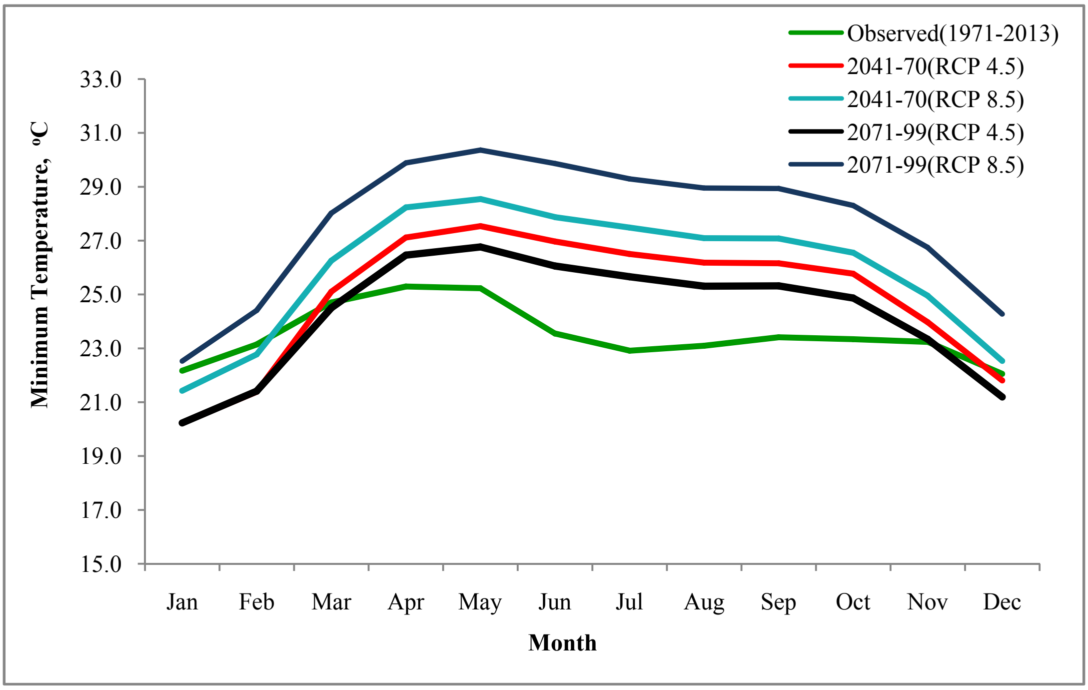

Fig. 4.23 Comparison of present and bias corrected future scenario minimum temperature

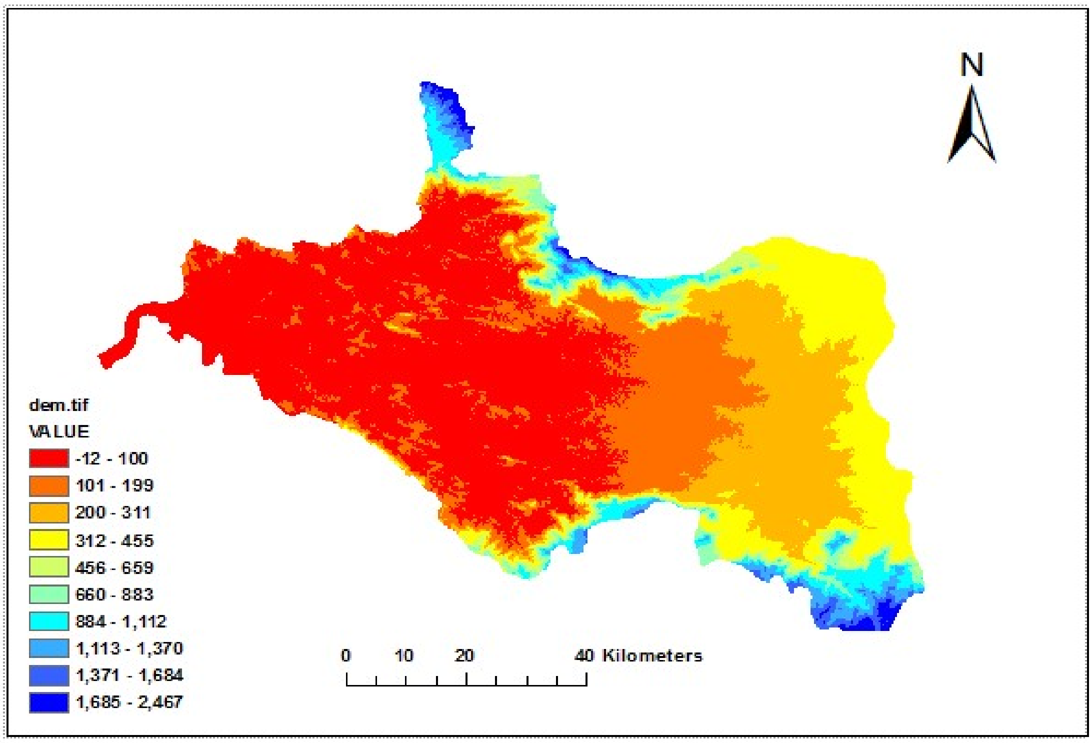

Fig. 4.24 Digital elevation model of Bharathapuzha river basin

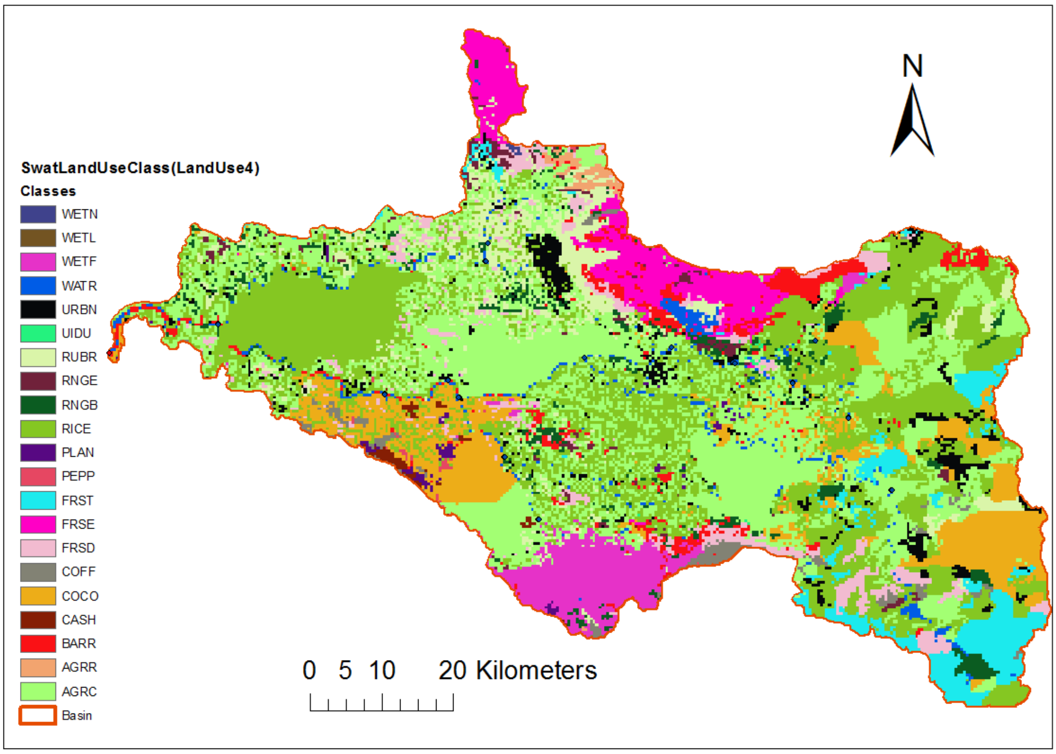

Fig. 4.25 SWAT land use classification of Bharathapuzha river basin

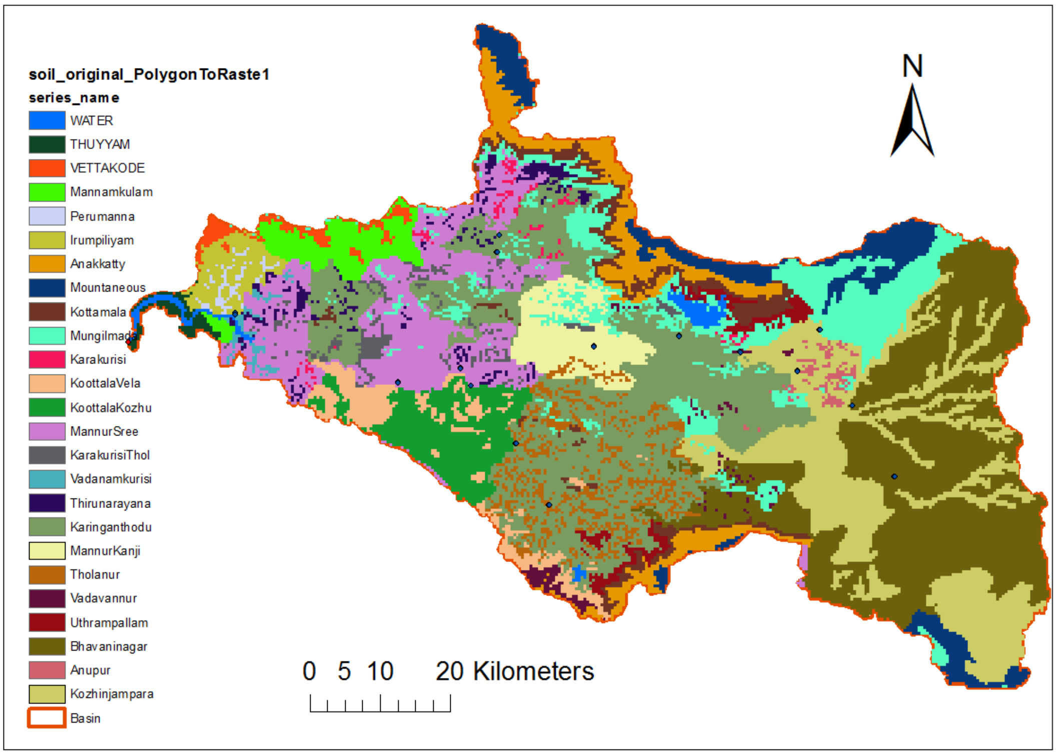

Fig. 4.26 SWAT soil classification of Bharathapuzha river basin

A soil dataset lookup table was also prepared in dbase format which is needed to define the soil classes in SWAT. The soil hydraulic properties computed using SPAW software was also fed as input to the model.

4.5 SWAT MODEL SET UP

The model set up is done mainly in four steps, watershed delineation, HRU analysis, writing input tables and editing of SWAT input. The details of model setup and the outputs obtained are discussed in brief.

4.5.1 Watershed Delineation

The SRTM DEM of 30 m spatial resolution for the area was downloaded and was used for watershed delineation. Watershed delineation helps the user to segment the watershed into hydrologically connected subwatersheds for further use in SWAT. Using the burn in option available in SWAT, the drainage network was superimposed to the DEM (as poly line shape file) so that accurate prediction of stream network and proper subwatershed boundary delineation is possible. The entire catchment was divided into 33 subcatchments (subbasins) based on the Digital Elevation Model (DEM) and the drainage network. The stream network based on DEM was then generated after assigning the threshold limit of 10900 ha. Subwatershed outlets were added at points in the drainage network at the location of monitoring stations. This was done for comparison of measured and predicted flows and sediment concentrations. Subbasin outlets were added at Mankara, Pudur, Thiruvegappura, Pulamanthole and Kumbidi where river gauging stations are available.

The inlet of draining watershed option was used so that the inflow from an area to the modelled area can be given as input and the inlet point was selected such that it coincides with Ambarampalayam gauging station. Using the whole watershed option, the lowest subbasin outlet was selected, and delineation of the watershed was done with respect to that point. Thus the first part of the model set up is done and is shown in Fig. 4.27.

The classified DEM of Bharathapuzha watershed showed that the elevation of the watershed ranges from (-)12 m to 2467 m, with a mean elevation of 204 m and standard deviation of 258 m. Area elevation details of the watershed is shown in the hypsometric curve (Fig. 4.28). A hypsometric curve is plotted on a graph in which the x-axis represents elevation (m) and the y axis represents percentage area above elevation. The curve shows how much area lies above a particular elevation value. About 80 per cent of the area of the watershed lies below 300 m elevation, and the rest 20 per cent lies between 300 m and 2500 m. Topographic details of the 33 subwatersheds delineated within the basin are shown in Table 4.8. The table also provides information on mean elevation, standard deviation of elevation and the geographical area of each watershed. The mean elevation of different subwatersheds varies from 31 m to 717 m.

Table 4.8 Topographic details of the subwatersheds generated by SWAT

Subwatershed No.	Minimum Elevation (m)	Maximum Elevation (m)	Mean Elevation (m)	S.D of Elevation (m)	Area (km^2)
1	48	2330	717.7	617.3	180.23
2	47	2050	349.0	342.3	197.40
3	46	160	77.6	18.4	8.16
4	43	1709	204.0	253.0	163.54
5	8	444	68.7	34.4	352.89
6	0	194	42.3	30.0	109.59
7	-12	152	40.5	33.6	130.13
8	169	1163	427.4	249.5	113.24
9	168	734	312.5	76.8	147.96
10	78	1916	537.3	433.0	153.67
11	53	83	63.1	6.4	0.48
12	105	1078	192.9	128.6	75.08
13	53	1094	118.8	105.1	120.36
14	78	899	121.9	64.8	47.11
15	47	278	76.6	23.1	32.22
16	24	365	82.7	34.2	134.50
17	104	171	131.9	12.2	23.41
18	132	445	293.9	79.6	163.67
19	16	73	31.0	13.4	0.53
20	22	172	51.9	20.8	9.58
21	28	256	71.6	17.6	183.06
22	-3	212	45.1	28.3	310.91

23	17	443	67.6	37.1	92.15
24	19	494	86	60.4	113.74
25	132	232	177.2	18.1	35.45
26	172	443	323.8	53.4	212.97
27	170	397	283.3	43.8	194.00
28	28	212	69.7	26.6	89.83
29	56	422	155.5	59.1	368.16
30	38	1608	181.6	206.0	512.55
31	37	517	84.0	41.7	125.64
32	47	1497	266.1	328.6	178.02
33	48	1280	241.2	231.6	135.11

4.5.2 HRU Analysis

The steps involved in HRU analysis are landuse/soils/slope definition and HRU definition.

4.5.2.1 Landuse/Soils/Slope Definition

In this step, the loading of the soil layer, land use layer and the slope classes to the SWAT model is done. After loading the soil and landuse map, the soil and landuse attribute codes will be assigned to all map categories and they are reclassified with SWAT land cover classes and soil classes. Five slope classes were selected, and on the basis of the slope classes, the slope map (Fig. 4.29) was prepared and added to SWAT. Once, the slope class definition is complete, reclassifying is again done and a new layer is added to the map. The model checks for proper projection of the maps and overlay of the land use, soil and slope map over the basin was done.

4.5.2.2 HRU Definition

Classification of the basin area to HRU's is done in this step. HRU's are defined so that each HRU represents unique soil/land use characteristics. Land use/soil/slope combinations (hydrologic response units or HRUs) were created for each subbasin. This will help to reflect the difference in evapotranspiration and other hydrologic conditions for different land covers/crops and soils.

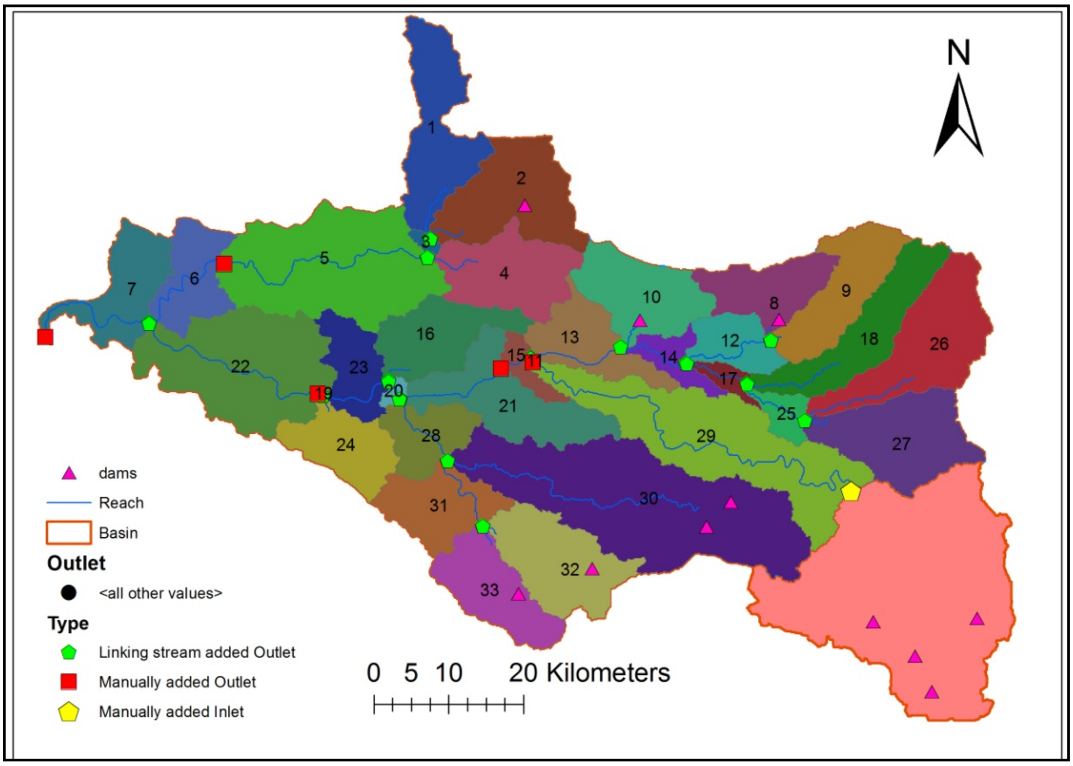

Fig. 4.27 Sub-basin delineation and selection of outlet and inlet points

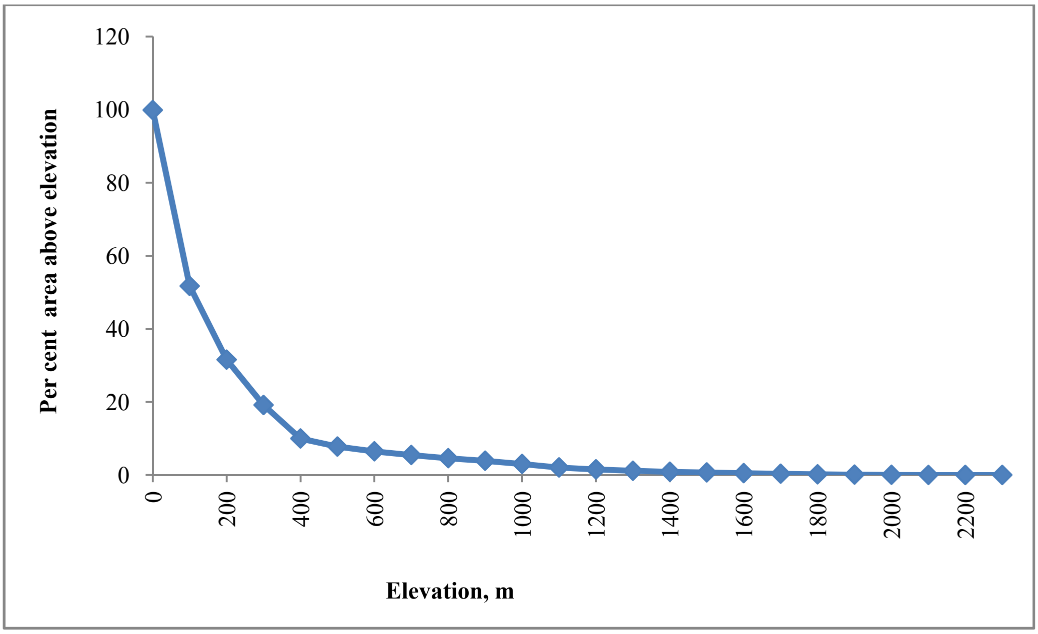

Fig. 4.28 Hypsometric curve of Bharathapuzha river basin

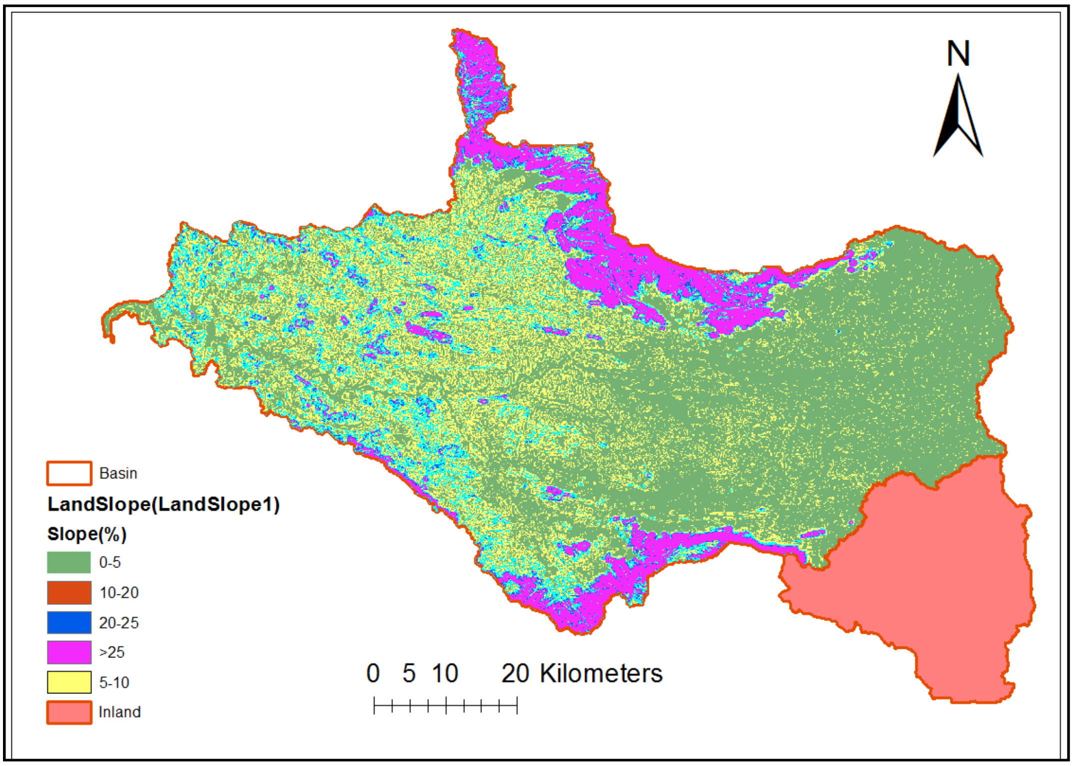

Fig. 4.29 Slope map of Bharathapuzha basin

The multiple HRU option was selected and the sensitivities or threshold percentage for the land use, soil, and slope data was selected so as to determine the number and kind of HRUs in each watershed. A threshold of 10 per cent for land use and 10 per cent for soil was used, which eliminates any land use that occupies less than 10 per cent of the land in the subbasin and any soil that represents less than 10 per cent in the subbasin.

After the elimination process, the area of the remaining land uses is reapportioned so that 100 per cent of the land area in the subbasin is modelled. Similarly, in case of slope 5 per cent was chosen and elimination and reapportioning was done. A total of 401 HRU's were defined within the basin. The details of land use, slope and soil classes are given in Appendix XI, XII and XIII respectively.

4.5.3 Writing Input Tables

When the HRU distribution is finished, the weather data is imported to SWAT. The weather data definition option under the write input tables is used for importing the data. The data prepared in text table format was imported to the SWAT model. The exact naming convention specified in Neitsch *et al*., 2005 was followed for the input text files. After importing all the necessary weather data, the initial watershed input values were defined. While writing the input tables, the values were set automatically based on the watershed delineation and landuse\soil\ slope characterization or from defaults. When all the default inputs have been generated, the model is ready for simulation and SWAT run can be performed.

4.5.4 Editing SWAT Input

The edit SWAT input option is used to edit the SWAT model databases and the watershed database files containing the current inputs for the SWAT model. The option to edit the inlet discharges was used to add the daily discharge to the area at the Ambarampalayam gauging station. The observed flow of the station for the period was loaded as daily loading file which is a text file prepared and saved earlier. The changes are saved and using the rewrite SWAT input option the files are written to the SWAT *i.dat files. The modified input files are selected and rewritten using the re-write SWAT input files option available.

The Reservoirs command was used to add the input parameters of the reservoirs located within the watershed. Among the eleven reservoirs coming in the area, four of them are in the upstream of Ambarampalayam gauging station, and the rest seven in the downstream of the gauging station, in the area that is simulated. The details of the reservoirs added in SWAT are given in Table 4.9. The release of the reservoirs was added as average annual release rate.

Table 4.9 Details of dams in the simulated area of the river basin

Name of dam	Year of impoundment	Catchment area (km^2)	Storage capacity (Mm^3)	Waterspread area (km^2)	Location
Malampuzha	1967	147.63	228.40	23.13	10.84°N, 76.69°E
Pothundi	1971	30.82	52.38	3.63	10.54°N, 76.63°E
Meenkara	1960	90.70	11.33	2.59	10.62°N, 76.80°E
Chulliar	1964	27.80	13.70	1.59	10.59°N, 76.77°E
Mangalam	1956	48.85	25.47	3.93	10.51°N, 76.54°E
Walayar	1964	106.35	18.40	2.59	10.84°N, 76.86°E
Kanjirampuzha	1980	70.00	70.00	5.12	10.98°N, 76.55°E

4.5.5 SWAT Model Run

The starting and ending dates of the simulation are selected and SWAT simulation is done. For calibration, simulation was done from 1st January, 1989 to 31st December, 2000, and for validation, simulation was done from 1st January, 2001 to 31st December, 2009.

A warm up period of three years were given in each case and is indicated as number of years to skip (NYSKIP) during the simulation. For climate change studies, simulations were done for 2041-70 and 2071-99. The files that are to be imported to the database are selected and imported and the simulation is saved with a proper name. The Run SWAT check option is used to check whether any aspects of the results raise concern.

4.6 SENSITIVITY ANALYSIS

Sensitivity analysis was performed using the SWAT Calibration and Uncertainty Program (SWAT-CUP). A new project was created in SWAT-CUP and during the project creation all files in the SWAT TxtInOut will be copied to the new project directory. The parameters for sensitivity analysis were selected based on the characteristics of the study area and literature (Heuvelmans *et al.*, 2004, Chu and Shirmohammadi 2004, Gosain *et al.*, 2006). After doing a one at a time analysis, thirteen parameters were selected initially for the global sensitivity analysis; Soil evaporation compensation factor (ESCO), Base flow alpha factor (Alpha_BF), Curve number (CN), Groundwater delay time (GW_DELAY), Baseflow alpha factor for bank storage (ALPHA_BNK), Effective hydraulic conductivity of main channel (CH_K2), Threshold depth of water in the shallow aquifer (GW_QMN), Available water holding capacity of soil (SOL_AWC), Surface lag coefficient (SURLAG), Ground water revap coefficient (GW_REVAP), Mannings n value for main channel (CH_N2), Soil hydraulic conductivity (SOL_K) and Soil bulk density (SOL_BD). The SUFI-2 method in SWAT-CUP was selected for the analysis.

The t-stat gives a measure of the sensitivity of a parameter, and the p-value, indicates the significance of the sensitivity of the parameter. These measures were used to rank the various parameters that influences streamflow, and the top ranked and most sensitive seven parameters were used for calibrating the model (Table 4.10). It is observed that the calibration effort can be very much reduced when the optimum parameter selection is limited to the parameters suggested in the sensitivity analysis. These parameters are highly responsible for model calibration and changes in the rest of the parameters had no significant effect on streamflow simulations. The dotty plots (Fig. 4.30) show the distribution of the number of simulations in parameter sensitivity analysis after comparing the parameter values with the objective functions for the monthly calibrations.

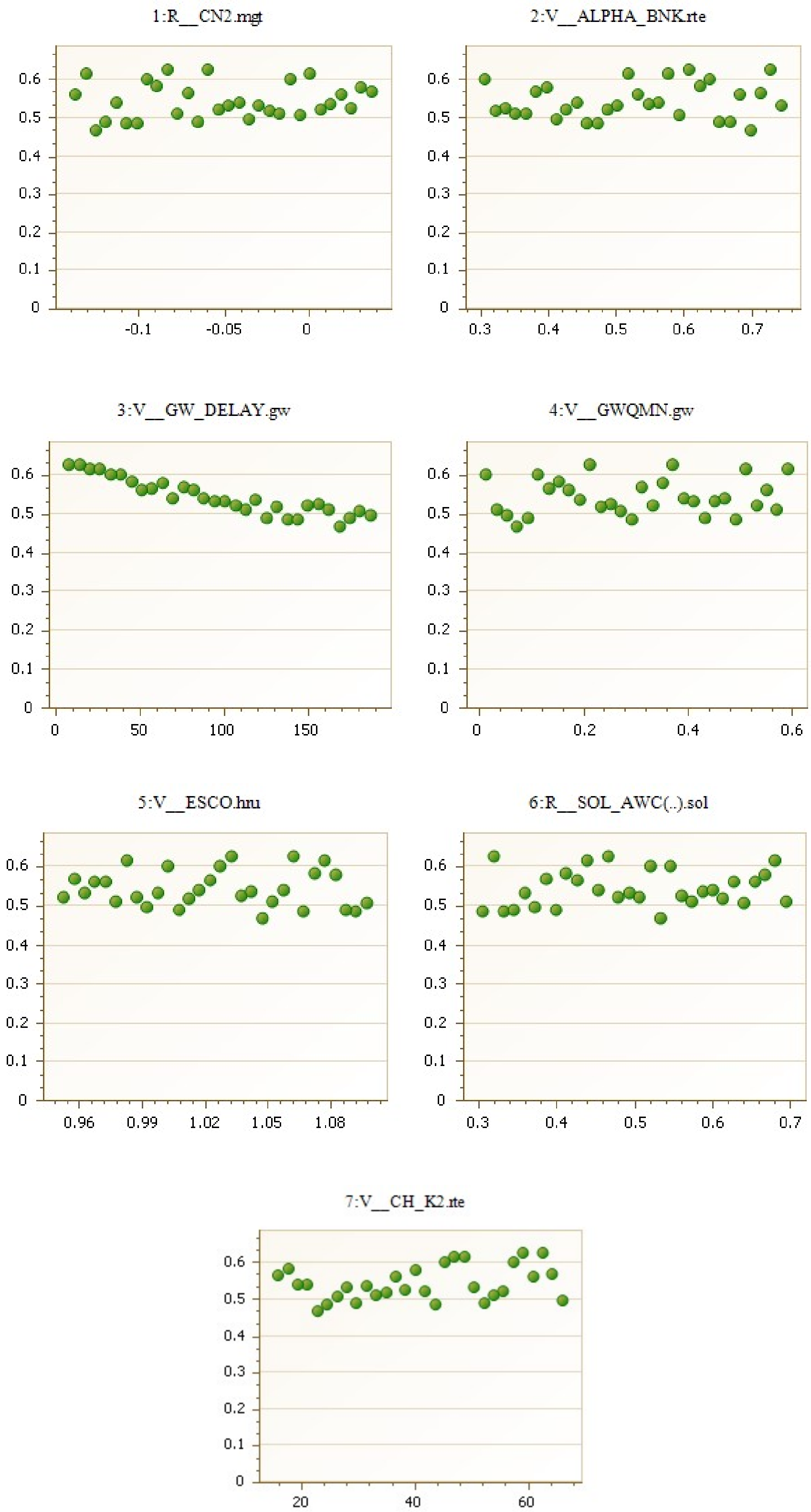

Fig. 4.30 Dotty plots showing most sensitive parameters during monthly calibration in SUFI-2.

From the similar studies reviewed, it is seen that the selected parameters were sensitive to streamflow (Schuol *et al*., 2008; Raneesh and Thampi, 2011; Faramarzi *et al*., 2009).

Table 4.10 Sensitive parameters and ranking for Bharathapuzha watershed

Sensitivity rank	Parameter	Description	t-value	p-value
1	CN2.mgt	SCS runoff curve number	**32.48**	**0.00**
2	GW_DELAY.gw	Groundwater delay time (days)	**-21.79**	**0.00**
3	ALPHA_BNK.rte	Baseflow alpha factor for bank storage (days)	**3.69**	**0.00**
4	ESCO.hru	Soil evaporation compensation factor	**3.02**	**0.003**
5	CH_K2.rte	Effective hydraulic conductivity of main channel	**1.24**	**0.22**
6	GW_QMN.gw	Threshold depth of water in the shallow aquifer	**1.06**	**0.29**
7	SOL_AWC.sol	Available water holding capacity of soil	**-0.65**	**0.53**

* t-value(large absolute value) and p-value(close to zero) show measure and significance of sensitivity for each parameter respectively

4.7 CALIBRATION OF THE MODEL

Model calibration is essential for the testing of a model and observed data can be tuned with it. Model calibration is needed for the successful use of any hydrologic simulation. Sequential Uncertainty fitting (SUFI-2), a program that is linked to SWAT was utilized for calibration and validation analysis. SUFI-2 has been used by many researchers for the calibration and uncertainty analysis, and is capable of analyzing a large number of parameters and measured data from many gauging stations simultaneously (Arnold *et al*., 2012; Patil *et al*., 2014). Out of the 21 years of observed data available, initial 12 years data was used for calibration, and last 9 years data for validation. This was done based on the suggestion by many researchers to divide the available meteorological data sets to two subdatasets (Thampi *et al*., 2010; Musau *et al*., 2015; Fukunga *et al*., 2015). Calibration was done for the period from 1st January 1989 to 31st December 2000.

The model parameters were adjusted manually by trial and error based on certain statistical indicators and the characteristics of the study area. In SWAT model, the soil water content, surface runoff, crop growth parameters, nutrient movement, and management practices are all simulated for each HRU, and the results are aggregated for the subbasin by weighted average. Hence, during calibration, the changes in model parameters make changes in the HRU level, subbasin level and finally the basin level parameters.

The statistical criteria used to evaluate the hydrological goodness of-fit were the coefficient of determination (R^2) and two other statistical operators, NSE (Nash and Sutcliffe, 1970) and PBIAS as recommended by Moriasi *et al.* (2007). The coefficient of determination indicates the strength of the relationship between the simulated and observed values, whereas, the NSE is an indication of how well the observed versus simulated values fit the 1:1 line (Santhi *et al*., 2001). The evaluation was done by comparing discharge computed by the SWAT model with measured discharge data from the corresponding gauging stations.

4.7.1 Multi-site Calibration

Calibration was carried out using the average monthly observed flow at 4 river gauging stations Kumbidi, Pulamanthole, Mankara and Thiruvegappura. The parameter values can vary from one subbasin to another and hence it was thoroughly examined during the calibration.

Among the parameters selected after sensitivity analysis, the surface response of the model is influenced mainly by the curve number (CN2), soil evaporation compensation factor (ESCO), and available soil water capacity (SOL_AWC). A high curve number indicates a higher runoff potential and it depends mainly on the landuse, soil, antecedent moisture conditions and slope of the basin. SWAT default values of curve number was adjusted based on these parameters while entering in the subbasins data by using the edit SWAT input option as well as during the calibration process. Around 20-30 per cent of the total flow of Bharathapuzha is contributed by the Kunthipuzha and hence attention was given to consider the forest areas coming in the area while modifying the curve numbers. Soil evaporation compensation factor (ESCO) has been incorporated to allow the user to modify the depth distribution used to meet the soil evaporative demand. As the value for ESCO is reduced, the model is able to extract more of the evaporative demand from lower levels. In the present study area, ESCO value was selected so that it is in the higher range of 0.95 to 1.0. A higher value of SOL_AWC means high capacity of soil to retain water and thereby causing less water available for percolation and surface runoff and vice versa. Different subbasins will be having variations in landuse and the structural and topographical changes taking place in the area during the calibration period. This was also taken into consideration and the value was adjusted accordingly for the area.

The subsurface response is influenced by the depth of water in the shallow aquifer required for return flow to occur to the stream (GWQMN), base-flow alpha factor for bank storage (ALPHA_BNK) and time needed for water to leave the bottom of the root zone to reach the shallow aquifer (GW_DELAY). The lag time taken by water to move past the lowest depth of the soil profile by percolation and flow through the vadose zone before becoming shallow aquifer recharge is referred to as GW_DELAY. The parameters GW_DELAY and GWQNMN depend on hydraulic properties of the geologic formations and the depth to the water table. Bank storage contributes flow to the main channel or reach within the subbasin. The baseflow alpha factor characterizes the bank storage recession curve. The value was adjusted such that the variation between observed and simulated flow is minimum.

Based on the sensitivity analysis, among the channel properties, the basin response is affected mainly by Channel hydraulic conductivity (CH_K2). The effective hydraulic conductivity of stream is set to zero by default in SWAT model, which means that there is no loss of water is expected from the stream bed. This is not the case in respect of the humid tropics and semi-arid tropics (Neitsch *et al.*, 2011) and hence this value was increased based on suggested value ranges.

Thus, during calibration, the model input parameters were adjusted based on sensitivity analysis, to match the observed and simulated streamflows.

Reiterations were continued until satisfactory results in terms of graphical comparison and statistical evaluation were met, for the simulated discharge against the measurements.

4.7.2 Calibration Results

Changes were made to the parameters so that they have physical meanings with respect to the characteristics of soil, topography, climate etc. The SWAT-CUP default range and the calibrated range of values for the sensitive parameters are given in Table 4.11.

Table 4.11 Sensitive parameters and fitted range of values

Parameter	SWAT-CUP default range	Range after calibration
r__CN2.mgt	-0.2 to 0.2	-0.14 to 0.04
v__ALPHA_BNK.rte	0 to 1	0.3 to 0.75
v__GW_DELAY.gw	30 to 450	5 to 190
v__GWQMN.gw	0 to 2	0.004 to 0.6
v__ESCO.hru	0.8 to 1.0	0.95 to 1.0
r__SOL_AWC.sol	-0.2 to 0.4	0.3 to 0.69
v__CH_K2.rte	5 to 130	15 to 67

In the table, r-represents that the existing value is multiplied by a value (got by adding one to the given value) and v indicates that the default value is replaced by the parameter.

4.7.3 Model Performance Evaluation Based on Statistical Comparison

The evaluation of the model and model simulations was done by statistical comparisons. Nash-Sutcliffe Efficiency (NSE) and the Coefficient of determination (R^2) and PBIAS was used to compare the observed and simulated datasets.

Table 4.12 Model evaluation statistics for Monthly Discharge

Gauging Station	NSE	R^2	PBIAS (%)	p-factor	r-factor
Calibration period					
Cheruthuruthy	0.84	0.85	1.4	0.48	0.43
Mankara	0.57	0.62	-11.7	0.44	0.47
Pulamanthole	0.74	0.66	14.6	0.51	0.38
Kumbidi	0.79	0.83	12.7	0.53	0.35
Validation period					
Cheruthuruthy	0.71	0.87	11.4	0.44	0.39
Mankara	0.74	0.81	18.1	0.52	0.53
Pulamanthole	0.65	0.74	9.0	0.36	0.32
Kumbidi	0.83	0.88	14.4	0.42	0.32

The model evaluation statistics for the calibration and validation period are shown in Table 4.12 and the results showed a good performance in modelling over the whole catchment. The coefficient of determination (R^2) varied from 0.62 to 0.85, Nash-Suchliffe efficiency varied from 0.57 to 0.84 and PBIAS ranged between -11.7 to 12.7 during the calibration period. The NSE, R^2 and PBIAS values showed good performance according to the performance rating by Moraisi *et al*. (2007). The strength of the model calibration and uncertainty procedure was also analysed using the *r*-factor which ranged from 0.35 to 0.47 during the calibration period. This also showed satisfactory results.

The NSE at the lower most gauging station Kumbidi was 0.79 during calibration period, and 0.83 during validation period. The R^2 values at Kumbidi also showed very good performance with 0.83 and 0.88 during the calibration period and validation period respectively. The prediction biases from upstream subcatchments may be self compensating at the larger catchment scale (Cao *et al*., 2006), and this may be the reason for the better performance of the model at the lowest gauging station, Kumbidi.

4.7.4. Performance Evaluation Based on Time Series and Scatter Plots

The time series graphs of predicted and observed monthly streamflows after calibration with respect to the four gauging stations are shown in Fig. 4.31 to 4.34. The model estimated well the low and average streamflow values in most cases, whereas it slightly underestimated the peak flows even after calibration. A little discrepancy was also seen in some cases in the timing of occurrence of simulated and observed peak flows also.

These model uncertainties can be accounted for due to large variations in topography and rainfall, some errors in data input sources like landuse and soil, data preparation etc. As reported by Nie *et al*. (2011), the duration and intensity of precipitation are not being considered in the SCS method for estimation of runoff in SWAT model. The uncertainties may also be due to human and instrumental errors occurred during the processing of data. Insufficient and inaccurate data availability, especially at micro level and inadequate availability of reservoir outflow data may also have added to these uncertainties.

Another graphical form of model evaluation is based on the scatter plot. The scatter plot of monthly streamflow for the calibration period and validation period are given in Fig. 4.35 and 4.36 respectively, which shows a good relationship between observation and simulation with good likelihood measures of R^2; 0.78 and 0.89 during calibration and validation period respectively.

4.8 VALIDATION OF THE MODEL

Validation of the model was done with another set of data from 1st January, 2001 to 31st December, 2009. The model evaluation statistics during validation is also given in Table 4.12. The coefficient of determination (R^2) varied from 0.74 to 0.88, Nash-Suchliffe efficiency varied from 0.65 to 0.83 and PBIAS ranged from 9.0 to 18.1 during the validation period. The time series graphs of predicted and observed monthly streamflows after validation with respect to the four gauging stations are shown in Fig. 4.37 to Fig. 4.40.

The overall statistics shows that the model can successfully be used for predicting monthly streamflow in the Bharathapuzha river basin.

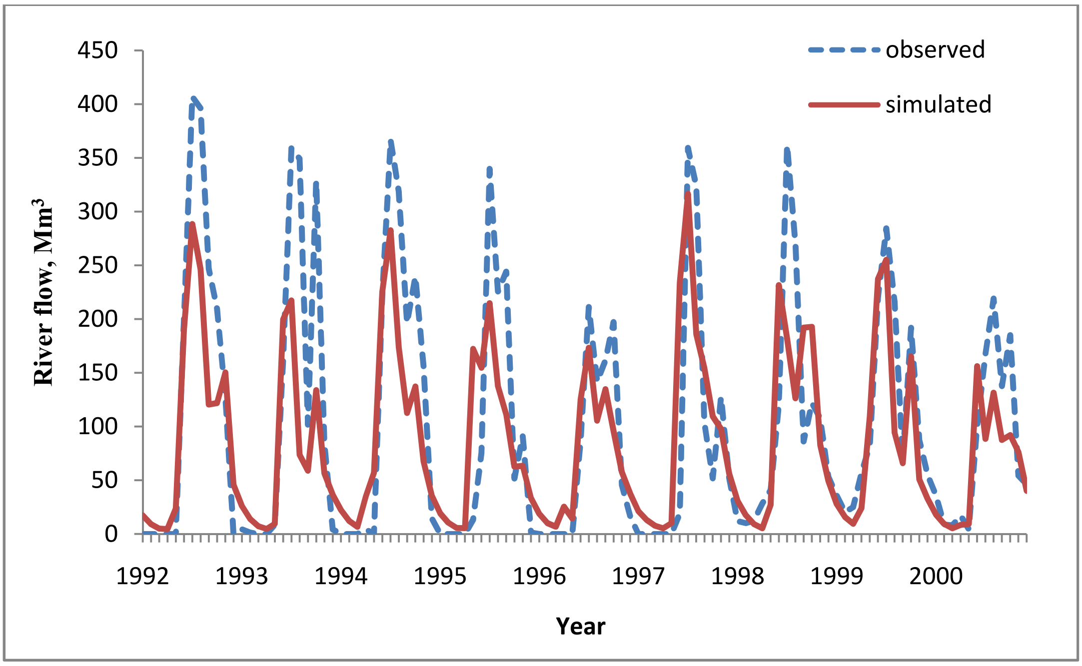

Fig. 4.31 Observed and simulated monthly streamflow at Pulamanthole for calibration period

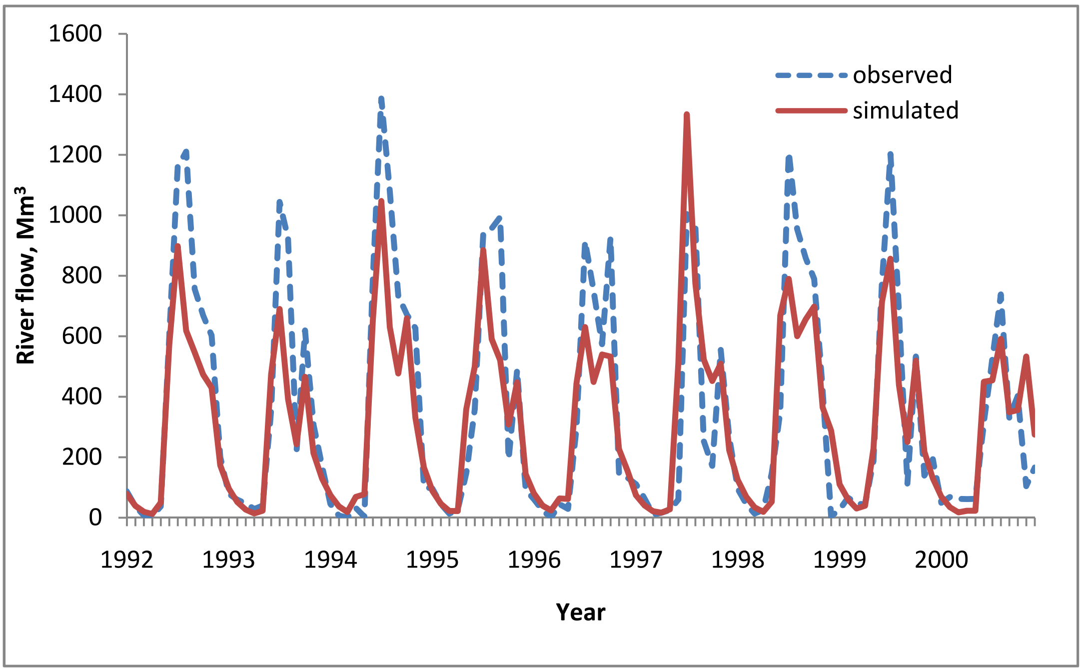

Fig. 4.32 Observed and simulated monthly streamflow at Kumbidi for calibration period

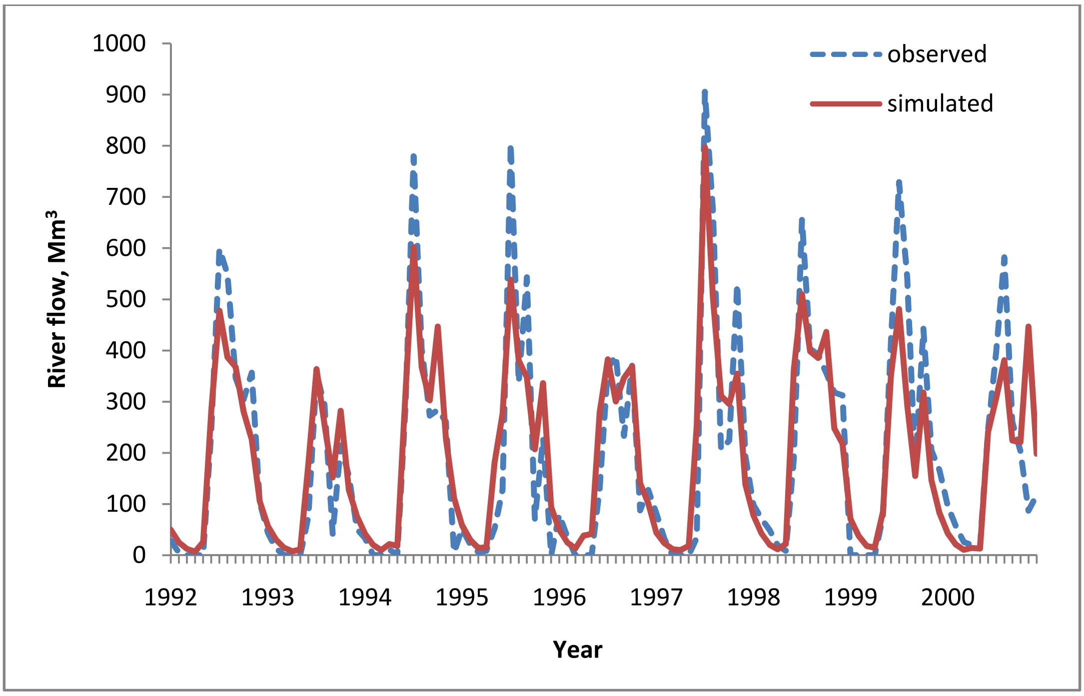

Fig. 4.33 Observed and simulated monthly streamflow at Cheruthuruthy for calibration period

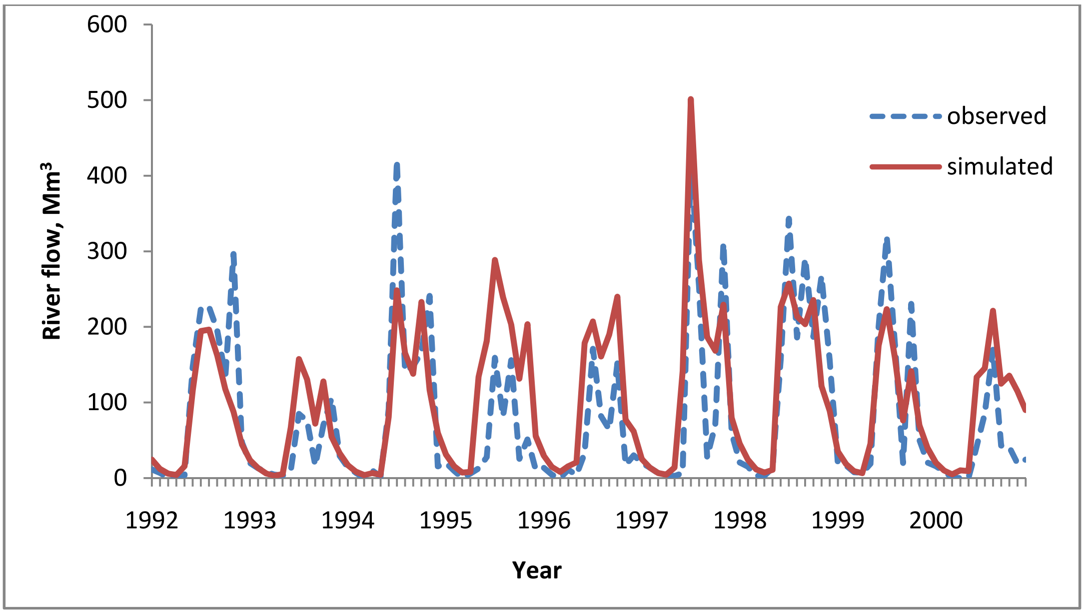

Fig. 4.34 Observed and simulated monthly streamflow at Mankara for calibration period

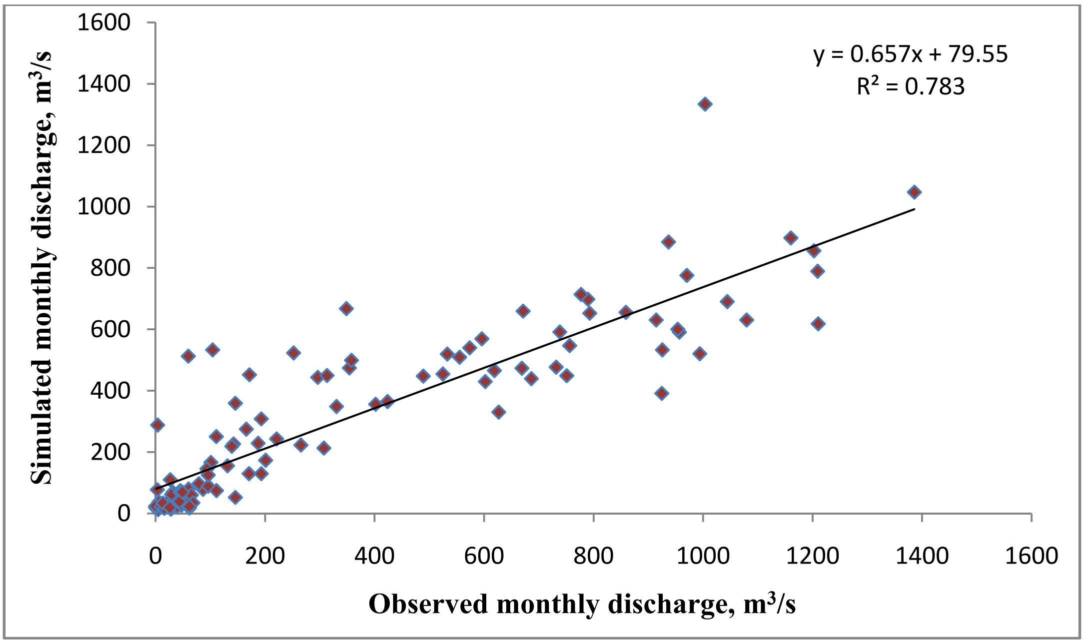

Fig. 4.35 Scatter plot of observed and simulated monthly discharge at Kumbidi gauging station during calibration period.

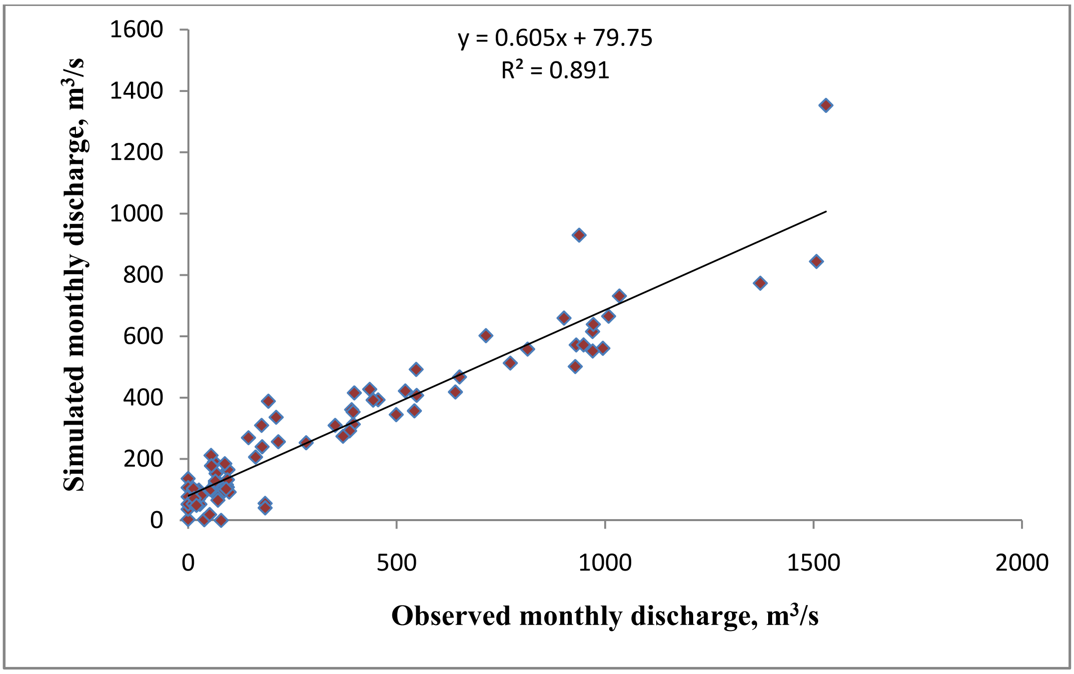

Fig. 4.36 Scatter plot of observed and simulated monthly discharge at Kumbidi gauging station during validation period.

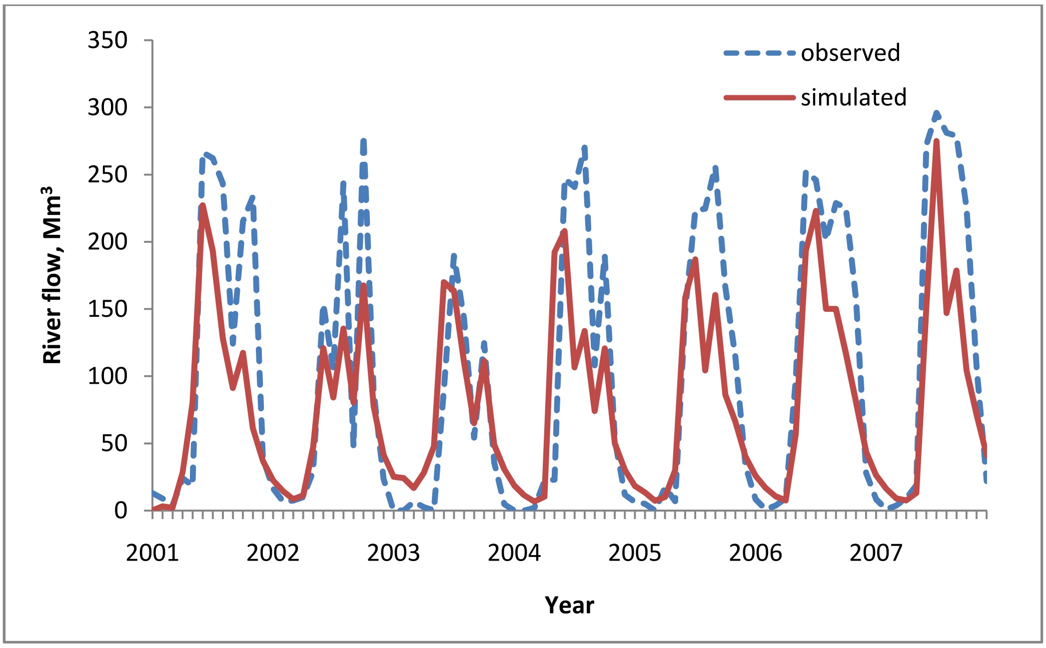

Fig. 4.37 Observed and simulated monthly streamflow at Pulamanthole for validation period

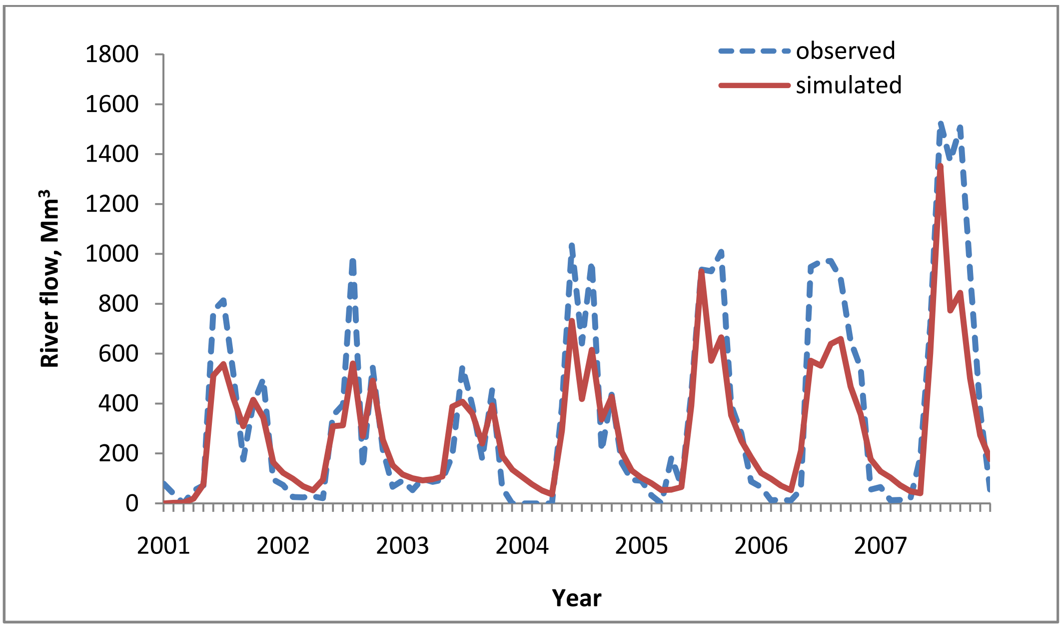

Fig. 4.38 Observed and simulated monthly streamflow at Kumbidi for validation period

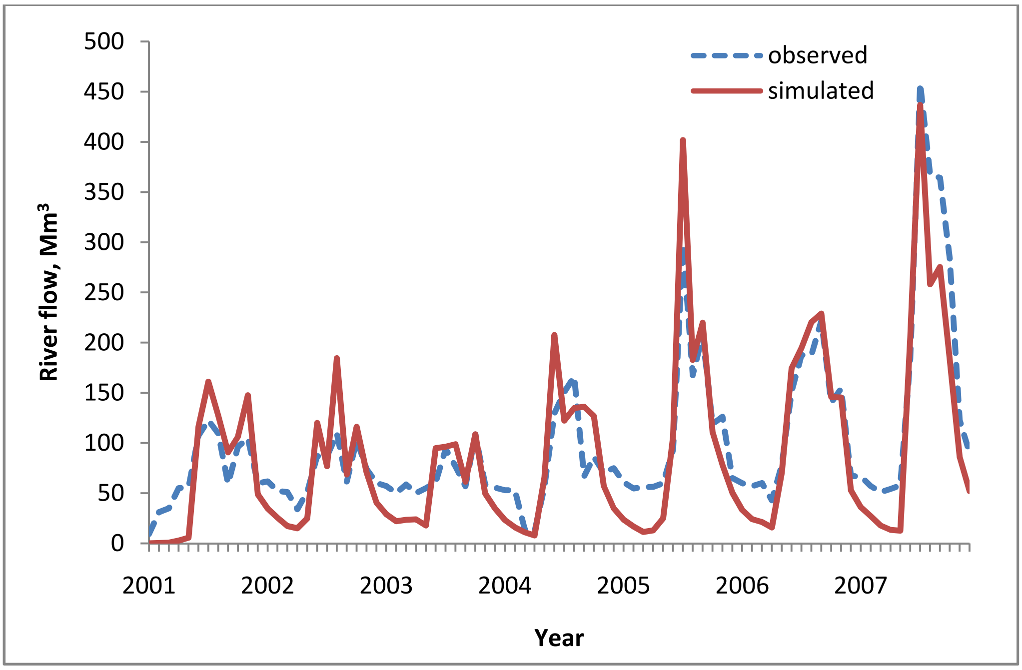

Fig. 4.39 Observed and simulated monthly streamflow at Mankara for validation period

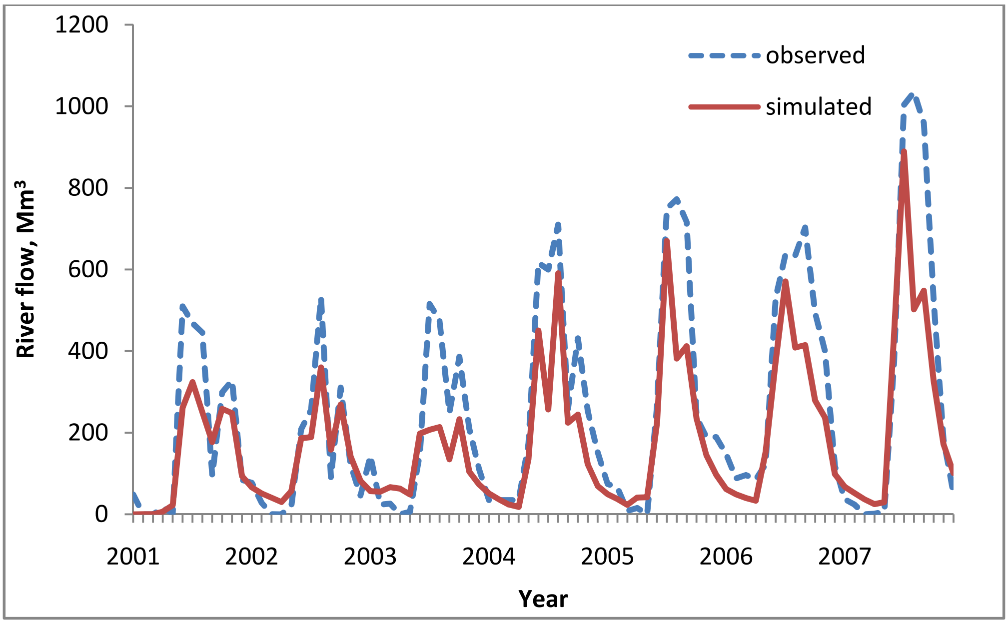

Fig. 4.40 Observed and simulated monthly streamflow at Cheruthuruthy for validation period

This calibrated model was later used for computing the impact of climate change and watershed interventions on the hydrologic response of the river basin.

4.9 MODEL EVALUATION BASED ON SEDIMENT LOSS

The observed values of sediment loss for the gauging station Kumbidi (station at the lowest part) for the period 1992-2007 was obtained from the Central Water Commission website. The sediment loss from the basin simulated by the model after calibration was compared with the observed values using the Nash-Sutcliffe coefficient (NSE) and Coefficient of determination (R^2). Observed values of sediment loss for the monsoon period (June-November) was considered for comparing with the simulated values.

The results of statistical comparison of monthly values of observed and simulated sediment loss at the basin outlet (Kumbidi gauging station) are shown in Table 4.13. The NSE value at Kumbidi (lower most gauging station) for monthly sediment loss ranged from 0.56 to 0.78 and the coefficient of determination ranged from 0.75 to 0.98 during the entire period of analysis. Comparison of monthly observed and simulated sediment loss during the calibration and validation periods are plotted in Fig.4.41 and 4.42 respectively.

Table 4.13 Statistical comparison of monthly observed and simulated sediment loss at Kumbidi gauging station.

Year	NSE	R^2	Year	NSE	R^2
1992	0.71	0.88	**2000**	0.67	0.98
1993	0.65	0.87	**2001**	0.61	0.90
1994	0.60	0.89	**2002**	0.56	0.89
1995	0.66	0.96	**2003**	0.58	0.89
1996	0.56	0.75	**2004**	0.73	0.94
1997	0.64	0.97	**2005**	0.58	0.89
1998	0.71	0.92	**2006**	0.60	0.94
1999	0.75	0.95	**2007**	0.78	0.93

A scatter plot of observed and simulated annual sediment loss at Kumbidi gauging station during 1992-2007 is shown in Fig. 4.43.

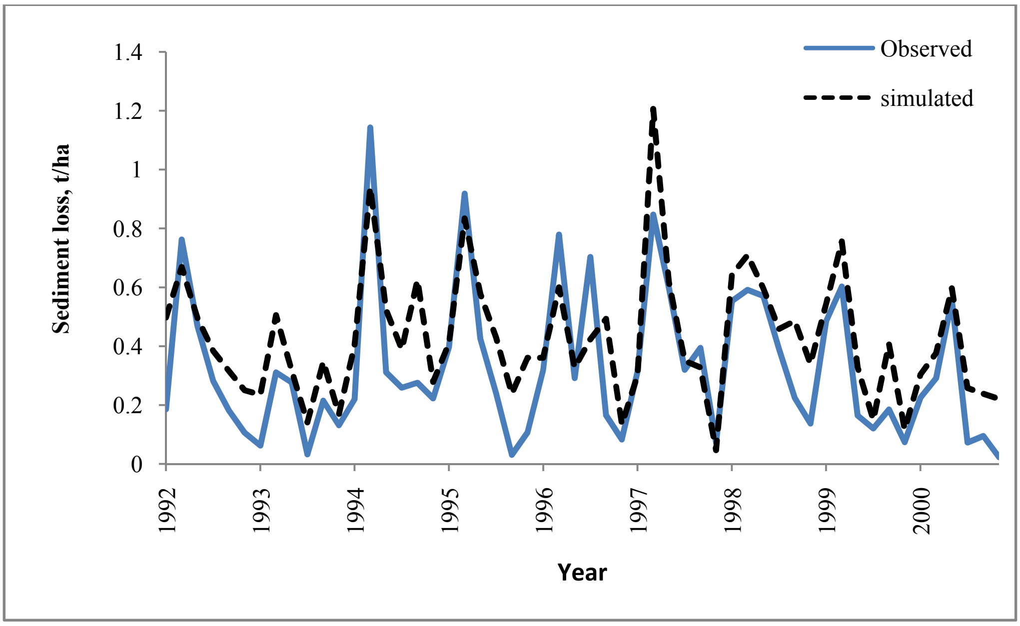

Fig. 4.41 Comparison of monthly observed and simulated sediment loss during the calibration period

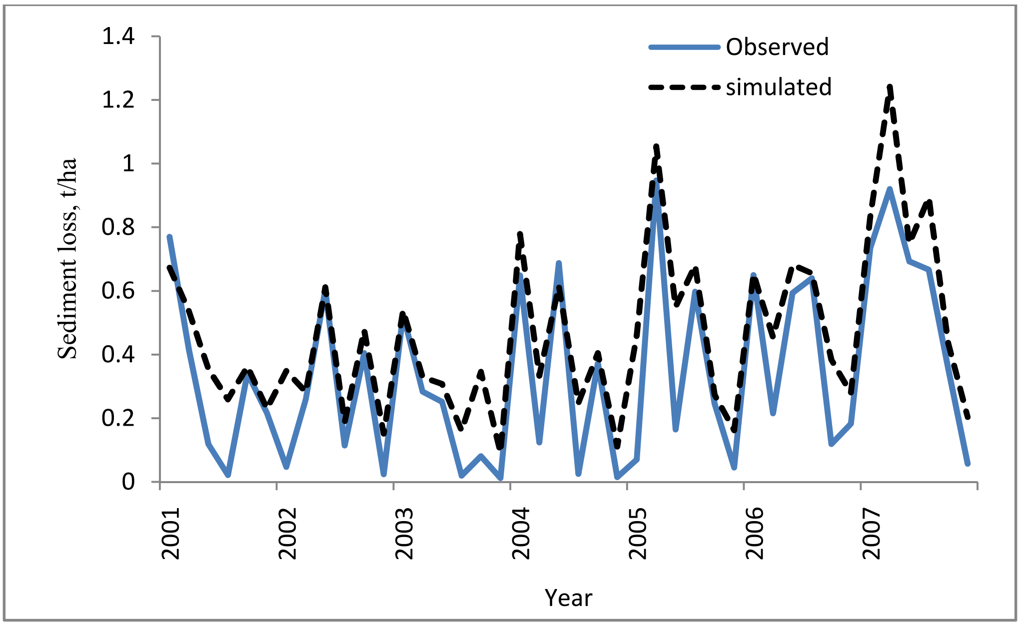

Fig. 4.42 Comparison of monthly observed and simulated sediment loss during the validation period

The trend line plotted between the annual observed and simulated sediment loss showed a R^2 value 0.869, indicating a strong correlation between the two.

The temporal variation of annual observed and simulated sediment loss during the calibration (1992-2000) and validation period (2001-2007) together is plotted in Fig. 4.44. The trend of both the curves is similar, and it is also noticed that the sediment loss is increasing after 2003 onwards till 2007. These results obtained can be utilised in formulating future water resources management plans and for assessing the impact of climate change using hydrologic models.

4.10 WATER BALANCE OF THE BASIN

For studying the water balance of the area, it is not enough to compare the river flow of the basin as a whole, but it is essential to analyse the components of river flow. The water balance components of Bharathapuzha basin predicted by the model have been estimated from the output files and are presented as a percentage of annual rainfall for the calibration period (Fig. 4.45 and 4.46) and validation period (Fig. 4.47). The predicted proportions of surface runoff, lateral flow, base flow and evapotranspiration for the years are plotted in the pie diagrams. It is seen that outflow from the basin takes place mainly in the form of base flow (33 to 37 per cent of annual rainfall) followed by surface runoff (31 per cent to 42 per cent). Lateral flow component varied from 8 to 11 per cent and ET varied from 15 to 22 per cent for the different years under consideration. Water balance components reveal that the major fraction of river flow is in the form of base flow and surface runoff.

The rainfall runoff relationship of the basin during the last three to four decades (1980-2013) was studied on the basis of the time series analysis of rainfall and observed streamflow (Fig. 4.48). The rainfall as well as the observed streamflow during this period is having a decreasing trend with the trend line of runoff having a slightly higher decreasing slope than that of rainfall.

This also highlights the need for studying the future hydrology of the basin with changing climate and with the influence of watershed interventions.

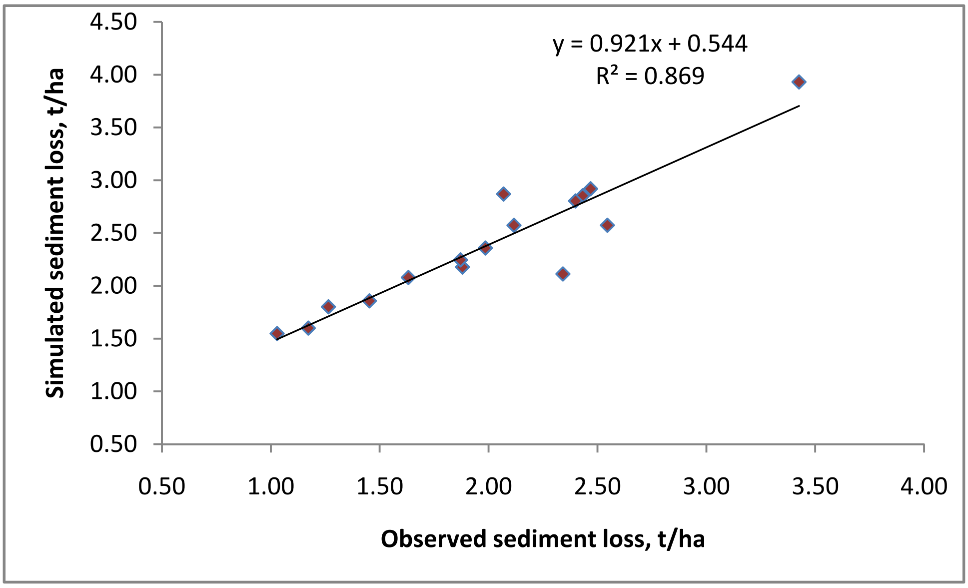

Fig. 4.43 Scatter plot of observed and simulated annual sediment loss at Kumbidi gauging station during 1992-2007.

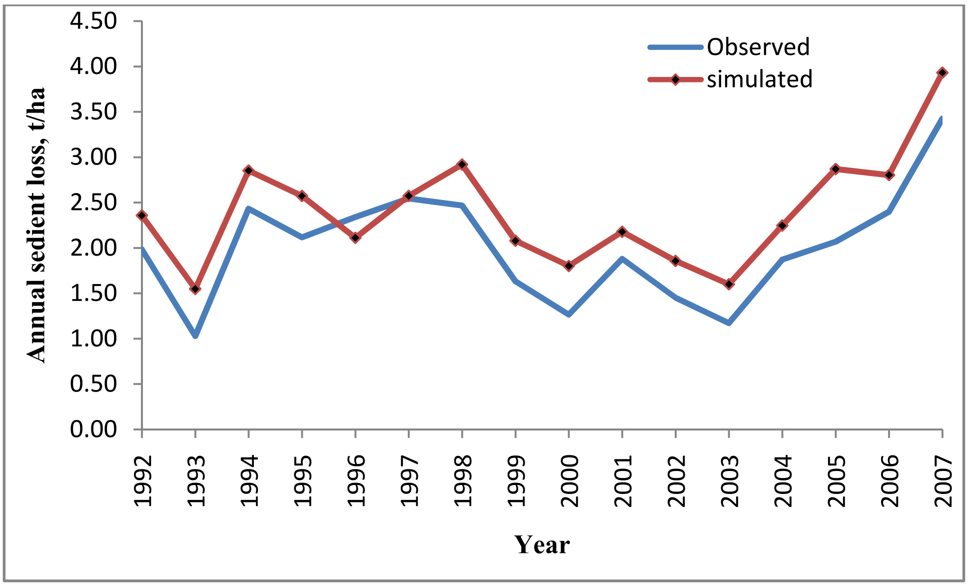

Fig. 4.44 Temporal variation of annual observed and simulated sediment loss

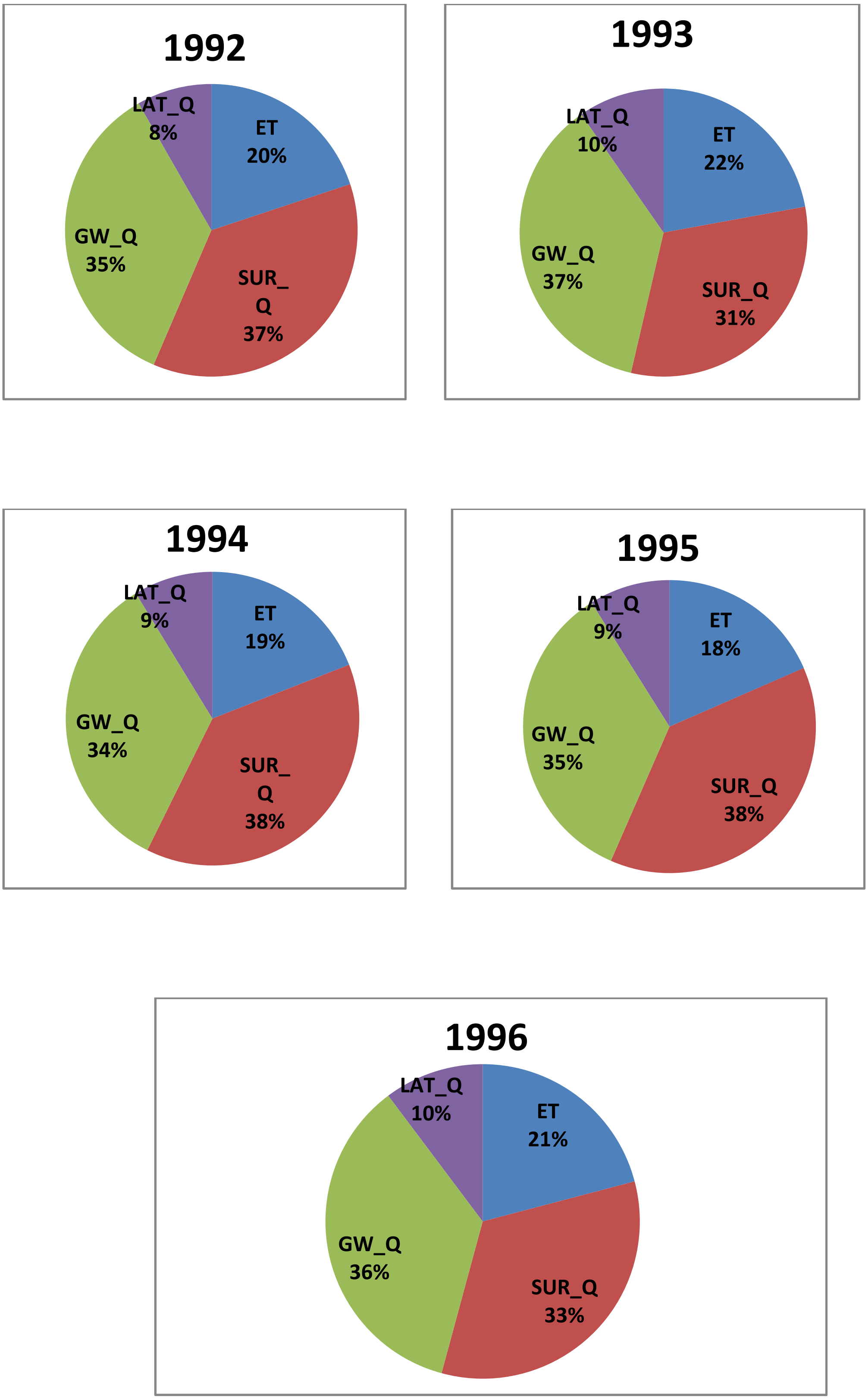

Fig. 4.45 Water balance of Bharathapuzha basin for the period 1992-1996

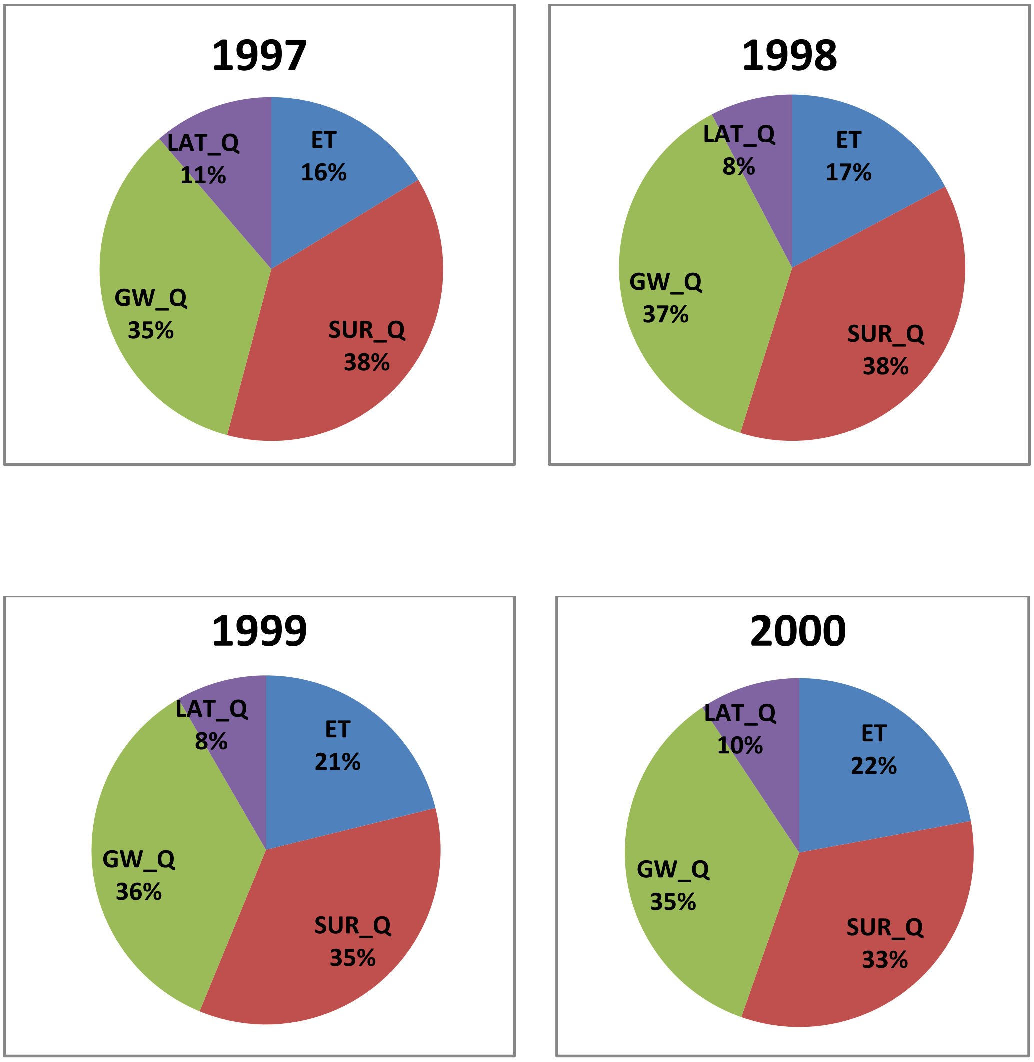

Fig. 4.46 Water balance of Bharathapuzha basin for the period 1997-2000

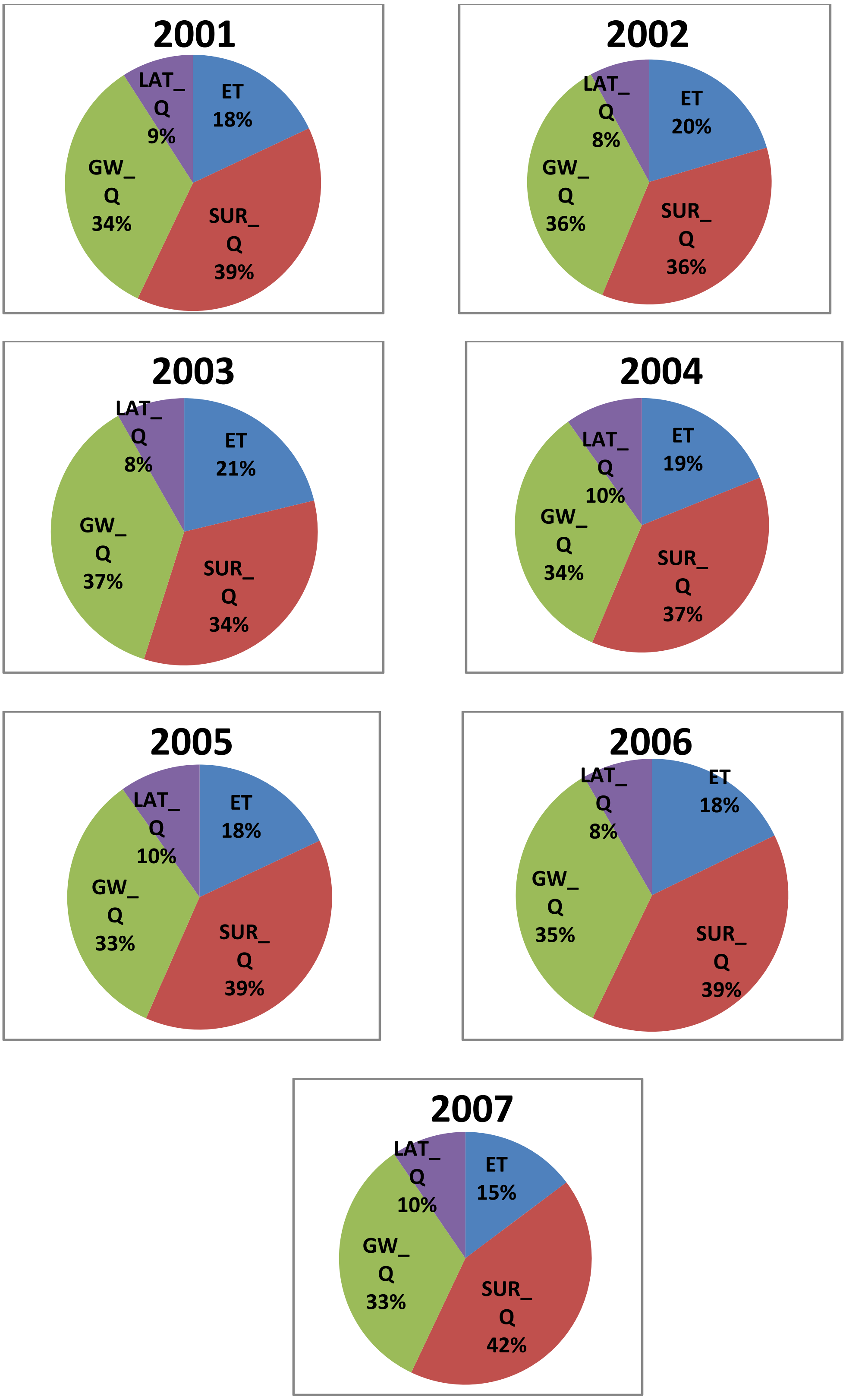

Fig. 4.47 Water balance of Bharathapuzha basin for the period 2001-2007

Since the base flow component is important for the summer river flow, an attempt was done to compare the simulated and observed base flow during the period. The summer flow was taken as base flow since only a very little rainfall occurs during summer in the region, and summer flow is mainly contributed by base flow. The graphical representation of observed and simulated base flow is given in Fig. 4.49. Even though slightly higher values were observed for simulated flow when compared to observed flow in most of the years, very close similarity was found between the two during the years under study. This shows thorough validation of the model.

4.11 IMPACT OF CLIMATE CHANGE ON RIVER BASIN HYDROLOGY

The calibrated SWAT model was applied to Bharathapuzha river basin for analysing the impact of climate change on water balance components. SWAT model has been used to assess the climate change impacts on the hydrological regime of various catchments across the world (Raneesh and Thampi, 2011; Devkota and Gyawali, 2015; Gurung *et al*., 2013; Lubini and Adamowski, 2013). Considering the projected data availability and suitability of data for the region, the GFDL-CM3 data for the two scenarios RCP4.5 and RCP8.5 during the period 2041-70 and 2071-99 was selected for the study.

Hydrologic simulations for the climate change periods (2041-70 and 2071-99) were performed with SWAT model using the bias corrected rainfall and temperature data for the two scenarios. The impact of climate change on hydrology was thus quantified by driving the calibrated SWAT model corresponding to the current scenario and two RCP's, viz., RCP4.5 and RCP8.5. Streamflow simulation for the current scenario was then compared with the predicted flow of future for the two periods and two scenarios.

4.11.1 Water Balance of Changing Climate Scenario

Water balance components of the basin predicted for the future climate are given in Table 4.14 and are compared with the calibration and validation periods.

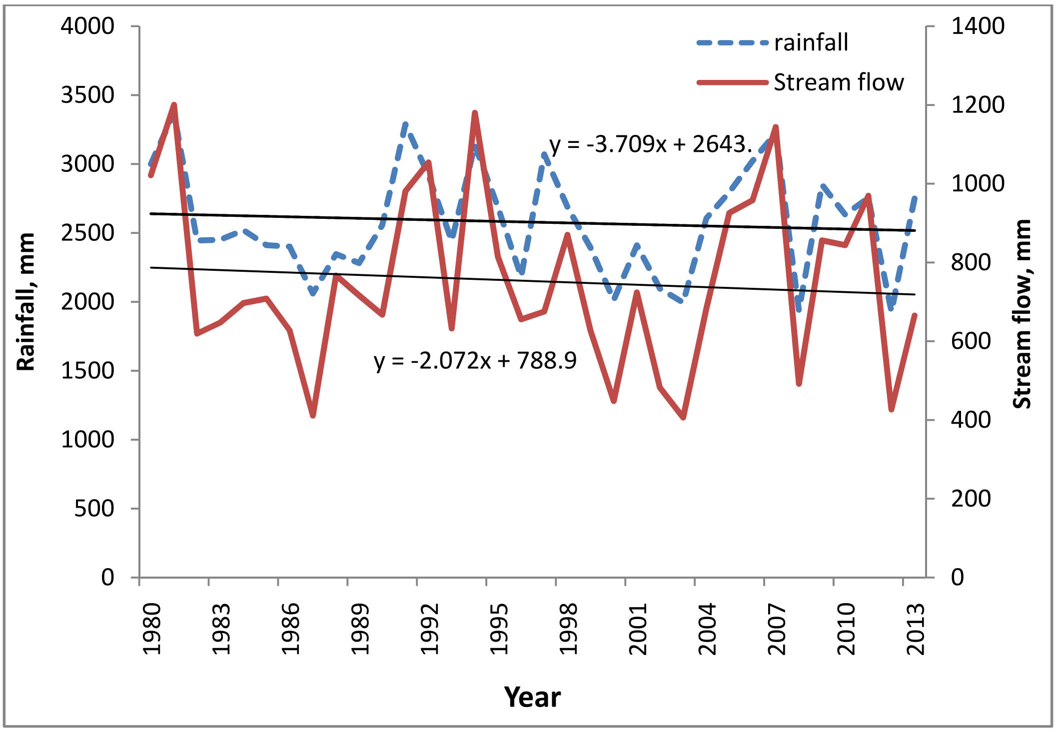

Fig. 4.48 Average annual rainfall and annual streamflow of Bharathapuzha basin

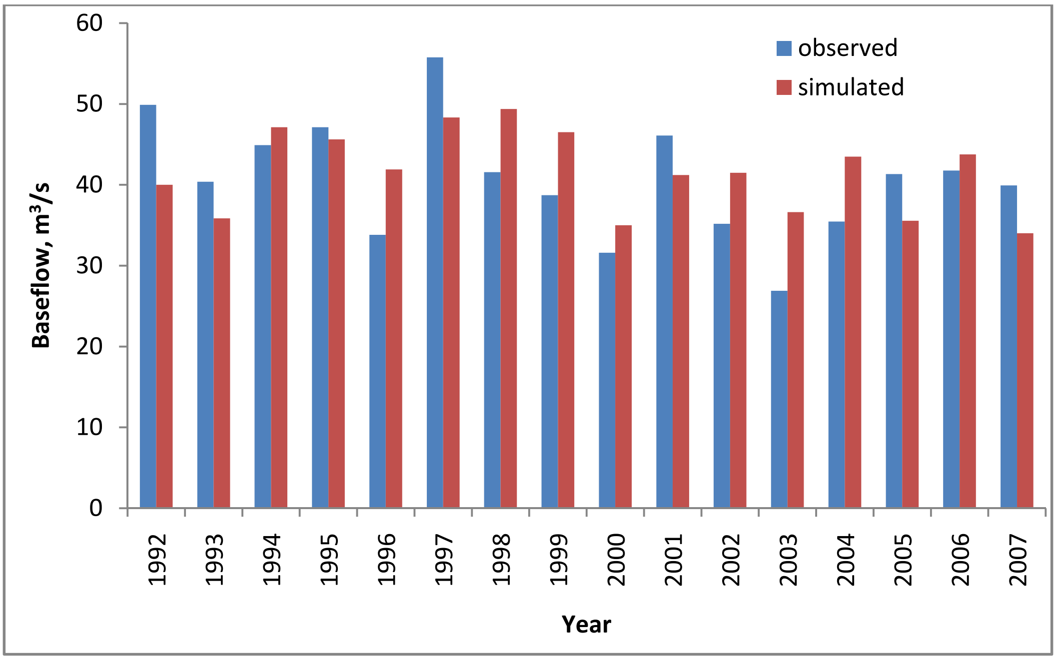

Fig. 4.49 Comparison of observed and simulated base flow

Table 4.14 Water balance components under changing climate scenario

	Precipitation (mm)	ET (mm)	SUR_Q (mm)	GW_Q (mm)	LAT_Q (mm)
1992-2000	2680.55	511.57	946.58	929.53	241.08
2001-2007	2567.46	463.26	980.67	876.96	230.78
RCP4.5_2046-58	1939.27	553.56	563.14	591.37	170.69
RCP4.5_2059-70	2074.88	581.67	544.48	619.65	193.92
RCP4.5_2076-87	2187.29	693.75	649.15	662.08	166.52
RCP4.5_2088-99	1920.06	595.47	536.62	541.23	190.04
RCP8.5_2046-58	2187.29	693.75	588.54	662.08	227.12
RCP8.5_2059-70	1850.06	595.47	496.32	561.54	190.04
RCP8.5_2076-87	2024.71	681.63	590.28	546.61	192.37
RCP8.5_2088-99	1819.74	626.20	528.31	498.31	158.10

In Table 4.14 it is seen that the water balance components in the catchment has also been affected by the decrease in precipitation and increase in temperature predicted for future on account of climate change. The earlier predictions of climate for the two scenarios indicate that the precipitation of the area may decrease by around 12 to 15 per cent by the middle of the century and by around 14 to 18 per cent by the end of the century and hence the river flow is also likely to be affected. From the trend analysis of rainfall, a 15 mm/year decrease in the annual rainfall was observed during the period 1971 to 2005. If the trend observed during this period continues in future, such a decrease in rainfall and streamflow can be expected in future. But in such a situation, it is worth mentioning that the predictions of climate change in the study was done on the basis of only one RCM, and more detailed research based on multiple RCM's is needed to make better conclusions. It has also been reported by researchers that multimodel ensembles predicting climate change reduces the uncertainty in impact studies (Cane *et al.*, 2013; Tebaldi and Knutti, 2007).

Water balance components viz., surface runoff (SUR_Q), lateral flow (LAT_Q), base flow (GW_Q) and evapotranspiration (ET) predicted for future for RCP4.5 and RCP8.5 are represented as percentage of the annual rainfall in Fig. 4.50 and 4.51 respectively. The water balance components exhibit variations between the periods and between scenarios. Analysis of the results showed that, in most cases, the contribution to base flow (GW_Q), surface runoff and evapotranspiration was almost equal unlike the current scenario prediction where the contribution to evapotranspiration was less.

ET ranges from 15 to 22 per cent of the annual rainfall in the current scenario while it has increased to 29 to 32 per cent in the RCP4.5 scenario and 32 to 35 per cent in RCP8.5 scenario. Lateral flow component is the lowest, comprising only 8 to 10 per cent of the total rainfall and there is no much variation for this component between the scenarios. Temperature is considered as a major factor controlling evapotranspiration (Heo *et al*., 2015) and the increase in temperature and decrease in precipitation will result in increased evapotranspiration (Abtew and Melesse, 2013). As rainfall decreases, humidity decreases, temperature increases and the clear sky helps in increasing the evapotranspiration. This increase in temperature predicted for the future scenarios may be the reason for increase in ET component in future. The contribution from surface runoff is less than that during the current scenario and the percentage contribution varies from 27 to 30 per cent during the future scenarios.

This analysis, based on possible changes in precipitation and temperature tries to illustrate the trend and magnitude of streamflow changes in a river basin.

4.11.2 Monthly Streamflow Prediction under Different Scenarios

Monthly average of streamflow predicted for the two periods 2041-2070 and 2071-2099 in comparison with the current scenario are given in Appendix XIV. The change in streamflow during 2041-2070 and 2071-2099 for both RCPs in comparison with current scenario are shown in Fig. 4.52 and 4.53 respectively. In both periods and scenarios, the streamflow was found to be less than that of the current scenario, for all months except August during 2041-2070.

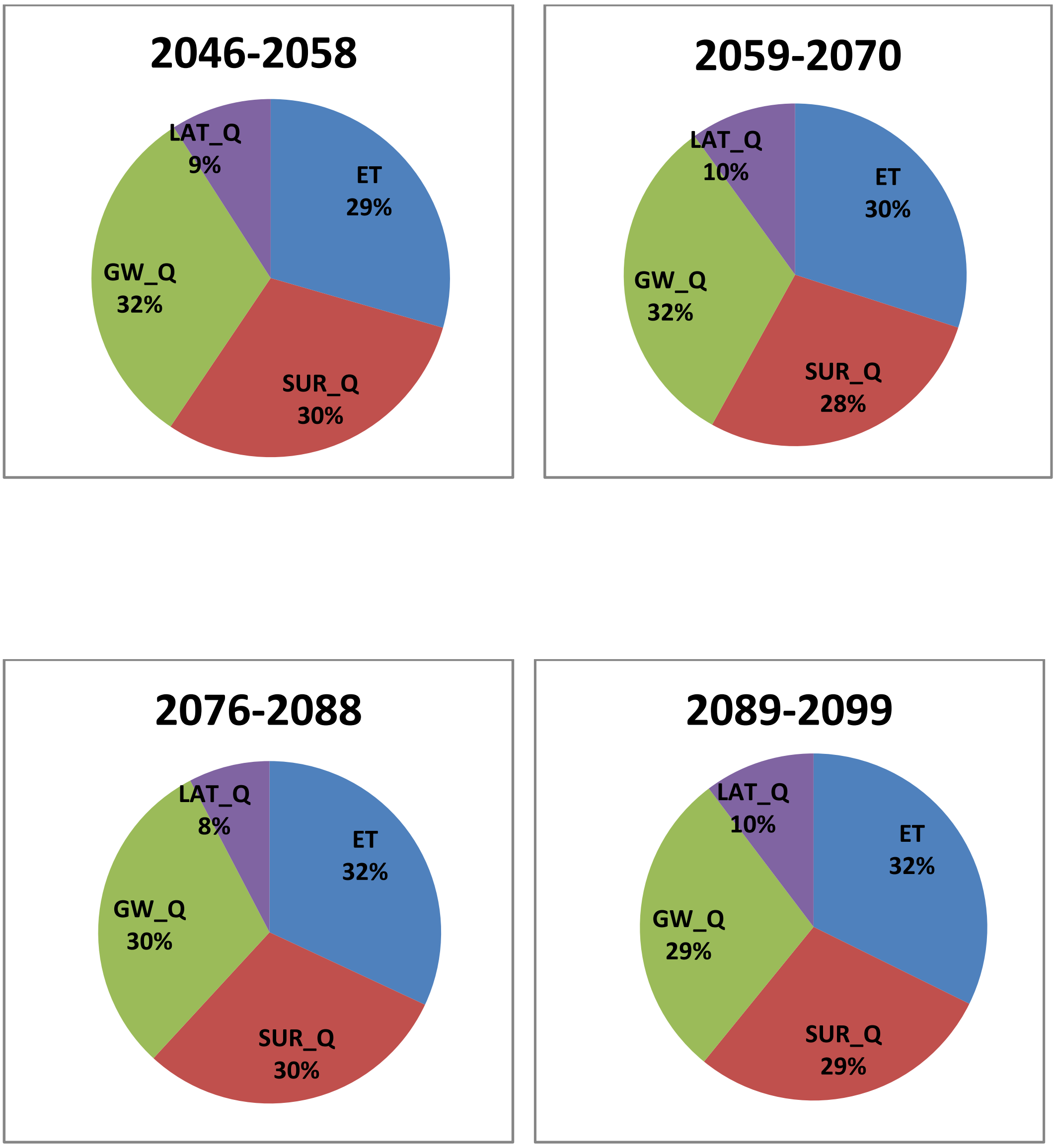

Fig. 4.50 Predicted water balance components in RCP 4.5 scenario

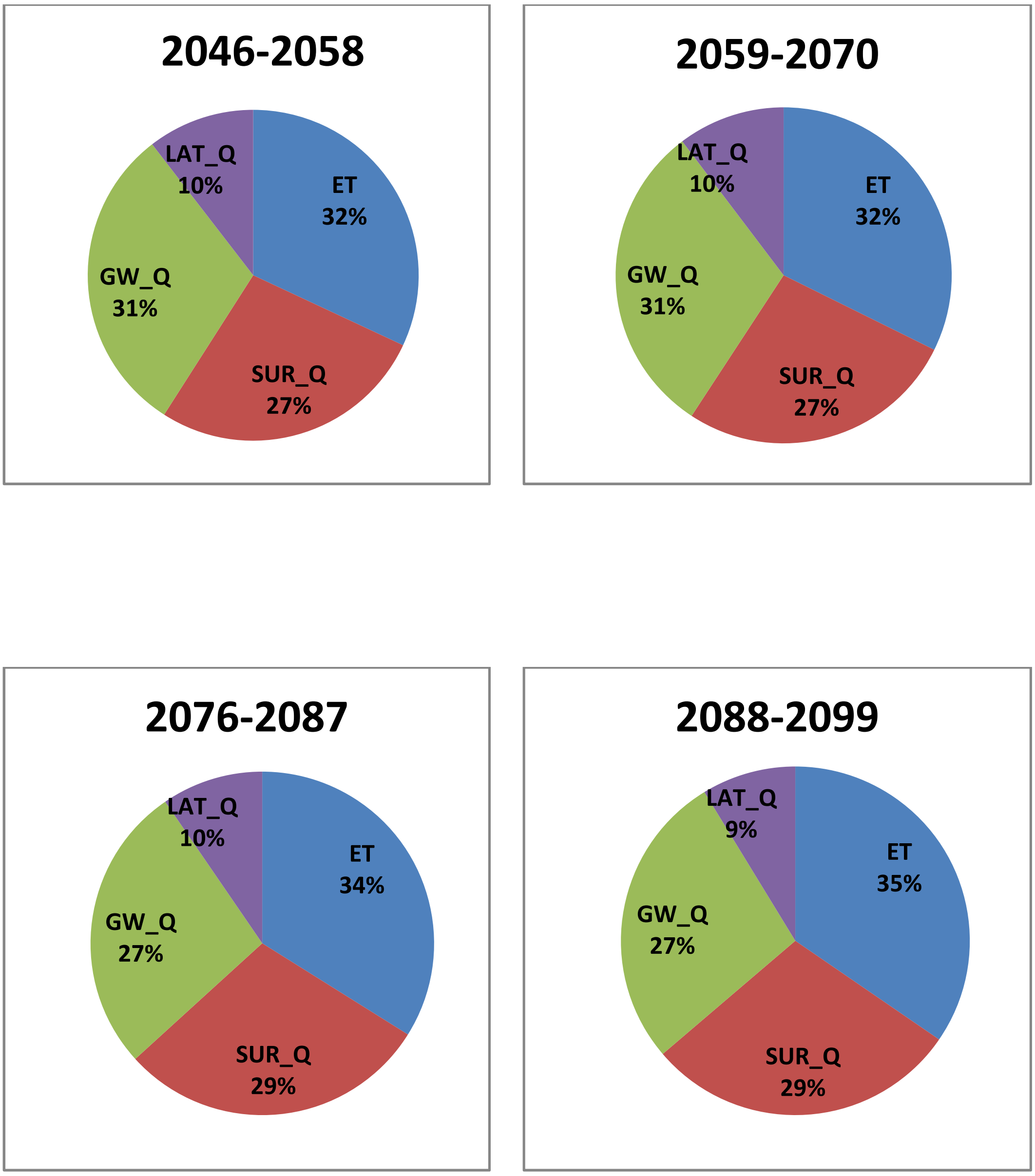

Fig. 4.51 Predicted water balance components in RCP 8.5 scenario

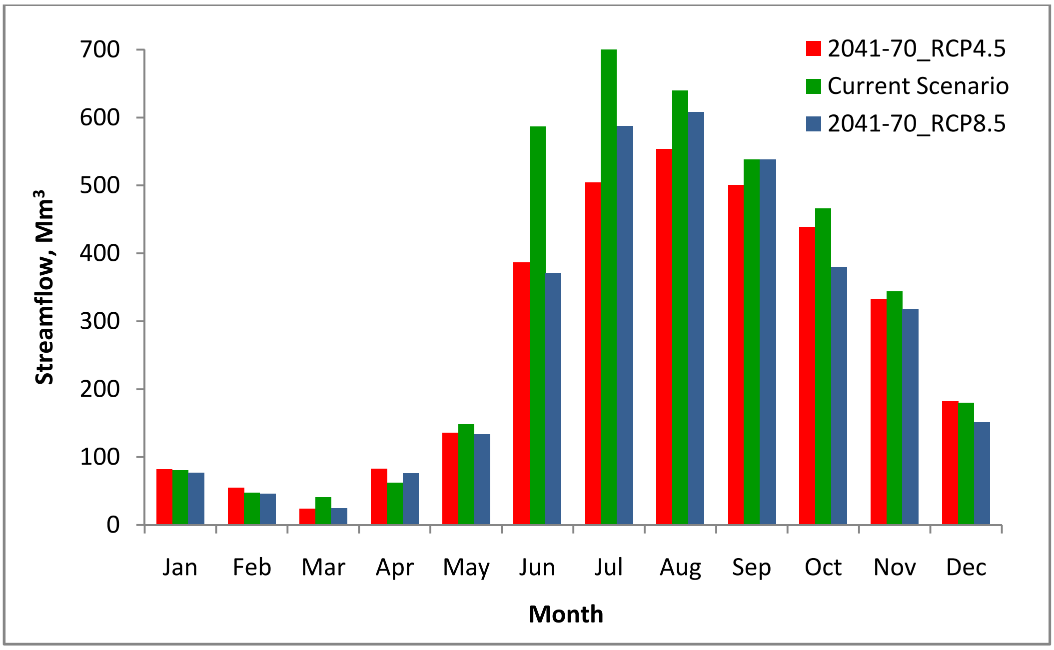

Fig. 4.52 Monthly future stream flow predicted (2041-2070) in comparison with the current scenario

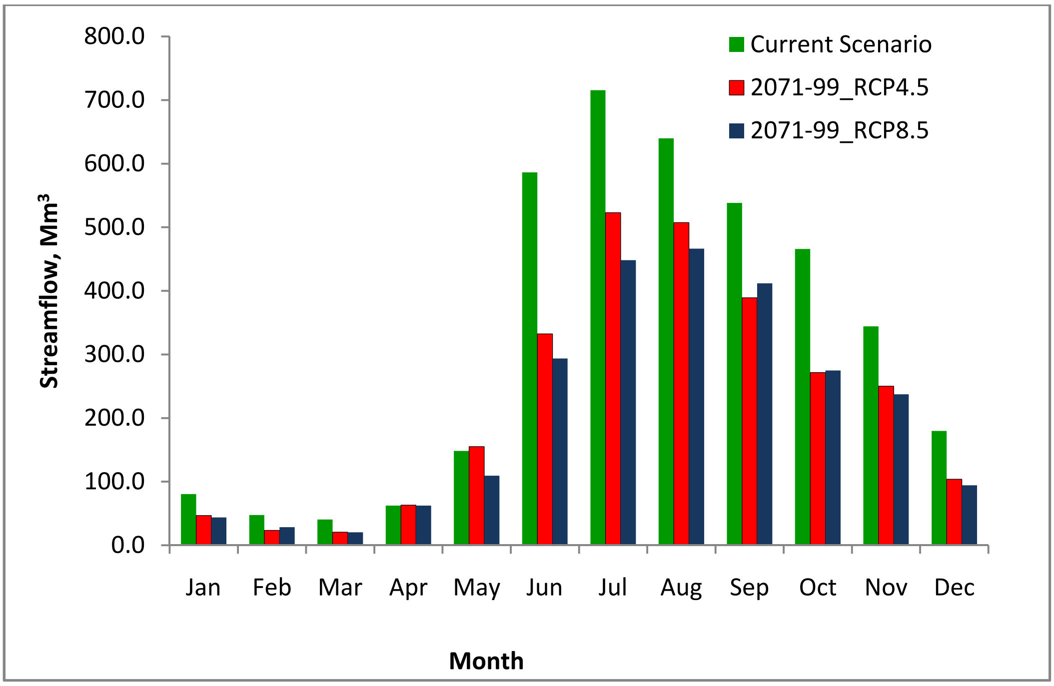

Fig. 4.53 Monthly future stream flow predicted (2071-2099) in comparison with the current scenario

In case of rainfall also, an increase in rainfall in August during 2041-2070 was predicted and this might have caused the increased flow during the month.

During 2041-70, the streamflow in RCP4.5 and RCP8.5 showed almost same variation from the current scenario streamflow. In most of the months, streamflow under RCP8.5 is less when compared to RCP4.5. RCP4.5 scenario developed by GCAM modelling team in US is a stabilisation scenario in which total radiative forcing is stabilised shortly after 2100. In this scenario, the emissions slightly increase to the middle of 21st century and then slightly decrease and stabilises to a value of 4.5W/m^2 by the end of the century (van Vuuren *et al.*, 2011). In RCP8.5 scenario, the emissions goes on increasing till the end of the 21st century and has a radiative forcing of 8.5W/m^2 to the end of the century. It is predicted that there may be up to 15 to 20 per cent decrease in streamflow by the end of the century if the worst situation of climate change continues. The decrease in streamflow in the changed scenarios may be mainly due to the factors like decreasing trend in precipitation and increasing trend in temperature. There are chances that other factors like increasing population, increase in demand for irrigation and changes in landuse can also add to it.

While comparing the monthly future streamflow predicted during 2071-2099 between the two scenarios, the streamflow in RCP8.5 is less than that under RCP4.5. It is also predicted that the climate will become drier and warmer in both scenarios in the future. RCP8.5 scenario corresponds to the pathway with the highest greenhouse gas emissions and the emissions continue to rise throughout the 21st century (Riahi *et al.*, 2011). This has caused increase in temperature levels, increased evapotranspiration and decrease in streamflow. A decrease of 6.6 to 27.7 per cent in annual streamflow was reported by Ma *et al.*, 2015 in both scenarios. A similar decrease in steamflow was also reported by Ouyang *et al.*, 2015 after using six global climate models from CMIP5 for simulating streamflow under RCP2.5, RCP4.5 and RCP8.5 scenarios. It is reported that the streamflow is likely to decline in the future, ranging from -6.9 to 0.8 per cent, mainly due to the increase in air temperature and evaporation. They also reported that the average monthly streamflow from all GCMs increased during August and September, but showed a decline during October to June, mainly due to the shift in the rainfall pattern.

Predicted monthly streamflow under different scenarios is given in Table 4.15 and the comparison with observed and current scenario streamflow shown in Fig. 4.54. The observed and simulated (current scenario) data for the period 1992 to 2007 show close correlation except for July and August, when there is peak flow in the catchment. During calibration of the model also this uncertainity in peak flow prediction was observed. Scientists have reported large uncertainty in discharge peaks during prediction with SWAT model (Rostamain *et al.*, 2010; Chu & Shirmohammadi, 2004). Tolson and Shoemaker (2004) have also reported that SWAT model is not designed to simulate extreme events and that it usually under predicts the peak flows. SWAT model uses a modified formulation of SCS curve number (CN) method to calculate surface runoff (Kolehmainen *et al.*, 2009) and this may be the reason for the uncertainty in the peak flows. In both future scenarios, the peak flow occurred one month later than that in the current scenario, mainly because of the changes in the predicted precipitation pattern.

Table 4.15 Monthly Stream flow as affected by climate change (Mm^3)

	Current Scenario	2041-70_RCP4.5	2071-99_RCP4.5	2071-99_RCP8.5	2041-70_RCP8.5
Jan	80.40	81.62	46.80	43.76	76.91
Feb	47.60	54.45	23.42	28.53	46.17
Mar	40.60	24.30	20.70	20.28	24.85
Apr	62.30	82.77	63.14	62.27	76.24
May	148.30	135.79	155.16	109.36	133.55
Jun	586.30	386.18	332.45	293.57	371.09
Jul	715.60	504.16	522.98	448.40	587.59
Aug	639.90	583.50	507.33	466.25	608.15
Sep	538.30	500.32	389.13	411.88	537.81
Oct	465.90	439.07	271.62	274.79	380.21
Nov	344.20	332.63	250.23	237.35	318.45
Dec	179.90	181.90	103.93	94.38	151.10

The decrease in flow in Bharathapuzha during the recent years has affected the livelihood of the people living nearby. Climate change, as discussed earlier, can be one of the several reasons for the decreasing flow over the years. Increasing temperature and decreasing precipitation over the years can be due to several other natural and manmade reasons. Riahi *et al*., 2011, based on a modelling framework, has reported that it is technically possible to limit the radiative forcing from RCP8.5 (worst condition with emission of 8.5 W/m^2) to lower levels (2.6 to 6 W/m^2). Hence necessary steps need to be undertaken to reduce the emission of greenhouse gases to the atmosphere and also to mitigate the ill effects of climate change.

4.11.3 Annual Streamflow Prediction under Different Scenarios

The annual total water yield at Kumbidi gauging station is based on the combined behavior of upstream subcatchments. The annual observed yield of Kumbidi gauging station was compared with the predicted future streamflow values. The predicted annual future streamflow during 2046-69 and 2076-99 for RCP4.5 and RCP8.5 in comparison with the observed streamflow are plotted in Fig. 4.55 and 4.56 respectively. For convenience of plotting the graph and analyzing the results, the average of four years data was taken and plotted. The figure shows that the annual river flow during the predicted periods for both RCP4.5 and RCP8.5 are very less than the present annual river flow. In both scenarios, to the end of the periods, the streamflow is slightly increasing, though not significant. The decrease in annual streamflow was more significant in case of RCP4.5 than in RCP8.5 during 2041-2070. Cousino *et al.,* 2015 also reported that while using CMIP5 data for the mid century, the streamflow under RCP4.5 was reduced by 24 per cent and under RCP8.5 it decreased only by around 10 per cent. During 2071-2099, the streamflow under RCP8.5 is less than that under RCP4.5 though there is no significant difference between the two. Impact of future climate change may adversely affect the water availability scenario of the basin which is already under water stress and is highly affected by the increasing population and trend for urbanisation.

4.11.4 Impact of Climate Change on Sediment Loss from the Catchment

Predicted monthly sediment loss under different scenarios in comparison with present loss was analysed. Annual sediment loss for the two climate scenarios (RCP4.5 and RCP8.5) during 2046-2070 and 2076-2099 were predicted and are plotted in Fig. 4.57 and 4.58 respectively. Although the streamflow in the two scenarios during 2046-2070 is almost on par during a few years, in most years the sediment loss in RCP4.5 scenario is considerably lower than the RCP8.5 scenario. Coming to the end of the century, the sediment loss in RCP8.5 scenario is greater than RCP4.5 scenario in almost all years, and the annual sediment loss goes up to 7 to 9 t/ha, from the present condition of 2.5 to 4 t/ha.

For analysing the monthly variation of sediment loss during different scenarios, a graphical representation as shown in Fig. 4.59 was made. Maximum sediment loss is observed in July and August during the South-West monsoon period.

Sediment loss during January to April is very meagre when the monthly streamflow from the basin is also less than 75 Mm^3. The sediment loss in RCP4.5 scenario was in general less than that in RCP8.5 scenario, except a few months during 2041-2070. The watershed characteristics need to be assessed in detail and proper mitigation measures including watershed interventions need to be adopted in time to reduce the loss of the fertile soil by erosion. The changes in landuse/landcover also need to be accounted while planning these measures.

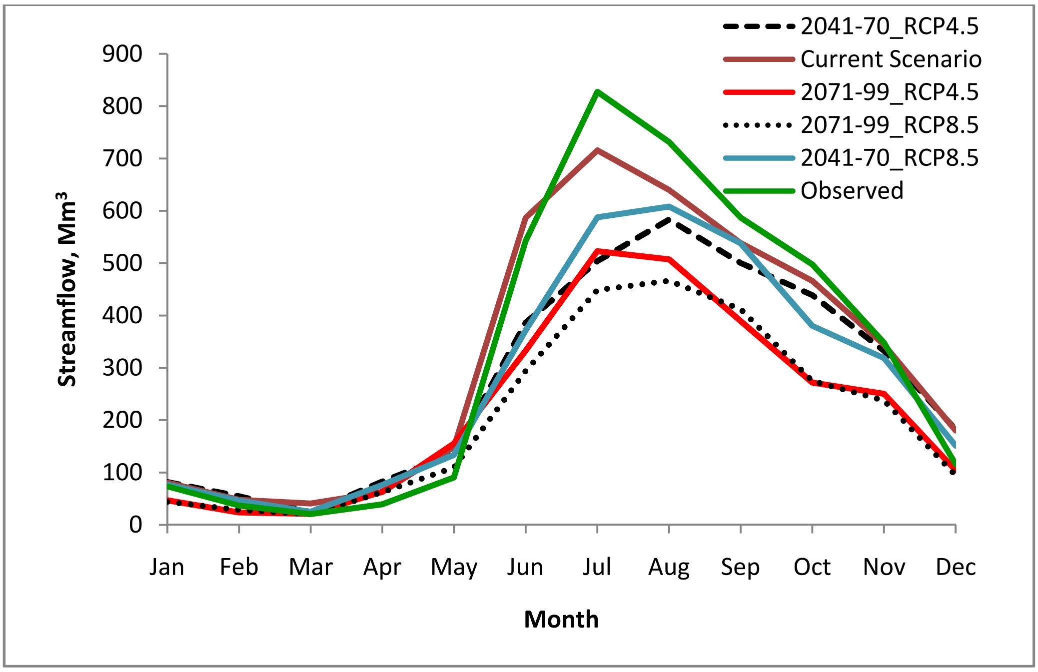

Fig. 4.54 Predicted monthly streamflow under different scenarios in comparison with observed and current scenario stream flow

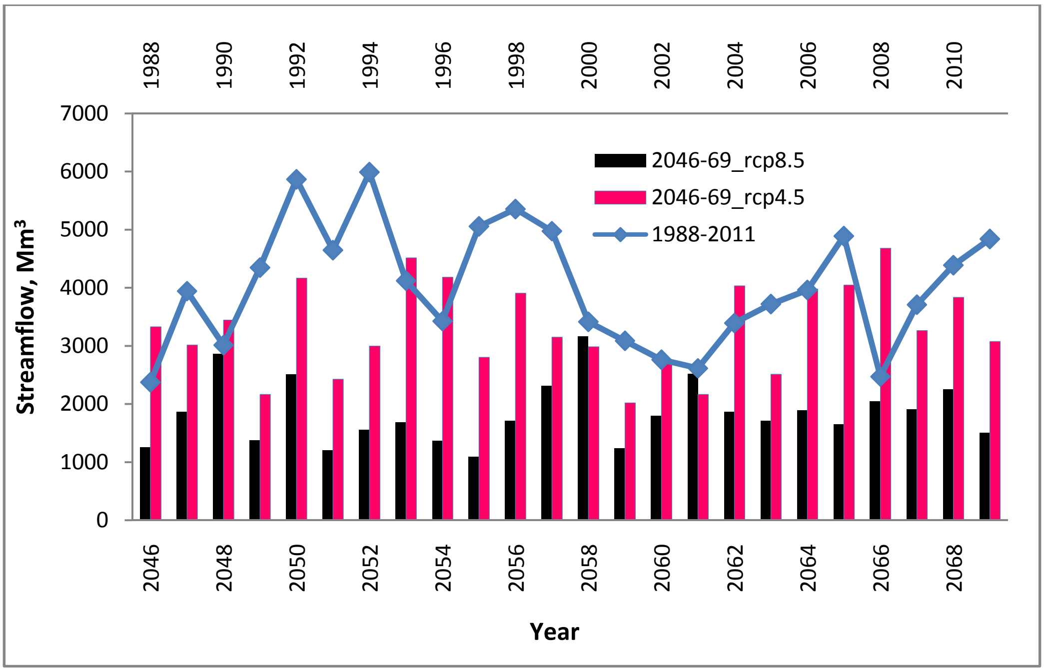

Fig. 4.55 Predicted annual streamflow during 2046-69 in comparison with observed stream flow

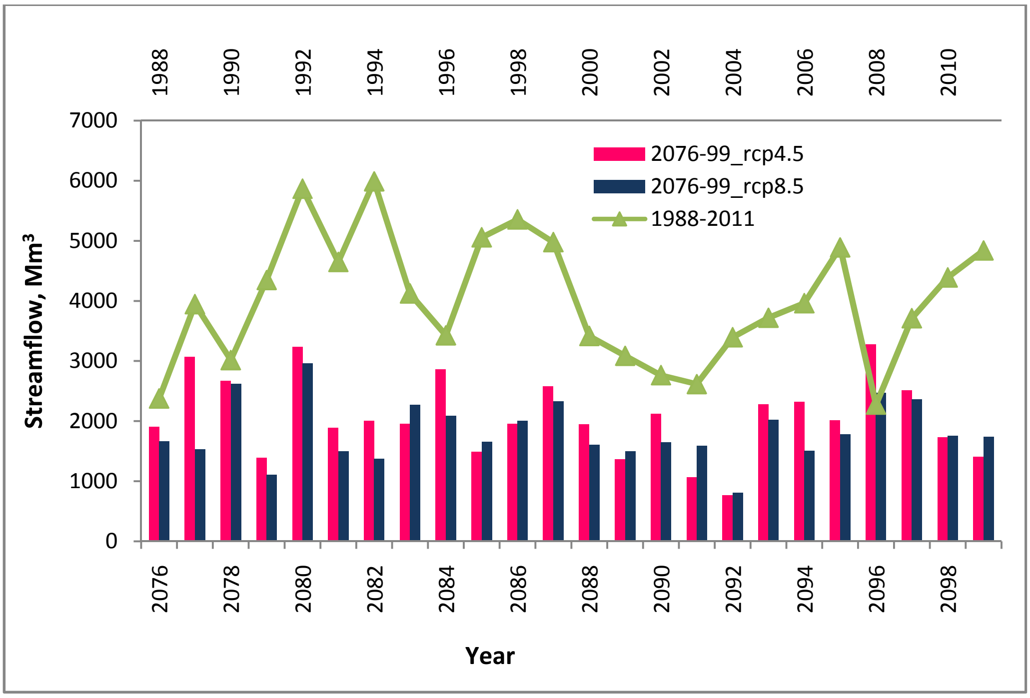

Fig. 4.56 Predicted annual streamflow during 2076-99 in comparison with observed stream flow

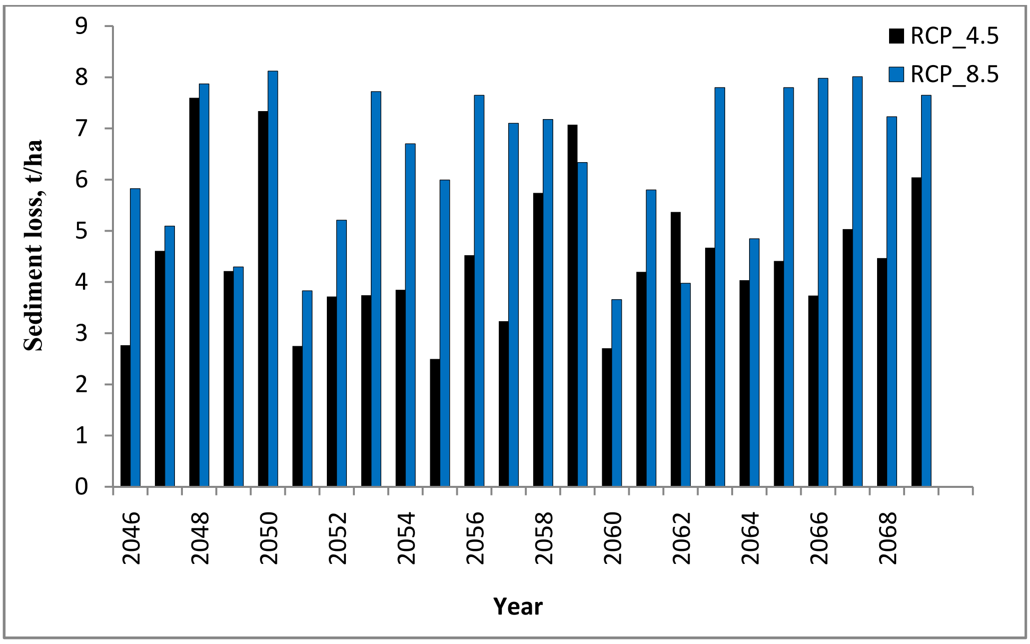

Fig. 4.57 Annual sediment loss for the two scenarios during 2046-2070

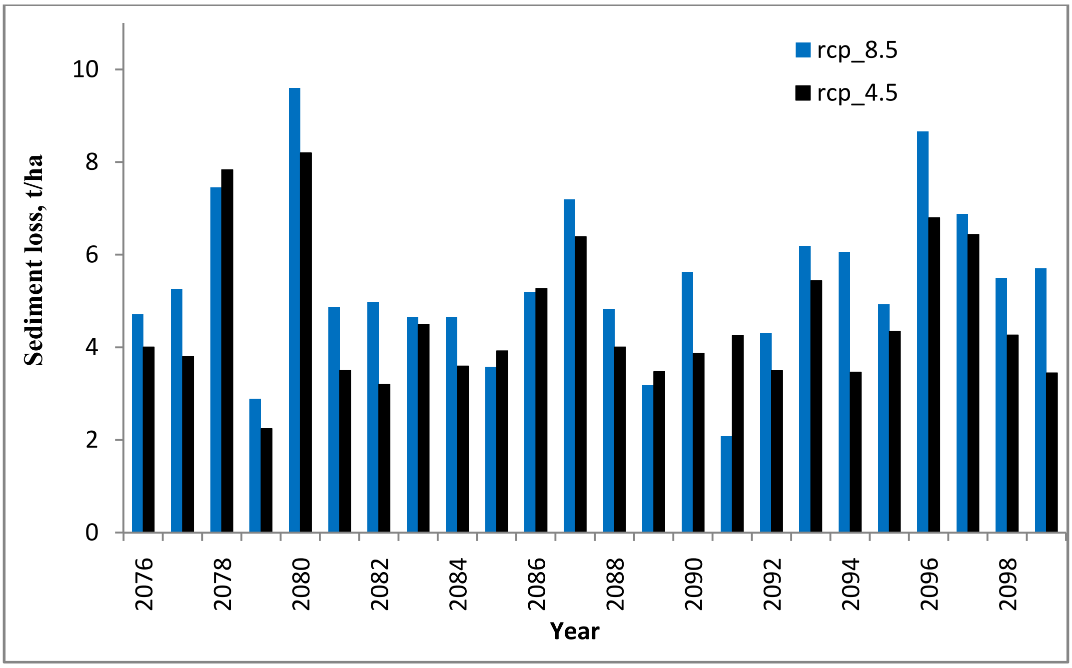

Fig. 4.58 Annual sediment loss during the two scenarios during 2076-2099

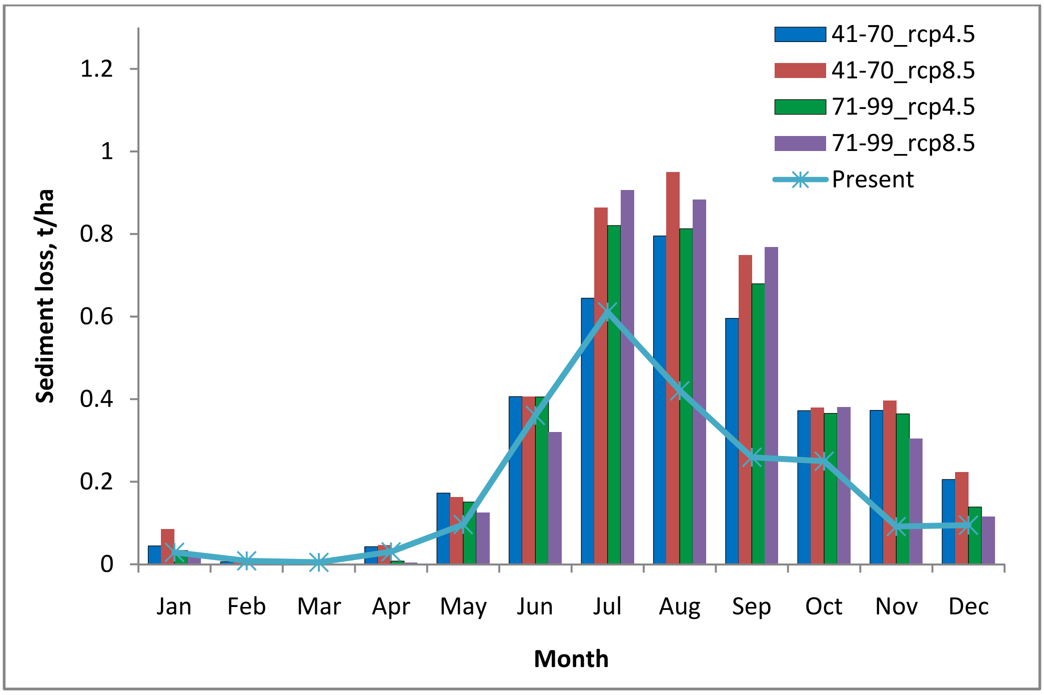

Fig.4.59 Monthly sediment loss under different scenarios

4.12 IMPACT OF WATERSHED INTERVENTION ON RIVER HYDROLOGY

Watershed development programs are implemented in India and in the state of Kerala for augmenting surface and groundwater resources mainly through rainwater harvesting. The hydrological impacts of large-scale implementation of watershed interventions can be significant. Therefore, the impacts of such changes on the hydrology need to be analyzed using a modelling framework. Along with climate change, this can also play an important role in the hydrology of the river basin.

Data on watershed development activities in the study area, mainly the construction of Water Retention Structures (WRS), was collected from different government departments. The field level study was restricted to selected watersheds in the Kunthipuzha subbasin which has a gauging station at Pulamanthole and joins the main river at Kudallur near Thrithala. This information was later scaled up to the entire Bharathapuzha river basin for use in the hydrologic model.

4.12.1 Land use Land cover Classes of the Area

Using temporal Resourcesat-1 Linear Imaging Self scanning Sensor (LISS)-III data, National Remote Sensing Centre (NRSC) under Natural Resources Census (NRC) Project has prepared Land Use Land Cover (LULC) data for Kerala state. LULC data is regrouped for use with emphasis on land cover classes and is published in the Bhuvan website. The details of LULC classes of the three districts through which the river is flowing in Kerala was taken from the site for analysis and is given in Table 4.16.

The land use land cover classes comprises among other things water bodies, reservoirs, lakes and ponds which represent areas with surface water in the form of ponds, reservoirs, check dams, VCB’s and other water storage structures. The increase in area under this category was taken into consideration to account for the change in surface area of the water storage structures that have come up in the area during the period. The average per cent change in surface area of waterbodies with respect to the total geographical area was calculated.

Table 4.16 Changes in Land use Land cover classes of various districts

	Thrissur District		Palakkad District		Malappuram District	
	Area (Km^2)					
LULC class	**2005**	**2011**	**2005**	**2011**	**2005**	**2011**
Builtup, Urban	20.5	111.8	37.24	40.67	23.63	22.49
Builtup, Mining	1.1	6.3	0.05	2.36	12.33	12.56
Agriculture, Plantation	1575.0	1306.9	1985.8	1763.1	2134.1	2024.3
Forest, Evergreen/ Semi evergreen	411. 8	441.8	841.3	837.5	537.23	62.94
Forest/Forest Plantation	119.6	148.9	86.5	90.8	176.3	72.61
Grass/Grazing	2.3	2.3	10.01	9.96	2.57	2.58
Barren/unculturable/ Wastelands, Sandy area	3.6	4.9	11.23	85.06	75.3	14.05
Wetlands/Water Bodies, Inland Wetland	32.2	24.7	5.79	4.3	17.3	21.95
Waterbodies, Reservoir/ Lakes/Ponds	**26.99**	**31.7**	**48.91**	**59.42**	**0.08**	**0.16**
Builtup,Rural	18.73	235.97	3.8	106.29	12.36	186.23
Agriculture,Crop land	347.0	298.8	646.8	746.06	297.18	243.71
Agriculture,Fallow	30.22	0.78	2.16	2.37	0.04	0.05
Forest,Deciduous	328.6	334.06	237.97	247.54	63.69	192.2
Forest,Scrub Forest	14.76	14.6	185.26	184.5	60.69	2.58
Barren/unculturable/ Wastelands, Scrub land	43.76	20.76	158.68	156.2	118.6	0.67
Barren/unculturable/ Wastelands/rocky	5.73	3.93	87.6	3.95	21.4	2.01
Wetlands/Water Bodies, River/Stream/canals	50.05	43.9	43.1	56.2	75.29	69.64
Total Area	3032		4392		3548	

The per cent increase in area of waterbodies with respect to the total area of the district ranges from 0.01 per cent in Malappuram district to 0.23 per cent in Palakkad district (Table 4.15).

4.12.2 Ground Water Level

The monthly groundwater levels of eight observation wells in the study area were collected from the State Groundwater Department. The groundwater level during different seasons was analysed and are shown in Fig. 4.60 to 4.67. During summer, the depth to water table is having an increasing trend, which indicates lowering of water table. The decline in water table may be due to decrease in natural recharge and increase in drawal for domestic and irrigation needs.

4.12.3 Irrigated Area

The change in irrigated area in the two districts through which the river is draining (Malappuram and Palakkad) was also analysed. The details of net irrigated area and area irrigated from tube wells in the Palakkad and Malapuram districts are given below (Table 4.17).

Table 4.17 Details of irrigated area in the districts drained by Bharathapuzha

District	Net irrigated area (ha)			Area irrigated from tube wells (ha)		
	2003-04	2006-07	2013-14	2003-04	2006-07	2013-14
Palakkad	71005	79344	90021	965	1481	10316
Malappuram	24077	24314	30621	6113	4619	942

Source: Department of Statistics and Economics

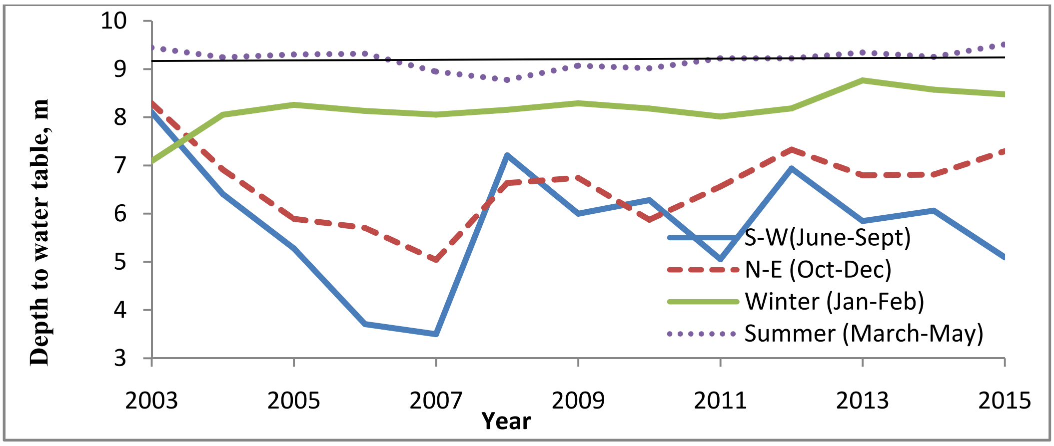

Fig. 4.60 Seasonal variations in depth to water table in open well No. 132

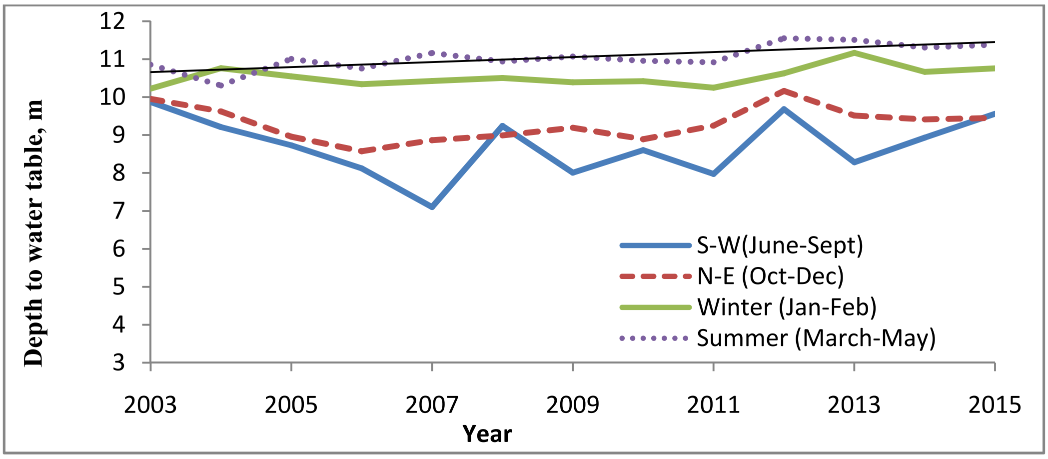

Fig. 4.61 Seasonal variations in depth to water table in open well No.135

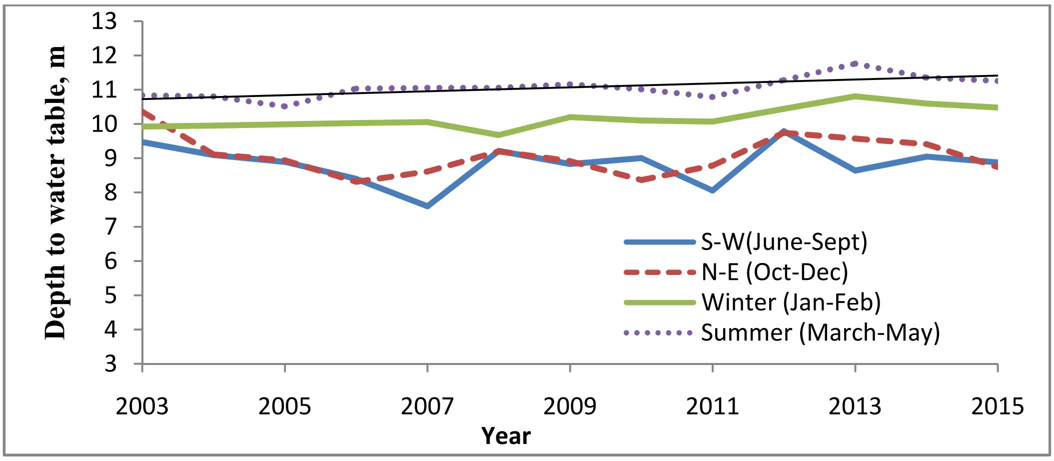

Fig. 4.62 Seasonal variations in depth to water table in open well No.PKD-S10

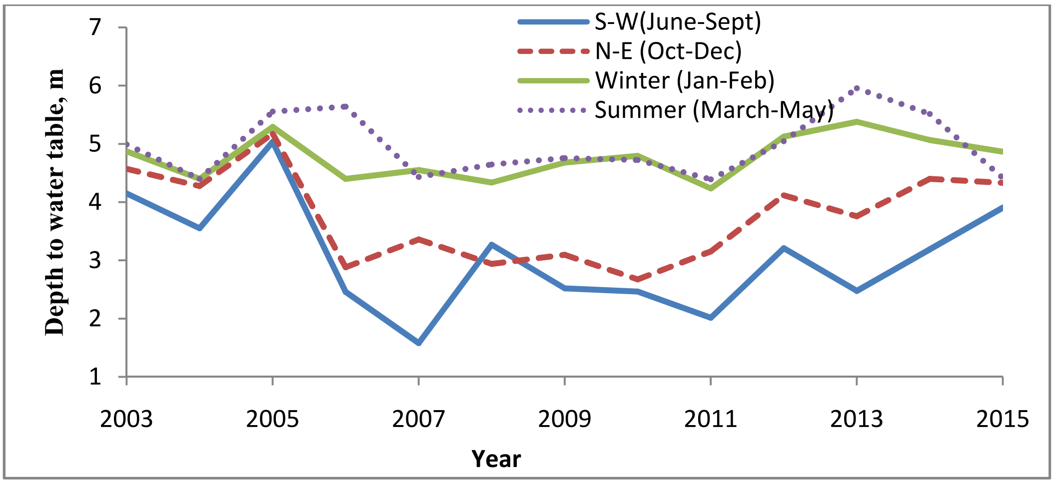

Fig. 4.63 Seasonal variations in depth to water table in open well No.PKD-S14

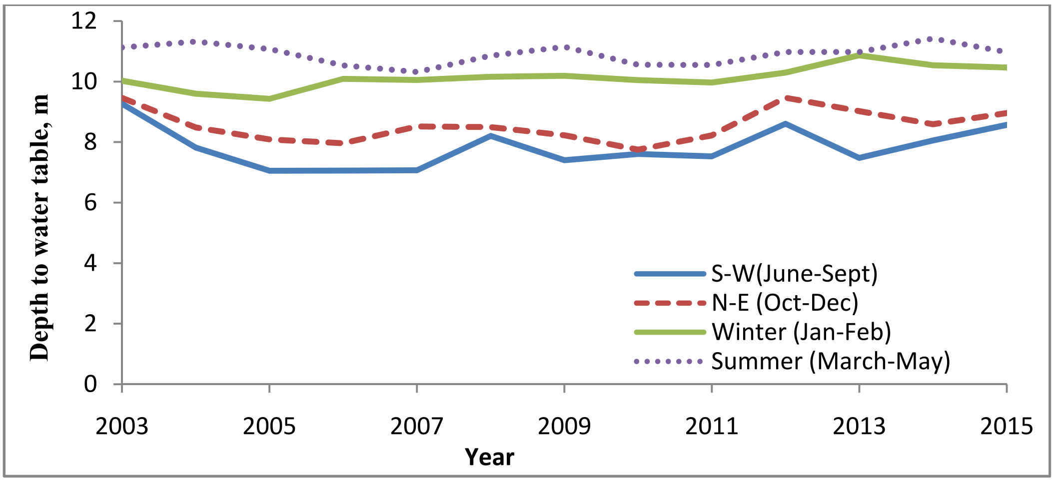

Fig. 4.64 Seasonal variations in depth to water table in Bore well No. 138

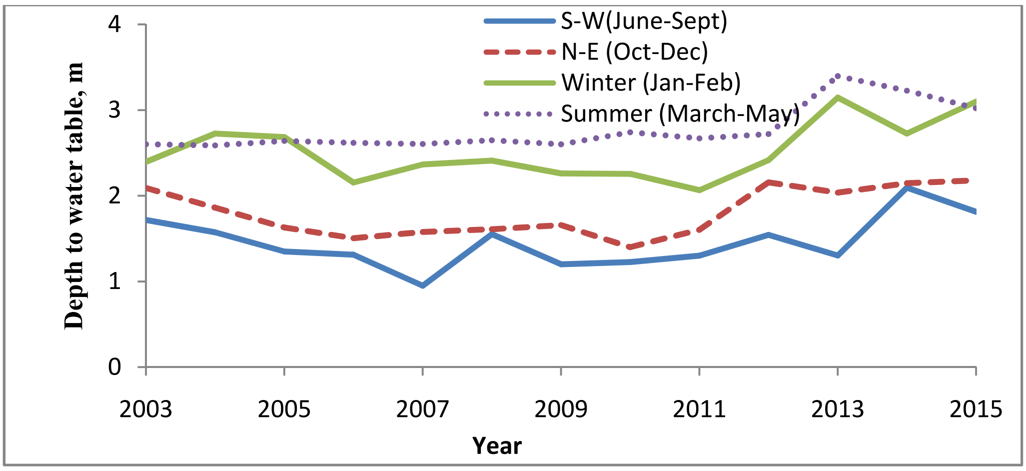

Fig. 4.65 Seasonal variations in depth to water table in Bore well No.154

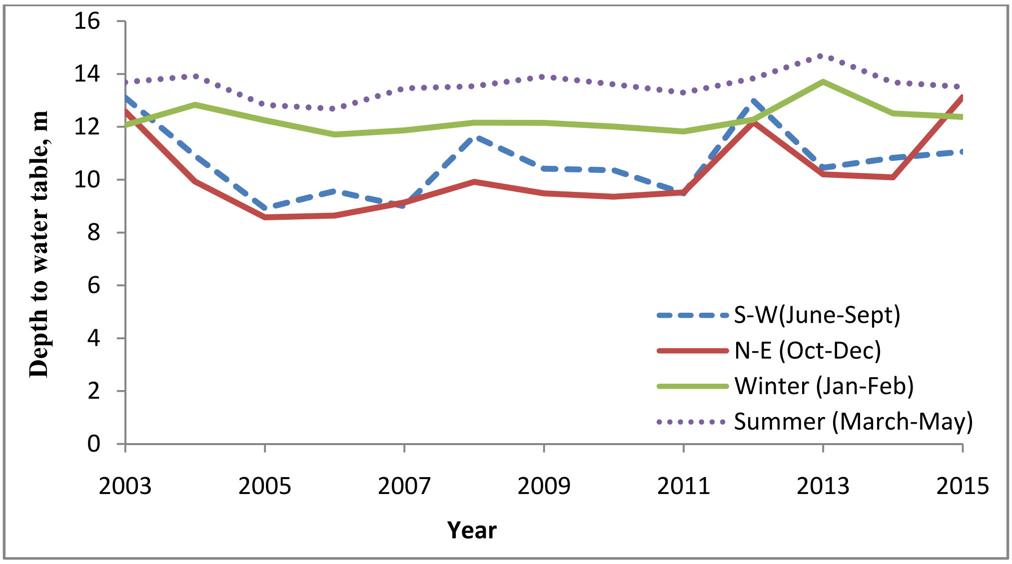

Fig. 4.66 Seasonal variations in depth to water table in Bore well No.155

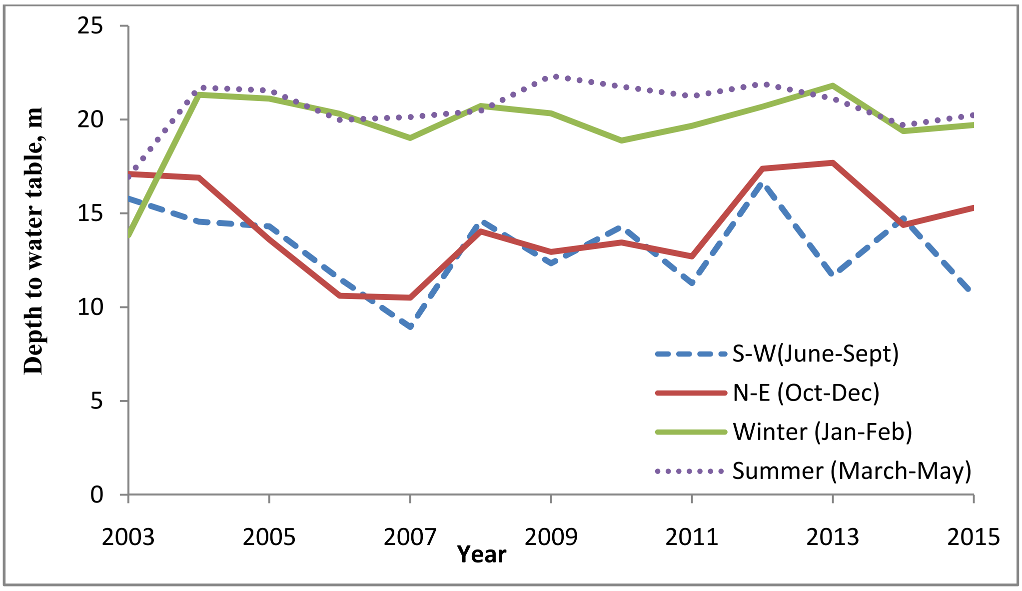

Fig. 4.67 Seasonal variations in depth to water table in Bore well No.156

The net irrigated area as well as the area irrigated from tube wells has increased in both districts. The depth to water table during 2003 to 2015 is having an increasing trend indicating the lowering of water table. These facts give indication that the groundwater extraction has increased and reduction in natural recharge has occurred during the years.

4.12.4 Details of Water Storage Structures

Details of the major water storage structures constructed in the Kunthipuzha subbasin during 2005-2015 were collected from the state irrigation department and through field survey and is given in Appendix XIV. On the basis of the data collected during field survey, the average depth area volume relationship of the water storage structures in the area was derived (Table 4.18).

Table 4.18 Details of water storage structures in the basin

	Average Area (m^2)	Average depth (m)	Average volume (m^3)
Check dams	800x15	1.2	14400
Percolation ponds	40x40	1.8	2880
Water harvesting pits	1.5x1.5	1.0	2.25
Vented cross bars	900x12	1.5	16200

Analysing the depth area volume relationships of all water harvesting structures constructed through watershed management, it is seen that retention structures like check dams and VCB's are more in number and percolation ponds are only a very few in number. Average depth of water stored in the retention structures helped to determine the area volume relationship. Hence, the average depth of the WRS was taken as 1.2 for arriving at the volume of water retained.

4.12.5 Criteria for Analysing the Impact of Watershed Interventions

The total storage capacity of Water Retention Structures (WRS) was then estimated based on the change in land use under the category of water bodies and on the average depth area volume relationships obtained from field. The increase in area in each subbasin was calculated separately based on the per cent changes considered. The increase in area under water bodies in the individual subbasins corresponding to 0.05, 0.1 and 0.2 per cent are given in Appendix XV.

In SWAT, all the WRS in a subbasin are pooled together as a single reservoir. For analyzing the impact of the water retention structures coming up in the area, three levels level 1, level 2 and level 3 with 0.05, 0.1 and 0.2 per cent of the subbasin area additionally coming under the land use water bodies were selected. The corresponding increase in storage volume was also calculated and this increase in storage was given as input to SWAT in the form of reservoir input.

4.12.6 Impact of Watershed Interventions on Monthly Streamflow

Monthly streamflow simulated for the period 2007 to 2011 without adding the WRS and after adding the WRS (0.05 per cent increase in surface area) are given in Table 4.19. The simulated monthly streamflow after adding WRS @ 0.1 per cent and 0.2 per cent increase in surface area are given in Table 4.20.

Table 4.19. Simulated monthly streamflow during 2007-2011 with (0.05 per cent increase in surface area) WRS and without WRS

	Simulated streamflow without WRS					Simulated streamflow with WRS (0.05%)				
	2007	**2008**	**2009**	**2010**	**2011**	**2007**	**2008**	**2009**	**2010**	**2011**
January	39.08	39.44	12.82	53.64	97.63	43.24	43.15	16.02	55.93	99.42
February	5.09	10.65	2.79	10.93	34.69	5.57	10.73	2.59	12.12	43.37
March	2.01	19.49	8.17	2.89	8.11	1.41	29.63	8.10	2.65	8.47
April	5.24	5.89	6.07	9.82	30.96	11.97	7.34	5.67	16.21	28.38
May	17.75	14.52	7.74	35.45	17.3	19.01	20.86	10.59	29.27	13.43
June	744.9	292.6	114.5	477.9	534.5	711.5	266.1	102.7	413.2	504.3
July	1286	373.5	953.2	550.9	410.6	1263	359.2	903	521.2	401.9
August	670.5	271.0	337	370.6	612.4	659	267.6	329	367.3	605.5
September	782.0	317.1	354.3	370.3	585.5	783.1	315.5	346.1	363.5	587.2
October	446.7	364.9	278.7	445.4	451.5	449.5	351.8	272.7	434.9	448.8
November	249.3	128.2	324.7	332.2	416.0	257.9	131.3	318.6	333.2	421.5
December	131.2	68.22	111.4	173.7	155.9	133.7	71.64	113.1	177.8	162.7

Table 4.20 Simulated streamflow with 0.1 and 0.2 per cent increase in surface area of WRS

	Streamflow with WRS (0.1%)					Streamflow with WRS (0.2%)				
	2007	**2008**	**2009**	**2010**	**2011**	**2007**	**2008**	**2009**	**2010**	**2011**
Jan	66.71	69.41	31.84	65.42	110.79	84.02	86.55	50.76	84.76	123.66
Feb	20.80	24.44	9.87	24.15	52.79	33.66	35.44	20.61	31.76	47.30
Mar	8.27	26.93	7.85	7.14	16.18	15.09	21.17	9.333	15.29	26.03
Apr	10.28	11.86	12.34	10.58	18.71	16.15	11.55	11.84	10.79	14.27
May	13.79	17.03	16.7	22.05	9.97	8.32	9.50	4.932	19.47	11.15
Jun	613.7	196.78	72.71	282.5	359.68	394.7	112.9	32.46	249.2	281.79
Jul	1160	300.39	724.03	416.8	342.72	979.2	264.2	594	381.5	339.7
Aug	681.1	264.32	376.79	349.4	566.21	664.7	278.0	395.1	389.8	515.7
Sep	780.7	308.48	338.47	333.7	575.61	698.9	289.1	372.7	365.3	565.2
Oct	498.4	301.25	255.31	340.2	411.60	511.1	303.6	284.4	370.6	432.09
Nov	311.0	144.97	274.42	309.4	424.15	333.2	173.9	277.4	339.7	412.38
Dec	166.1	82.82	124.32	195.0	195.98	181.6	106.5	150.3	233.0	220.23

The percent change in streamflow after adding the WRS (with 0.05, 0.1 and 0.2 per cent increase in surface area of water bodies) with respect to the simulated flow before adding the retention structures was calculated and is depicted in Fig. 4.68, 4.69 and 4.70 respectively. From these graphs it is clear that the river flow during the summer months (base flow) increased after adding the WRS. The per cent increase in flow was high during the months of January to April when the river has a very lean flow. Rather than utilizing the stored water in the upper reaches for irrigation and domestic purpose, the increase in summer flow will be helpful for maintaining a better environmental flow regime. Now a days, during summer when the river is having a very lean flow, sufficient water is not available even to support the critical ecosystems. In such a situation, adding WRS can increase the summer flow and it will be helpful for supporting the environmental flows.

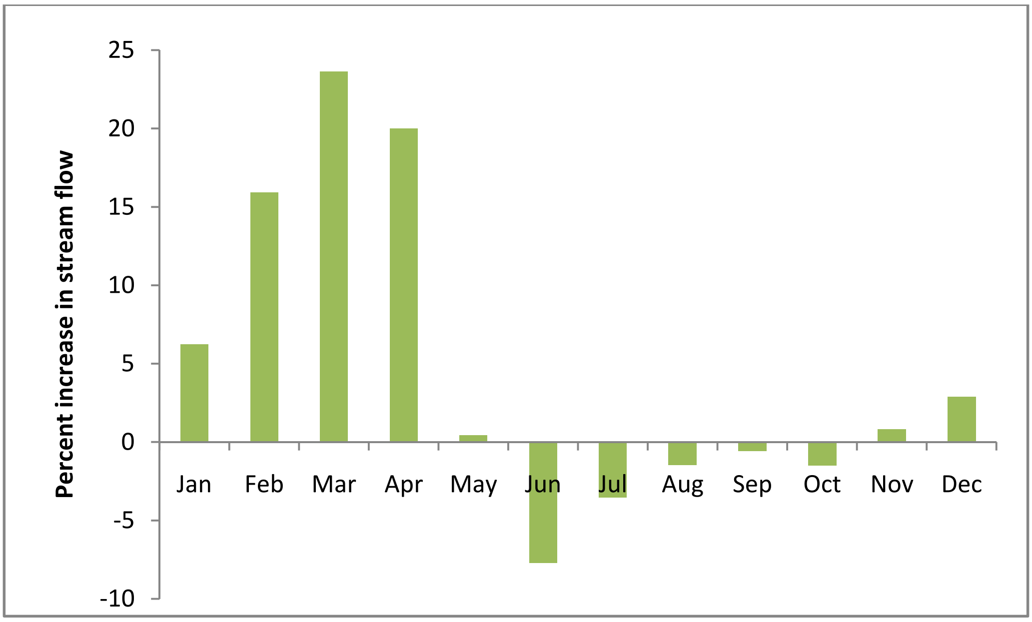

Fig. 4.68 Percent change in stream flow after adding reservoirs to subbasins (0.05% increase in area of water bodies) during 2007-2011

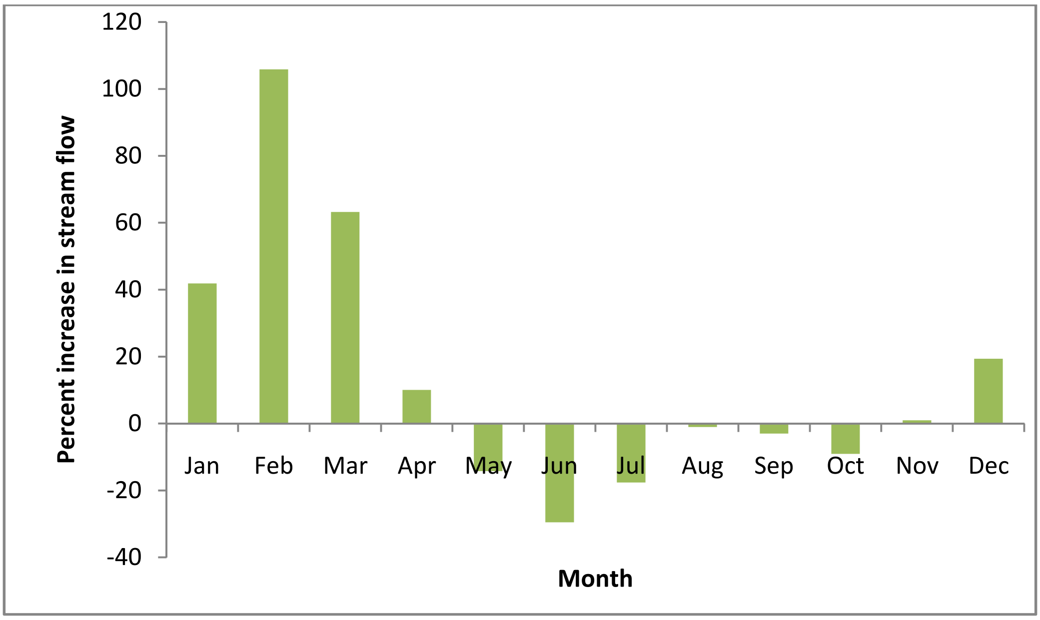

Fig. 4.69 Percent change in stream flow after adding reservoirs to subbasins (0.1% increase in area of waterbodies) during 2007-2011

4.12.7 Impact of Watershed Interventions on Annual Streamflow

The impact of adding WRS in the basin was also studied on the basis of the annual streamflow. The annual streamflow simulated under different conditions are given in Appendix XVI. The annual streamflow is found to be decreasing with increasing capacity of the water storage structures (Fig. 4.71). Though the decrease in annual streamflow is small (1 to 6 per cent), the redistribution of peak flow to the summer months is of great significance. This redistribution may also help in increasing the groundwater storage also, which need to be studied in detail with the help of groundwater flow models which can be associated to SWAT.

4.12.8 Impact of Watershed Interventions on Future Streamflow and Sediment Loss

A scenario assessment that includes the combined effects of climate change and watershed interventions would be of great interest for water resource planners and hence, the impact of both aspects together was also studied. The prediction for the period 2041-2069 was only used in this study, since it was not justifiable to extrapolate the increase in WRS in the basin to a long term to get the data for the period 2071-2099. Prediction for the period 2041-2069 under the two scenarios RCP4.5 and RCP8.5 was done with the assumption that the WRS were added by 2030 which increases the surface area of the WRS by 0.1 per cent. The monthly streamflow with added WRS under climate change was compared with that of no WRS under the same climate change scenario. The monthly streamflow with and without WRS (0.1 per cent increase in surface area of WRS) during 2041-2070 are shown in Fig. 4.72 and 4.74 respectively. The per cent change in streamflow after adding the WRS under RCP4.5 and RCP8.5 during the same period is shown in Fig. 4.73 and 4.75 respectively. In both scenarios, it is seen the streamflow increases for almost all months except March to May or June. The summer rains received during this period may be stored in the water retention structures, thus decreasing the streamflow. The monthly sediment loss without WRS was compared with the sediment loss with 0.1% increase in WRS and is given in Fig. 4.76. It is seen that sediment loss decreases in almost all months with added WRS.

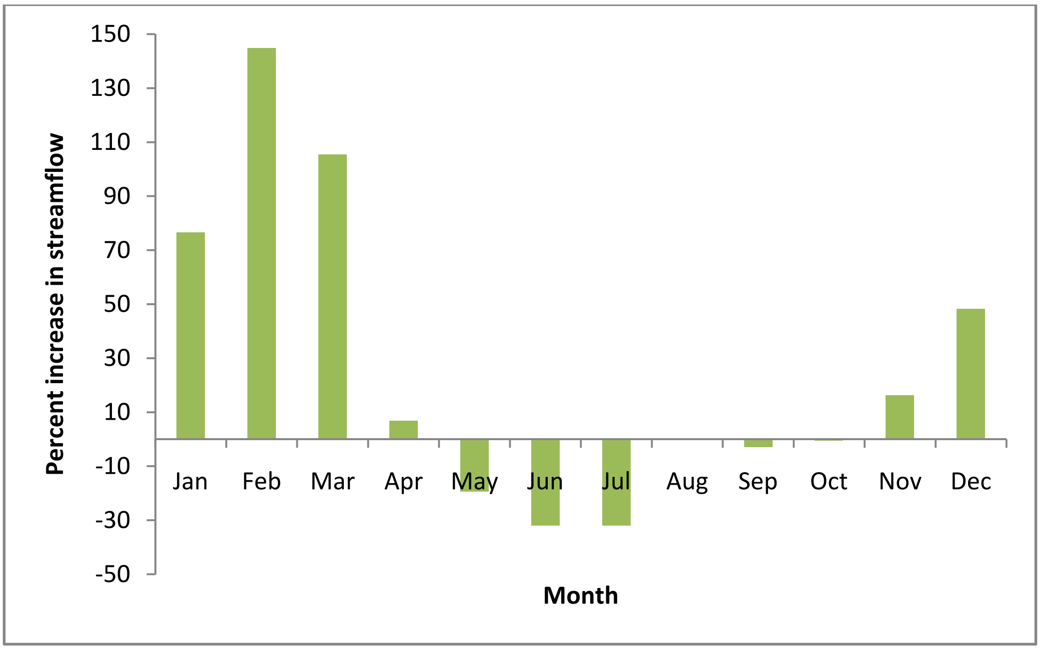

Fig. 4.70 Percent change in stream flow after adding reservoirs to subbasins (0.2% increase in area of waterbodies) during 2007-2011

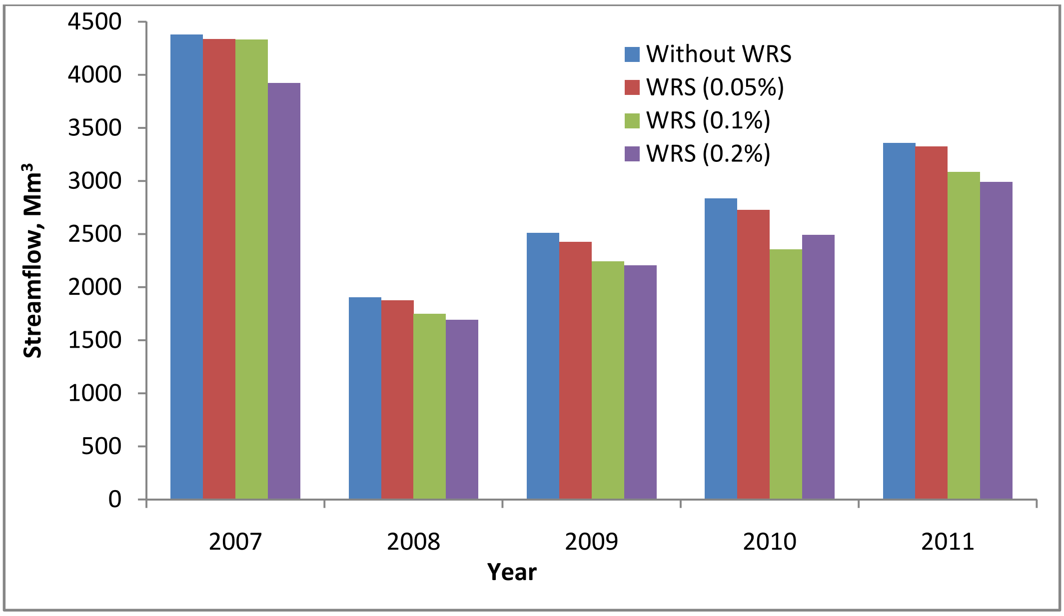

Fig. 4.71 Annual streamflow under different levels of WRS

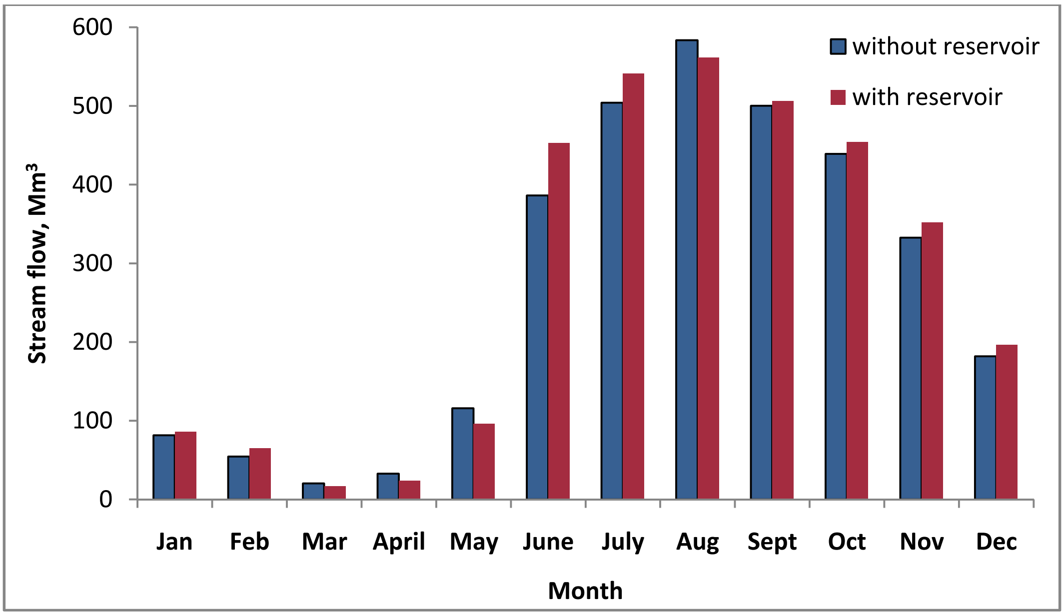

Fig. 4.72 Monthly streamflow with and without reservoirs (0.1% increase in area of waterbodies) during 2041-2070 under RCP4.5

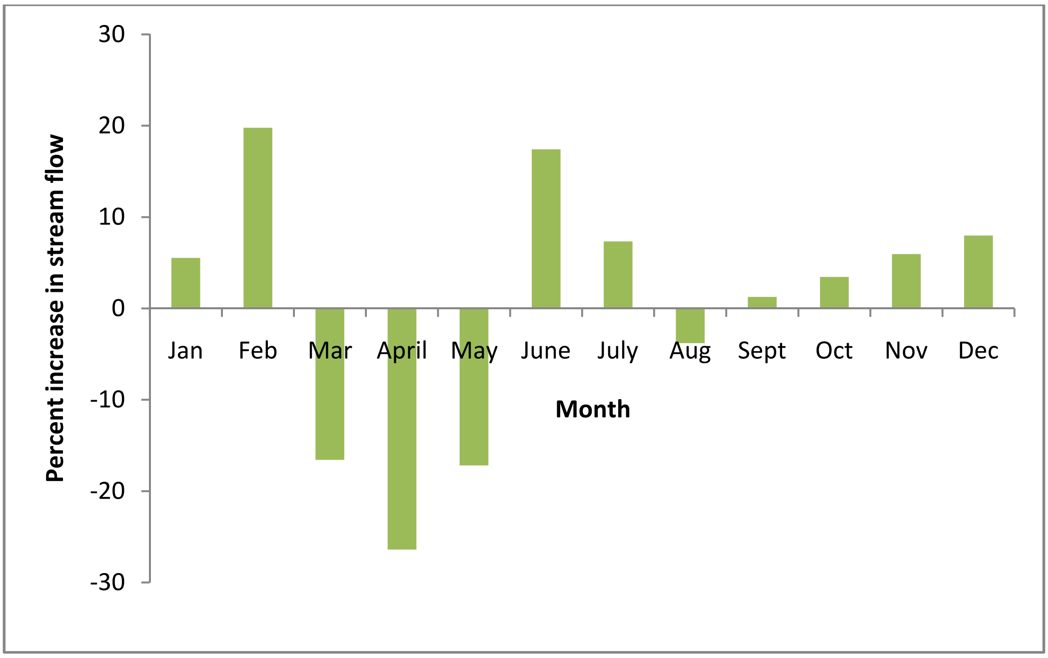

Fig. 4.73 Percent change in stream flow after adding reservoirs to subbasins (0.1% increase in area of waterbodies) during 2041-2070 RCP4.5

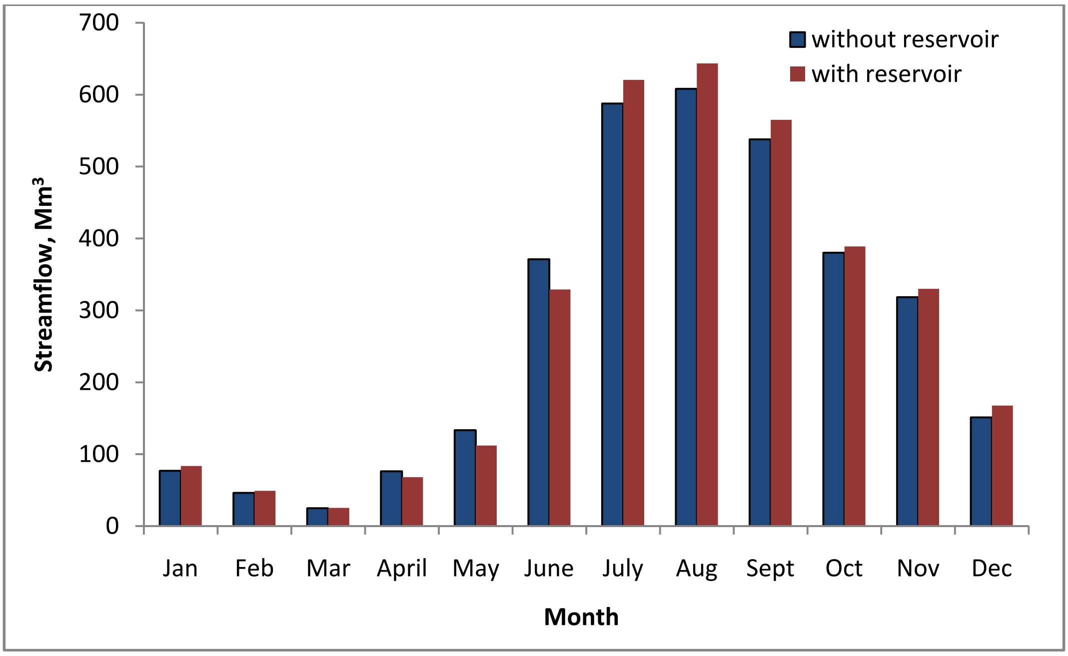

Fig. 4.74 Monthly streamflow with and without reservoirs (0.1% increase in area of waterbodies) during 2041-2070 under RCP8.5

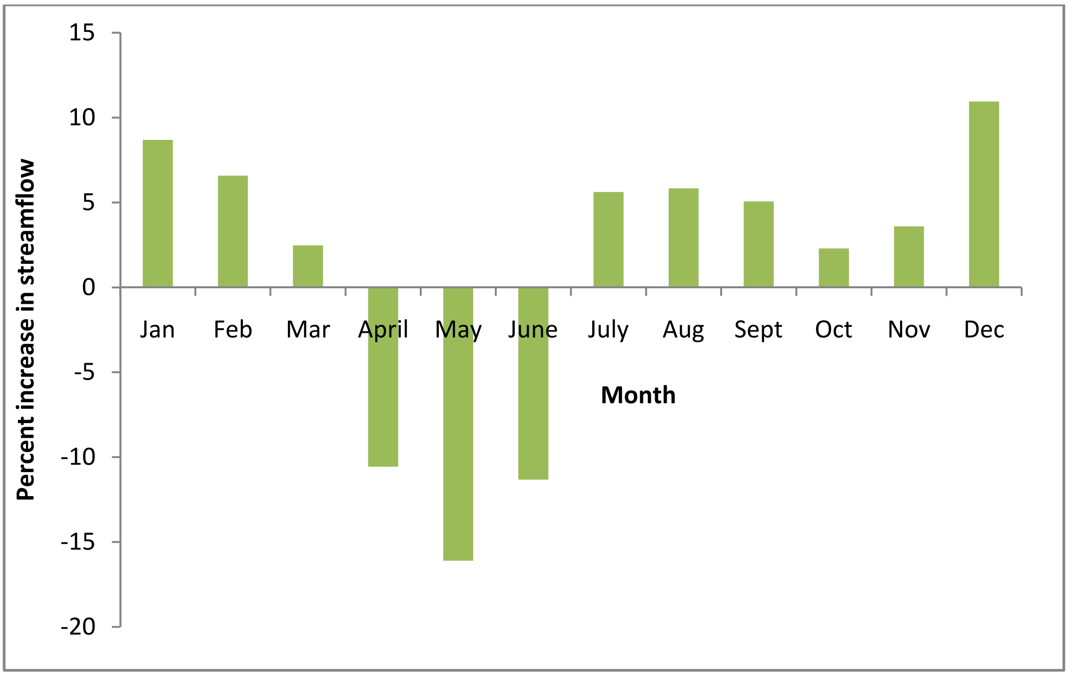

Fig. 4.75 Percent change in streamflow after adding reservoirs to subbasins (0.1% increase in area of waterbodies) during 2041-2070 RCP8.5

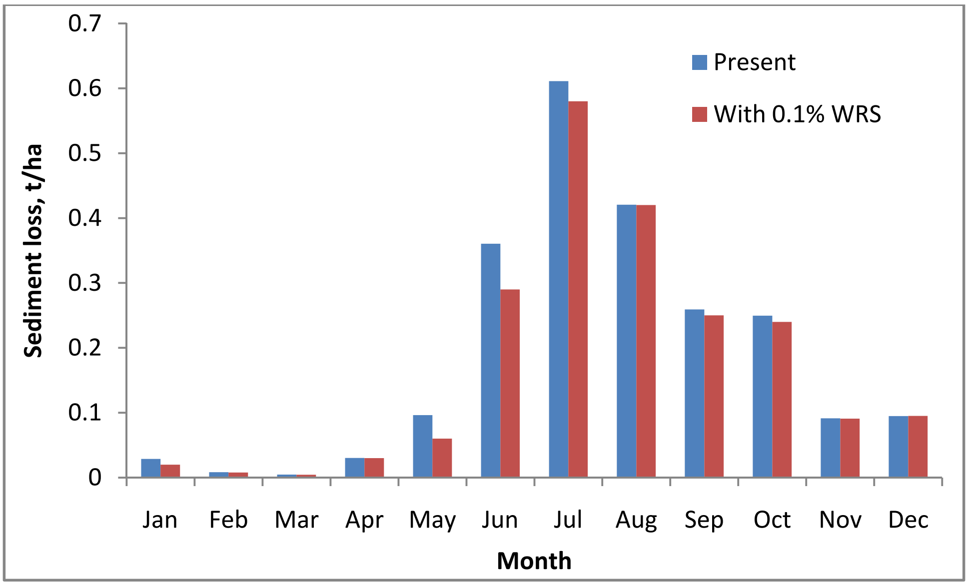

Fig. 4.76 Monthly sediment loss with and without reservoirs (0.1% increase in area of waterbodies) during the current scenario

4.13 IMPACT OF THE STUDY IN WATER RESOURCES AND PLANNING

This study analysed changes in temperature and precipitation in the Bharathapuzha river basin based on the gridded data provided by IMD and the

trend analysis of mean temperature during 1951-2013 showed an increasing trend with an increase of 0.0069°C/year. The maximum and minimum temperatures during the period also showed a similar trend.

The trend in average rainfall showed statistically significant decreasing trend and the decrease is at the rate of 15 mm/year during 1971-2005. While analysing the seasonal trend, it was seen that there was significant decreasing trend in the south-west monsoon and insignificant changes in other seasons. The extent and frequency of drought in the area was analysed using the Standardised Precipitation Index (SPI) tool and it is seen that more droughts are experienced during the recent years, compared to the past.

With the use of properly calibrated hydrological model SWAT, it was able to predict the streamflow in the Bharathapuzha river basin on a monthly basis. The results obtained from the model demonstrate how the changes in the climatic parameters such as rainfall and temperature can significantly affect the streamflow. The overall statistics shows that the SWAT model can very well be used for predicting the impact of climate change and watershed interventions in a watershed in the tropical region. The climate change effects, especially the seasonal shifts in rainfall increases the complexity and uncertainty of agricultural management. The simulated results imply that modifications are needed in the cultivation practices, mainly in those cases which are highly seasonal and are in the marginal limits of the seasons. The vulnerability of agriculture to climate change is dependent on the methods adopted by the people to cope up with the changes. Effective strategies which will promote sustainable agriculture need to be adopted. Scientific understanding of the response of different crops to climate change (change in carbon dioxide, temperature and other factors) is also needed for the planning.

A drastic increase in urban areas, deforestation and decrease in natural vegetation in the area might have caused increase in temperature and decrease in rainfall over the area. This study will give an insight to the hydrologists and planners in arriving at potential solutions which can bring down the ill effects of temperature variability and climate change in the study area.

The comparison of the results obtained after including the watershed interventions showed that there was increase in base flow even though there was decrease in average annual streamflow. Due to the addition of the WRS, the summer flow is increased which will help to maintain the river flow, water quality and the fish and other habitats in the river during the lean period. If more water can be made available in the rivers during the summer, it will help in maintaining the irrigation systems and thereby increasing irrigated agriculture of the area. Predictions on soil loss in the current scenario as well for the climate change scenario were also done. This will also be helpful for the management of the soil and water conservation measures and for planning proper mitigation measures in the area.

This research work is an indicative example of how well GIS tools and SWAT model can be effectively utilized for proper planning in the tropical river basins of India. Limitation in data availability on a fine spatial scale was the major limitation during the study. Under the constantly warming climate of the region, it is expected that the results of the study may arouse serious concern about water resource availability in the region, especially among the water resource planners and managers. Further detailed studies are needed in this regard with more accurate climate models along with hydrological and meteorological data having high spatial resolution.

Summary and Conclusion

SUMMARY AND CONCLUSION

Climate change is recognized as one of the most serious challenges mankind is facing today. It has a profound impact on the water cycle and water availability at the global, regional, basin, and local levels. Changes in temperature and precipitation alter the climatic conditions and subsequently hydrological and watershed processes in the long run.

Bharathapuzha river in the State of Kerala in India faces severe drought and dearth of water flow during the recent times. It has become necessary to analyse the reasons for the reduced river flow during the non monsoon periods with the help of hydrologic models. Before doing the hydrologic modelling studies, an attempt was made to understand the trend in the historical climate change of the region. Observed climate data of the area for the period 1975 to 2013 was first analysed to study the past scenario. The monthly averages of minimum temperature in the area ranged from 20.1 to 24.6^{o}C and maximum temperature ranged from 29.1 to 36.5^{o}C. The monthly average of relative humidity ranges from about 81% in January to up to 95.8% in July and the average evaporation is highest during the month of March (6.03 mm) and lowest during July (2.78 mm). The monthly average of minimum wind speed in the area is during October, and maximum during January ranging from 2.4 to 5.56 km/h.

To analyse the trend in mean, maximum and minimum temperatures and daily rainfall in the river basin, the gridded data obtained from IMD for a longer duration (1951-2011) was used. The gridded data was first compared with the observed data of the corresponding time period and the coefficient of determination (R^2) values showed that there is moderate to strong correlation between the two data sets. Hence the gridded data which was available for a longer time period was used for doing the trend analysis. The trend analysis of mean, maximum and minimum temperatures during 1951-2013 showed a significant warming trend with Mann-Kendall test statistic values of 4.63, 5.52 and 3.63 respectively. The increase in mean, maximum and minimum temperatures during the period was at the rate of 0.07°C/decade, 0.14°C/decade and 0.04°C/decade respectively.

Trend analysis of gridded rainfall data for the period 1971-2005 showed statistically significant decreasing trend, at the rate of 15 mm/year. Mann-Kendall and t-test gave a statistical significance at a level of a=0.1 and a=0.05 respectively. In case of rainfall, seasonal trend was also analysed. Significant decreasing trend occurs in case of south-west monsoon in the area during 1971-2005. In all the other cases (north-east, summer and winter) there is no significant trend in seasonal rainfall at 99% level of significance.

The comparison of drought duration estimation was done by Standardized Precipitation Index (SPI) for the period 1971-87 and 1988-2005. The results (6-month and 12-month SPI values) indicated that the basin has experienced more droughts during the recent years when compared to the past. The variation in 6-month and 12-month SPI values between the two periods indicates that the chance of seasonal droughts is increasing with decreasing stream flow, reservoir levels and groundwater levels. A drastic increase in urban areas, deforestation, sand mining and decrease in natural vegetation might have caused the increase in temperature and decrease in rainfall over the area.

Hydrologists around the world use hydrologic models as important tools for climate change impact studies. The hydrologic models are often forced with predicted climate data which are not assessed for quality or reliability. To find out the best suitable climate model for the region, the downscaled reanalysis data on precipitation and temperature from five regional climate models (RCM's) derived from different Global Climate Models (GCM's) were compared with observed data of Bharathapuzha river basin, Kerala on the basis of the four statistical parameters (Standard deviation, Correlation coefficient, coefficient of variation and centred root mean square difference).

The GFDL-CM3 RCM gave better comparison with the observed data and hence was used for further analysis. Without proper bias correction, the impact studies of hydrologic models using future climate data obtained from regional climate models will not be operational. Bias in precipitation was corrected using power transformation which corrects the mean and coefficient of variation (CV) of the observations. Since temperature is approximately normally distributed, it was corrected by fitting it to the mean and standard deviation of the observations. The coefficient values determined by this method for each month were used to correct the precipitation and temperature data for the future periods also. Comparison of the post-processed climate data to observed climate data was also done.

The model data for two emission scenarios RCP4.5 and RCP8.5 and two scenario periods 2041-70 and 2071-99 were selected for the study based on the availability of data and so as to get a long term trend of the impact studies. The downscaled data on precipitation and temperature (maximum and minimum) was bias corrected using the above explained methods. It is predicted that there may be a decrease of 4% to 7% in average annual rainfall during 2041-70 whereas the decrease may be up to a tone of 10% to 15% during 2071-99.

The monthly variation of the bias corrected data of precipitation for the two emission scenarios RCP4.5 and RCP8.5 for the periods 2041-70 and 2071-99 showed that there is consistent decrease in rainfall during all months except May, August, September, November and December for the two emission scenarios and for both future periods. A seasonal shift in the rainfall pattern is predicted with a significant decrease in southwest monsoon (June to September) rainfall and an increase in rainfall during the northeast (October to November) monsoon period.

The annual maximum and minimum temperatures is predicted to increase in future. The annual maximum temperature in the basin may increase by 3-5^{o}C (with an increase percentage of 8% to 9%) during 2041-70 under both scenarios. The increase in temperature under RCP4.5 during 2071-99 is almost to the same range as in 2041-70, where as in the RCP8.5 scenario the increase was to the range of 4-8^{o}C (8% to 15%). A similar increasing trend in temperature was also noted in the case of minimum temperature and the annual minimum temperature may increase by 5% to 8% during 2041-70 under both RCPs, whereas the increase during 2071-99 under RCP8.5 may be up to 15%. The results obtained can be utilised in formulating future water resources management plans and for assessing the impact of climate change in the area using hydrologic models.

Research works integrating the climate change predictions with hydrologic models are needed to understand the climatic influence on hydrologic extremes. The physically based distributed hydrologic model SWAT serves as a useful tool for predicting the components of the hydrologic cycle in many parts of the world. With the use of SWAT along with the available GIS techniques, it has been able to analyse the impact of changes in landuse, climate and other watershed interventions. The changes in the watersheds are occurring year by year due to increasing population and economy as well as due to the urge for urbanisation.

The preparation of the spatial data sets needed for the SWAT model (landuse and soil) was done in ArcGIS 10.3. Datum and projection used were WGS_1984 and UTM_Zone 43. The SRTM DEM of 30 m spatial resolution for the area was downloaded and was used for watershed delineation. The catchment area was delineated using Soil and Water Assessment Tool (SWAT) model in ArcGIS platform. The entire catchment was divided into 33 subcatchments (subbasins) based on the Digital Elevation Model (DEM) and the drainage network. Subbasin outlets were added at Mankara, Pudur, Thiruvegappura, Pulamanthole and Kumbidi where river gauging stations are available. The inflow from an area to the modelled area can be given as input and hence Ambarampalayam gauging station was selected as an inlet point to the rest of the basin area. Classification of the basin area to HRU's was done such that each HRU represents unique soil/land use characteristics. A total of 401 HRU's were defined within the basin. The river basin area comprises of land having elevation from below sea level to around 2400 m above M.S.L. About 80% of the area of the watershed lies below 300 m elevation, and the rest 20% lies between 300 m and 2500 m. The mean elevation of the subbasins varies from 31 m to 717 m.

Sensitivity analysis was performed using the SWAT Calibration and Uncertainty Program (SWAT-CUP). Sequential Uncertainty fitting (SUFI-2), a program that is linked to SWAT was utilized for the calibration and validation analysis. A warm up period of three years was given in each case and is indicated as number of years to skip during the simulation. The parameters which are considered to have greater influence on streamflow in the area were ranked based on the t-stat value and the p-value, and the top ranked and most sensitive seven parameters were used for calibrating the model. Changes in the rest of the parameters had no significant effect on streamflow simulations and hence were not considered. Calibration of the model was done using the data for the period 1989 to 2000 and validation using the data from 2001 to 2009.

The model evaluation statistics used for the calibration and validation periods were Nash-Sutcliffe Efficiency (NSE), Coefficient of determination (R^2) and PBIAS. The coefficient of determination (R^2) varied from 0.62 to 0.85, Nash-Suchliffe efficiency varied from 0.57 to 0.84 and PBIAS ranged between -11.7 to 12.7 during the calibration period. The strength of the model calibration and uncertainty procedure was also analysed using the r-factor which ranged from 0.35 to 0.47 during the calibration period. The coefficient of determination (R^2) varied from 0.74 to 0.88, Nash-Suchliffe Efficiency varied from 0.65 to 0.83 and PBIAS ranged from 9.0 to 18.1 during the validation period. The overall statistics shows that the model is very good for predicting streamflow in the Bharathapuzha river basin on a monthly basis.

The water balance components of Bharathapuzha basin predicted by the model have been estimated for the calibration period and validation period from the output files. It is seen that outflow from the basin takes place mainly in the form of base flow (33 to 37% of annual rainfall) and surface runoff (31% to 42%). Lateral flow component varied from 8 to 11% and ET varied from 15 to 22% for the different years under consideration. Water balance components reveal that the major fraction of river flow is in the form of base flow and surface runoff.

The calibrated and validated model was applied to Bharathapuzha river basin for studying the impact of changes in climate and watershed interventions on the hydrology of the river basin. The decrease in precipitation and increase in temperature may affect the future streamflow in the catchment and it is predicted that there may be up to 15 to 20% decrease in streamflow by the end of the century if the worst situation of climate change continues. There are chances that other factors like increasing population, increase in demand for irrigation, changes in landuse etc. can also add to it.

ET ranges from 15% to 22% of the annual rainfall in the current scenario while it has increased to 29% to 32% in the RCP4.5 scenario and 32 to 35% in RCP8.5 scenario. Lateral flow component is the lowest, comprising only 8% to 10% of the total rainfall and there is no much variation for this component within the scenarios.

Monthly streamflow predicted for the two periods 2041-2070 and 2071-2099 was compared with the current scenario and it was found that in all months of prediction, irrespective of the scenarios, the streamflow is found to be less than that of the current scenario, except during 2041-2070 in the month of August. During 2041-70, the streamflow in RCP4.5 and RCP8.5 showed almost same variation from the current scenario flow. While comparing the monthly future streamflow predicted during 2071-2099 with the current scenario, the streamflow in RCP8.5 is less than that under RCP4.5. It is also predicted that the climate will become drier and warmer in both scenarios in the future. RCP8.5 scenario corresponds to the pathway with the highest greenhouse gas emissions and the emissions continue to rise throughout the 21st century.

The annual sediment loss for the two climate scenarios (RCP4.5 and RCP8.5) during 2046-2070 and 2076-2099 was also predicted. During 2046-2070, the sediment loss in RCP4.5 scenario is predicted to be much less than the RCP8.5 scenario. To the end of the century, the sediment loss in RCP8.5 scenario is greater than RCP4.5 scenario in almost all years, and the annual sediment loss goes up to 7 to 9 t/ha, from the present condition of 2.5 to 4 t/ha. While analysing the monthly variation of sediment loss during different scenarios, maximum sediment loss is observed in July-August during the South-West monsoon period and the loss during January to April is very meagre.

The magnitude or extent of climate change is not fully known. The increase of emission of greenhouse gases, increasing use of non-renewable resources, burning of fossil fuels, urbanisation etc. are all adding to it even though the extend is not known. Measures must be taken to analyse, minimise and prevent the causes of climate change and to mitigate the adverse effects that can occur.

To analyse the impact of watershed interventions on the river hydrology, the storage capacity of Water Retention Structures (WRS) that have come up in the area during the period 2005 to 2011was estimated based on the change in land use under the category of water bodies and on the average depth area volume relationships obtained from field. The increase in area under water bodies in the individual subbasins corresponding to 0.05%, 0.1% and 0.2% was calculated separately and was used in the analysis. In SWAT, all the WRS in a subbasin are pooled together as a single reservoir and hence this increase in storage was given as input to SWAT in the form of reservoir input.

The simulated monthly streamflow for the period 2007 to 2011 after adding WRS @ 0.05%, 0.1% and 0.2% in surface area showed that even though the annual river flow decreased, the flow during the summer months (baseflow) increased after adding the WRS and the percent increase in flow was highest during the months of January to April when the river has a lean flow. Rather than utilizing the stored water in the upper reaches for irrigation and domestic purpose, the increase in summer flow will be helpful for maintaining a better environmental flow regime. Though the decrease in annual streamflow due to the WRS is less (1% to 6%), the redistribution of peak flow to the summer months is significant.

Streamflow prediction for the period 2041-2069 under the two scenarios RCP4.5 and RCP8.5 was also done with the assumption that the WRS were added by 2030 which increases the surface area of the WRS by 0.1%. When the streamflow after addition of WRS was compared with that without WRS, under both scenarios it was seen that although the annual streamflow decreased slightly, the monthly streamflow increased in most of the months. The monthly stream flow could be increased by 5-10% due to the addition of the WRS during

December to March. This is very much important in the changing climate scenario.

Bharathapuzha basin is the major drinking water source for most of the villages in the Palakkad, Thrissur and Malappuram districts of Kerala. A drastic increase in urban areas, deforestation, sand mining and decrease in natural vegetation in the area might have caused increase in temperature and decrease in rainfall over the area. This study will give an insight to the hydrologists and planners in arriving at potential solutions which can bring down the ill effects of climate change and variability in the study area.

The results of the research work may also serve as an eye opener to those who manage water and other natural resources in similar watersheds across the world. The addition of WRS in the watersheds can affect the hydrology of the basin in different ways based on the rainfall pattern of the area, soil and landuse characteristics, topography of the area and the drainage pattern. It is not essential that the results obtained for the humid tropical watershed may be obtained in other areas. Studies need to be conducted in a site specific manner and appropriate mitigation measures need to be undertaken for controlling future scarcity of water considering the decreasing rainfall pattern, increasing frequency of drought and decreasing streamflow. The engineers, administrators and scientists working in this line must be updated with the latest technologies and the predictions should be incorporated into the framework of developmental policy. This will help to plan and execute intense action towards water conservation and provision of water resources and to mitigate the ill effects of climate change.

Suggestions for Future Research

1. Multiple climate models may be used for prediction for getting more accurate results

2. Changes in landuse and other human activities also need to be predicted and incorporated

3. The impact of other watershed interventions may also be studied in detail

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IMPACT OF CLIMATE CHANGE AND WATERSHED DEVELOPMENT ON RIVER BASIN HYDROLOGY USING SWAT – A CASE STUDY

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ABSTRACT OF THESIS

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ABSTRACT

Climate change is considered as a global phenomenon, but investigation at the regional level is essential to understand the changes induced, and to suggest suitable adaptation strategies. This study is mainly concerned with the analysis of possible changes in the hydrology of Bharathapuzha river basin in the state of Kerala, India. Initially the trend in historic climate data was analysed to get an idea about the changes happening in the area. The trend analysis of gridded data using Mann-Kendall and t-test showed that the mean, maximum and minimum temperatures during 1951-2013 showed a significant increasing trend and the increase in mean, maximum and minimum temperatures during the period was at the rate of 0.07°C/decade, 0.14°C/decade and 0.04°C/decade respectively. Trend analysis of gridded rainfall data for the period 1971-2005 showed statistically significant decreasing trend, at the rate of 15 mm/year. Trend analysis of seasonal rainfall indicated that there was no significant trend in seasonal rainfall except during the south-west monsoon period when there was an increasing trend.

To find out the best suitable climate model for the region, the downscaled reanalysis data on precipitation and temperature from five regional climate models (RCM's) derived from different Global Climate Models (GCM's) were compared with observed data of area on the basis of the four statistical parameters (standard deviation, correlation coefficient, coefficient of variation and centred root mean square difference). The GFDL-CM3 RCM gave better comparison with the observed data and hence was used for further data analysis. Bias in precipitation was corrected using power transformation which corrects the mean and coefficient of variation (CV) of the observations. Since temperature is approximately normally distributed, it was corrected by fitting it to the mean and standard deviation of the observations. The model data for two emission scenarios RCP4.5 and RCP8.5 and two scenario periods 2041-70 and 2071-99 were selected for the study. Comparison of the post-processed climate data to observed climate data was carried out. Based on the results obtained, the annual maximum and minimum temperatures is expected to increase in future. It is also predicted that there will be

a decrease of 4 to 7 per cent in average annual rainfall during 2041-70 compared to the present day average values, whereas the decrease will be up to 10 to 15 per cent during 2071-99.

To evaluate the surface runoff generation and soil erosion rates from the area, the Soil and Water Assessment Tool (SWAT) model was used. The model was calibrated and validated on a monthly basis using the observed data and it could simulate surface runoff and soil erosion to a good level of accuracy. The model evaluation statistics used for the calibration and validation periods were Nash-Sutcliffe Efficiency (NSE), Coefficient of determination (R^2) and PBIAS. The study demonstrated that the SWAT model can be used to predict the monthly stream flow and sediment loss from the basin. So the calibrated and validated model was then used for studying the impact of changes in climate and watershed interventions on the hydrology of the river basin.

The model predicts 15 to 20 per cent decrease in stream flow by the end of the century if the worst situation of climate change continues (RCP8.5). While analysing the water balance components, it is seen that ET ranges from 15 to 22 per cent of the annual rainfall in the current scenario, while it may increase to 29 to 32 per cent in the RCP4.5 scenario and 32 to 35 per cent in RCP8.5 scenario. Lateral flow component is the lowest, comprising only 8 to 10 per cent of the total rainfall and there is no much variation for this component within the scenarios. Monthly streamflow predicted for the two periods 2041-2070 and 2071-2099 when compared with the current scenario values shows that irrespective of the scenarios, the streamflow is found to be less than that of the current scenario in almost all months.

During 2046-2070, the sediment loss in RCP4.5 scenario is predicted to be much less than the RCP8.5 scenario, whereas to the end of the century, the sediment loss in RCP8.5 scenario is greater than RCP4.5 scenario in almost all years, and the annual sediment loss goes up to 7 to 9 t/ha, from the present condition of 2.5 to 4 t/ha.

The impact of watershed interventions on the river hydrology was studied based on 0.05, 0.1 and 0.2 per cent increase in Water Retention Structures (WRS) in the area. The monthly stream flow simulated for the period 2007 to 2011 after adding WRS showed that even though the annual river flow decreased, the flow during the summer months (base flow) increased after adding the WRS and the percent increase in flow was highest during the months of January to April when the river has a very lean flow. Rather than utilizing the stored water in the upper reaches for irrigation and domestic purpose, the increase in summer flow will be helpful for maintaining a better environmental flow regime. Though the decrease in annual streamflow due to the WRS is small (1 to 6 per cent), the redistribution of peak flow to the summer months is significant.

The annual streamflow in the current scenario is found to be decreasing with increasing capacity of the water storage structures. Streamflow prediction for the period 2041-2069 under the two scenarios RCP4.5 and RCP8.5 with WRS showed that the monthly stream flow could be increased by 5 to10 per cent due to the addition of the WRS during December to March. The water stored on account of increased WRS can be utilized for irrigation and domestic purpose in the upper reaches and at the same time the increase in summer flow will be helpful for maintaining a better environmental flow regime.

Appendix I. Monthly average of minimum temperature (^oC) during 1975-2013

Year	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1975	19.2	22	23.3	24.5	24.2	22.5	22.7	22.6	22.9	22.8	22.3	20.9
1976	20	19.7	22.4	23.9	24.5	23.1	22.5	23	23	22.8	22.7	21.5
1977	19.6	21.3	23.9	24.9	23.7	22.9	22.6	23.2	23.2	22.2	22.4	20.1
1978	19.6	22.2	23.1	24.2	24.3	22.1	22.3	22.6	22.8	22.8	22.4	22.2
1979	21.5	22.1	23.6	24.5	24.5	23.3	22.6	22.5	23.1	22.9	23	21.8
1980	19.4	20.8	23.2	24.3	25	23.5	23	23.1	23	23.3	22.8	21.9
1981	21.2	20.3	23.5	25.3	24.6	23.3	23.5	23.3	22.9	23.4	22.3	21.3
1982	20.4	21.1	23.5	25.2	24.8	23.8	23.3	22.5	23	23	23.5	21.8
1983	20.1	21.9	23.4	24.7	25.7	24.7	23.5	23.8	23.3	23	21.7	22.9
1984	22	23.8	23.8	24.6	25.6	22.9	23	23.2	23.1	22	22.5	19.5
1985	21.9	21.4	23.8	25.2	25	22.9	22.7	23.1	23	22.7	21.9	21.5
1986	20.9	21	23.8	24.9	24.8	23.3	23.3	22.6	22.8	23	20.7	21.7
1987	20.7	20.9	21.4	24.7	23.5	22.9	22.8	22.5	22.7	22.7	21.4	21.3
1988	19.1	20.7	22.8	22.8	23.7	21.4	19.7	20.4	20.2	20.9	19.3	17.8
1989	19.2	18.5	22.3	25	24.6	22.4	23.2	22.8	22.8	23.1	21.6	20.9
1990	17.1	17.5	19	20.9	20.4	19.2	20	22.7	23.4	23.3	22.2	21.9
1991	20.3	20.2	24.4	24.8	25.4	23.4	22.5	22.3	23.1	22.9	21.8	19.6
1992	18.6	20.8	21.9	23.7	24	22.7	22.2	22.4	22.3	21.8	21.5	19.5
1993	18.7	20.5	22.8	24	23.9	22.9	22	22.4	22	22.3	21.3	19.9
1994	19.8	19.9	21.3	22.1	22.7	21.2	20.3	20.9	20.5	20.7	20.1	19.4
1995	20.7	22.3	22.9	24.3	23.7	23.3	22.3	22.7	22.4	22.1	21.4	17.7
1996	18.5	19.6	21.2	23.5	24.1	23.1	22.3	22.4	22.5	21.7	21.5	19.6
1997	19	18.8	21.6	22.3	24.6	23.6	23	23.3	23.5	23.3	23.4	23.1
1998	21.9	22.4	23.2	26.1	25.7	23.7	23.4	23.8	23.4	23	22.8	21.2
1999	19.8	21.5	23.3	24.6	23.8	23.1	22.8	23.3	23.3	23.5	22.2	21.4
2001	21.1	22.1	23.2	24.2	23.7	22.8	22.5	23.3	23.3	23.2	22.6	20.7
2002	21.2	21.6	23.8	24.8	24.3	22.6	23.4	23.3	23.2	23.7	23.2	19.7
2003	21	22.8	23.9	24.5	25.7	24	23.4	23.8	23.2	23.6	22.5	20.4
2004	20.8	21.3	23.7	25.1	24.2	23.5	23.5	23.2	23.5	23.2	22.3	20.9
2005	20.7	20.9	23.7	24.3	24.6	23.7	23.3	23.1	23.4	23.5	22.5	20.9
2006	21	20.5	23.3	24.5	24.8	24	23.5	23.5	23.4	23.5	23.2	21.3
2007	20.2	20.8	23.8	24.7	24.7	24.1	23.4	23.4	23.6	23.2	21.6	21.1
2008	19.6	21.6	22.1	24.8	24.9	23.8	23.7	23.9	23.3	23.4	22.8	20.5
2009	19.9	20.8	23.7	24.8	24.5	23.7	22.9	23.7	23.8	23.8	23.4	22.7
2010	21.4	22.9	24.2	25.3	25.7	24.2	23.5	23.6	23.6	23.4	23.1	21.1
2011	20.8	19.8	23.2	24.3	24.7	23.8	23.3	23.5	23.3	23.6	22	21
2012	20	21.1	23.9	25	25.5	24.1	23.9	23.8	23.7	23.7	22.3	21.7
2013	20.6	22.7	24.6	25.7	25.4	23.5	23.2	24	23.7	23.4	23.4	20.7

Appendix II. Monthly average of maximum temperature (^oC) during 1975-2013

Year	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1975	33.3	34.9	36.1	36.0	33.0	28.9	28.9	28.5	30.1	29.2	31.5	32.8
1976	32.0	35.2	36.8	34.3	33.5	32.0	28.9	29.2	30.9	32.1	32.1	33.0
1977	33.5	35.3	36.7	35.9	32.8	30.0	28.5	29.9	30.9	32.0	31.2	32.3
1978	33.5	35.2	36.4	35.8	33.4	28.8	28.8	28.7	31.7	32.1	31.9	32.8
1979	33.7	35.1	36.2	35.7	34.1	31.1	28.6	29.5	31.2	32.7	31.9	33.2
1980	33.5	35.7	36.2	34.4	35.3	30.7	29.0	29.1	31.0	32.1	33.1	33.3
1981	33.7	35.9	37.0	35.2	35.3	28.6	29.6	29.0	28.9	31.2	32.4	33.3
1982	33.7	36.2	36.6	36.4	34.9	30.8	29.7	29.1	31.0	33.0	33.0	32.9
1983	34.2	35.5	36.7	37.0	35.5	32.1	29.9	29.1	29.4	31.3	32.4	32.5
1984	33.2	35.2	35.8	34.7	35.7	29.1	28.4	28.9	30.1	30.1	32.4	32.6
1985	32.8	34.8	36.5	35.7	34.5	28.5	28.1	29.2	30.5	31.0	32.4	32.7
1986	32.7	34.2	36.4	36.0	34.6	30.7	29.7	29.2	30.7	31.7	31.7	33.9
1987	34.0	35.2	36.7	36.9	35.7	30.8	29.5	29.8	31.6	32.5	32.1	32.4
1988	33.1	35.6	36.1	35.7	34.1	30.1	28.9	29.1	29.9	31.5	33.4	33.9
1989	34.3	36.3	37.1	35.9	34.2	29.9	29.8	29.7	30.1	31.3	32.5	33.1
1990	33.5	35.0	36.2	36.1	32.5	30.1	29.0	29.3	31.4	32.4	31.7	32.5
1991	33.5	35.6	37.8	35.6	34.8	29.9	29.5	29.2	31.7	31.1	31.7	32.2
1992	32.8	34.6	37.0	36.6	34.1	30.6	29.0	29.0	30.4	30.8	31.7	31.5
1993	32.8	34.5	35.5	36.4	34.8	30.5	29.1	29.7	31.1	31.2	31.6	31.6
1994	33.3	34.9	36.8	34.4	34.5	29.4	28.6	29.7	31.3	31.6	31.9	32.3
1995	32.9	34.9	36.8	36.3	32.8	30.9	29.1	29.6	30.5	32.1	31.6	32.5
1996	33.4	35.2	36.7	34.6	34.1	31.3	29.4	29.6	30.0	30.7	32.3	31.7
1997	32.8	34.7	36.6	34.9	34.9	31.7	28.8	29.2	31.5	32.4	32.1	32.3
1998	33.5	34.4	36.3	36.4	34.9	30.6	29.3	29.9	29.4	29.6	31.5	31.2
1999	32.6	35.0	36.0	33.9	31.1	29.8	28.9	29.9	31.7	30.8	31.6	32.2
2000	33.7	34.1	36.1	34.7	34.5	29.8	29.7	29.1	30.8	30.4	32.3	31.0
2001	33.1	34.2	35.2	34.5	33.0	29.4	29.3	29.5	31.6	31.1	31.8	31.9
2002	33.1	34.8	37.0	35.6	33.3	30.1	30.1	28.8	31.5	31.2	31.9	32.9
2003	33.5	35.2	35.2	34.8	33.7	31.3	29.5	30.2	31.1	31.3	31.9	32.6
2004	33.6	35.5	36.6	34.8	30.5	29.7	29.5	29.5	30.9	31.3	32.0	32.9
2005	33.9	35.1	36.3	34.0	34.1	30.6	29.0	30.0	29.8	31.3	31.5	32.2
2006	33.5	34.8	35.3	35.2	33.4	30.3	29.5	30.1	30.0	31.0	31.4	32.1
2007	33.1	34.5	36.5	36.4	34.0	30.3	28.5	29.6	29.4	30.5	32.1	32.1
2008	32.7	33.9	33.9	34.1	33.9	30.3	29.6	30.1	30.4	31.8	32.5	32.3
2009	33.3	35.7	35.6	34.6	33.4	31.0	28.9	30.7	30.4	32.2	32.1	32.8
2010	33.7	35.8	37.1	35.7	33.9	30.8	29.5	29.4	30.7	30.5	30.7	31.0
2011	33.1	34.3	35.6	34.5	33.7	29.8	29.4	29.6	30.2	32.1	31.5	32.4
2012	32.9	35.4	35.6	35.3	33.5	30.6	29.9	29.3	30.6	32.4	32.0	33.2
2013	34.4	35.5	35.8	35.8	34.1	28.9	28.6	30.4	30.1	31.3	32.2	31.8

Appendix III. Monthly average of Relative humidity (%) during 1975-2013

Year	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1975	81	87	94	91	95	97	97	97	95	95	93	85
1976	76	82	91	90	90	93	95	95	93	94	93	83
1977	77	83	84	87	93	95	96	94	94	95	94	88
1978	84	84	84	88	95	97	97	96	95	96	89	82
1979	76	88	86	85	87	93	96	95	95	94	93	85
1980	82	87	89	88	90	96	97	96	95	96	90	85
1981	82	83	87	90	91	97	96	96	96	95	92	84
1982	81	92	91	89	91	96	96	96	95	95	87	76
1983	75	89	90	86	85	92	97	98	98	97	91	85
1984	81	82	88	92	90	94	95	94	94	92	90	87
1985	85	90	92	88	91	96	95	96	95	94	88	83
1986	82	83	87	90	90	91	95	91	95	97	93	84
1987	77	78	85	89	90	95	97	97	96	95	96	93
1988	88	93	93	92	94	97	96	97	96	96	92	91
1989	83	87	86	85	91	95	93	93	94	94	88	82
1990	86	85	89	88	93	94	94	94	94	93	92	83
1991	85	86	90	88	88	93	94	94	93	94	89	84
1992	76	91	90	89	91	92	94	94	93	93	91	78
1993	80	83	89	86	89	93	93	93	94	92	88	83
1994	80	85	85	90	88	93	94	92	93	93	83	77
1995	78	84	86	85	91	94	94	94	94	94	94	78
1996	76	76	85	90	90	92	95	93	95	95	92	87
1997	85	90	86	84	89	92	96	96	94	93	93	89
1998	82	83	90	86	90	95	95	95	95	95	93	87
1999	83	84	89	88	92	94	94	92	92	92	87	79
2000	75	84	85	87	87	94	93	95	93	94	88	84
2001	81	93	90	90	90	94	94	94	94	94	92	85
2002	85	82	88	87	89	94	94	95	94	94	89	85
2003	74	84	90	90	90	93	95	94	93	94	87	86
2004	80	80	89	90	94	95	94	94	94	92	87	81
2005	83	88	89	91	92	95	95	95	95	94	92	92
2006	83	80	90	89	89	95	95	95	95	94	90	81
2007	82	87	90	88	89	93	96	95	95	94	90	83
2008	87	90	87	86	87	93	93	93	93	92	92	83
2009	80	87	90	90	90	93	96	94	94	94	92	83
2010	79	79	87	86	89	93	95	93	93	94	93	90
2011	88	87	88	88	89	96	94	95	93	93	89	86
2012	83	86	89	87	89	93	94	95	94	92	93	85
2013	84	83	86	84	86	95	95	93	93	93	90	85

Appendix IV. Monthly average of daily evaporation (mm) during 1975-2013

Year	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1975	7.1	6.8	6.9	7.5	5.5	4.5	3.7	3.7	4.3	4.0	4.2	5.4
1976	6.9	7.0	7.4	6.4	6.7	4.9	3.8	4.0	4.8	4.0	4.0	6.0
1977	6.3	6.9	7.2	6.7	4.6	3.5	3.9	3.7	4.1	3.7	3.7	4.8
1978	5.5	6.0	6.3	5.5	4.3	4.1	3.4	3.2	4.7	4.3	4.0	5.4
1979	5.9	5.6	6.9	6.5	5.9	4.5	3.1	3.7	4.3	4.4	3.7	5.2
1980	6.1	6.8	6.9	6.5	6.1	3.9	3.6	3.5	4.4	3.8	3.8	4.5
1981	5.8	6.6	6.4	6.2	6.2	3.5	4.1	3.8	4.3	4.3	3.9	5.5
1982	6.4	6.2	7.0	7.2	5.6	3.7	3.8	3.6	4.6	4.2	4.6	6.4
1983	6.3	5.9	7.3	7.3	6.3	3.3	3.2	3.2	4.2	4	3.7	4.7
1984	5.0	5.2	5.3	3.9	5.1	1.6	1.6	2.4	3.7	3.6	3.7	4.0
1985	5.2	5.3	6.1	5.6	4.6	1.3	2.1	2.4	3.1	2.7	3.1	4.2
1986	4.6	5.0	5.6	5.3	4.4	3.2	2.9	3.5	2.9	2.5	3.1	5.3
1987	6.4	6.2	7.2	6.4	5.2	2.2	3.0	2.3	3.0	2.6	2.4	3.4
1988	5.2	5.4	5.5	3.9	4.1	1.0	2.6	2.2	2.2	3.2	4.1	5.0
1989	5.5	6.0	6.0	5.1	4.1	1.9	2.9	2.3	1.8	2.4	4.3	5.7
1990	4.9	5.7	6.1	6.1	5.1	2.9	2.5	4.9	4.0	4.2	3.0	4.7
1991	5.2	6.2	5.2	5.3	4.7	3.2	2.9	2.6	4.5	2.8	3.3	4.5
1992	5.8	5.0	4.1	5.7	4.8	3.6	2.7	3.3	3.3	3.2	3.3	4.9
1993	5.3	5.9	5.9	6.2	5.2	3.7	3.5	3.1	3.8	2.9	3.2	3.9
1994	5.6	5.0	6.2	4.3	4.9	3.0	2.3	3.1	4.1	3.3	4.5	5.3
1995	5.5	6.3	6.3	5.8	4.0	3.2	2.7	2.9	3.9	3.7	4.4	5.4
1996	6.1	6.9	6.3	4.9	4.9	3.4	2.4	3.3	3.0	2.5	2.7	3.1
1997	4.6	4.8	5.8	6.3	5.3	4.0	2.4	2.5	3.6	3.7	3.1	3.8
1998	5.3	5.8	6.2	5.9	4.9	3.0	2.7	2.8	2.8	2.4	2.9	3.4
1999	4.9	6.4	6.1	5.5	3.9	3.5	2.7	3.7	4.8	3.1	3.9	5.1
2000	6.5	5.5	6.3	5.0	5.6	2.7	3.3	2.5	4.0	3.0	4.0	4.2
2001	5.6	4.6	6.2	5.0	4.5	3.2	3.0	2.8	3.7	2.6	2.9	4.0
2002	4.8	6.0	6.3	6.1	4.9	3.0	3.1	2.5	4.1	3.5	3.5	4.7
2003	6.2	5.3	4.9	4.4	4.8	3.5	2.7	3.5	3.9	3	4	4.5
2004	5.1	6.1	5.9	5.6	3.3	3.2	2.6	3.2	3.3	3.1	3.4	4.3
2005	4.8	5.5	6.3	4.3	4.6	2.3	2.4	3.2	3.3	2.9	2.9	3.3
2006	4.9	6.5	5.6	5.3	5.5	3.3	3.0	3.6	2.9	2.9	3.1	5.2
2007	5.4	6.0	5.8	5.0	4.9	3.1	2.0	2.6	2.4	2.9	3.5	4.4
2008	5.2	4.8	4.7	4.6	5.0	2.5	2.3	3.1	3.0	3.2	2.9	4.6
2009	5.8	5.7	5.0	4.0	3.6	2.7	2.0	3.0	2.5	3.2	3.1	4.1
2010	4.6	5.6	5.5	4.6	3.8	2.6	1.9	2.2	2.6	2.1	2.1	3.3
2011	4.7	5.6	5.7	4.8	4.3	1.9	2.0	2.0	2.5	3	3.5	4.3
2012	4.8	5.9	5.4	4.8	4.6	2.6	2.3	2.3	3.1	3.4	2.8	4.5
2013	5.4	5.6	5.3	5.7	4.7	1.9	1.4	3.0	2.6	2.8	3.1	4.1

Appendix V. Monthly average of daily wind speed, km/h during 1975-2013

Year	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1975	7.1	6.8	6.9	7.5	5.5	4.5	3.7	3.7	4.3	4.0	4.2	5.4
1976	6.9	7.0	7.4	6.4	6.7	4.9	3.8	4.0	4.8	4.0	4.0	6.0
1977	6.3	6.9	7.2	6.7	4.6	3.5	3.9	3.7	4.1	3.7	3.7	4.8
1978	5.5	6.0	6.3	5.5	4.3	4.1	3.4	3.2	4.7	4.3	4.0	5.4
1979	5.9	5.6	6.9	6.5	5.9	4.5	3.1	3.7	4.3	4.4	3.7	5.2
1980	6.1	6.8	6.9	6.5	6.1	3.9	3.6	3.5	4.4	3.8	3.8	4.5
1981	5.8	6.6	6.4	6.2	6.2	3.5	4.1	3.8	4.3	4.3	3.9	5.5
1982	6.4	6.2	7.0	7.2	5.6	3.7	3.8	3.6	4.6	4.2	4.6	6.4
1983	6.3	5.9	7.3	7.3	6.3	3.3	3.2	3.2	4.2	4.0	3.7	4.7
1984	5.0	5.2	5.3	3.9	5.1	1.6	1.6	2.4	3.7	3.6	3.7	4.0
1985	5.2	5.3	6.1	5.6	4.6	1.3	2.1	2.4	3.1	2.7	3.1	4.2
1986	4.6	5.0	5.6	5.3	4.4	3.2	2.9	3.5	2.9	2.5	3.1	5.3
1987	6.4	6.2	7.2	6.4	5.2	2.2	3.0	2.3	3.0	2.6	2.4	3.4
1988	5.2	5.4	5.5	3.9	4.1	1.0	2.6	2.2	2.2	3.2	4.1	5.0
1989	5.5	6.0	6.0	5.1	4.1	1.9	2.9	2.3	1.8	2.4	4.3	5.7
1990	4.9	5.7	6.1	6.1	5.1	2.9	2.5	4.9	4.0	4.2	3.0	4.7
1991	5.2	6.2	5.2	5.3	4.7	3.2	2.9	2.6	4.5	2.8	3.3	4.5
1992	5.8	5.0	4.1	5.7	4.8	3.6	2.7	3.3	3.3	3.2	3.3	4.9
1993	5.3	5.9	5.9	6.2	5.2	3.7	3.5	3.1	3.8	2.9	3.2	3.9
1994	5.6	5.0	6.2	4.3	4.9	3.0	2.3	3.1	4.1	3.3	4.5	5.3
1995	5.5	6.3	6.3	5.8	4.0	3.2	2.7	2.9	3.9	3.7	4.4	5.4
1996	6.1	6.9	6.3	4.9	4.9	3.4	2.4	3.3	3.0	2.5	2.7	3.1
1997	4.6	4.8	5.8	6.3	5.3	4.0	2.4	2.5	3.6	3.7	3.1	3.8
1998	5.3	5.8	6.2	5.9	4.9	3.0	2.7	2.8	2.8	2.4	2.9	3.4
1999	4.9	6.4	6.1	5.5	3.9	3.5	2.7	3.7	4.8	3.1	3.9	5.1
2000	6.5	5.5	6.3	5.0	5.6	2.7	3.3	2.5	4.0	3.0	4.0	4.2
2001	5.6	4.6	6.2	5.0	4.5	3.2	3.0	2.8	3.7	2.6	2.9	4.0
2002	4.8	6.0	6.3	6.1	4.9	3.0	3.1	2.5	4.1	3.5	3.5	4.7
2003	6.2	5.3	4.9	4.4	4.8	3.5	2.7	3.5	3.9	3.0	4.0	4.5
2004	5.1	6.1	5.9	5.6	3.3	3.2	2.6	3.2	3.3	3.1	3.4	4.3
2005	4.8	5.5	6.3	4.3	4.6	2.3	2.4	3.2	3.3	2.9	2.9	3.3
2006	4.9	6.5	5.6	5.3	5.5	3.3	3.0	3.6	2.9	2.9	3.1	5.2
2007	5.4	6.0	5.8	5.0	4.9	3.1	2.0	2.6	2.4	2.9	3.5	4.4
2008	5.2	4.8	4.7	4.6	5.0	2.5	2.3	3.1	3.0	3.2	2.9	4.6
2009	5.8	5.7	5.0	4.0	3.6	2.7	2.0	3.0	2.5	3.2	3.1	4.1
2010	4.6	5.6	5.5	4.6	3.8	2.6	1.9	2.2	2.6	2.1	2.1	3.3
2011	4.7	5.6	5.7	4.8	4.3	1.9	2.0	2.0	2.5	3.0	3.5	4.3
2012	4.8	5.9	5.4	4.8	4.6	2.6	2.3	2.3	3.1	3.4	2.8	4.5
2013	5.4	5.6	5.3	5.7	4.7	1.9	1.4	3.0	2.6	2.8	3.1	4.1

Appendix VI. Seasonal rainfall during 1971-2005 based on the gridded data

	South-West	North-East	Winter	Summer
1971	2205.62	346.33	41.00	363.98
1972	1211.93	472.22	161.63	237.83
1973	1487.72	390.95	19.30	176.47
1974	1905.54	203.25	0.00	283.36
1975	2283.79	560.72	20.52	346.72
1976	1104.96	569.66	8.20	312.92
1977	1476.84	878.21	11.99	267.81
1978	1765.95	498.25	33.01	257.00
1979	1775.14	579.02	29.82	174.73
1980	1859.89	492.88	21.56	264.48
1981	2150.77	347.25	22.74	317.29
1982	1217.44	334.59	4.93	166.67
1983	1494.26	242.52	72.23	114.68
1984	1458.85	261.37	82.52	145.44
1985	1038.61	183.46	68.88	231.70
1986	1013.29	336.53	22.41	70.48
1987	772.15	372.45	182.12	102.90
1988	1082.15	72.32	14.57	315.16
1989	1110.50	252.39	13.71	140.52
1990	1214.77	330.88	21.89	320.21
1991	1872.07	379.34	2.67	123.39
1992	1689.98	312.97	0.00	189.81
1993	1064.91	384.82	22.29	123.05
1994	1672.79	551.47	21.15	140.58
1995	1609.05	385.43	5.16	305.63
1996	1463.81	347.71	37.41	331.32
1997	1431.07	539.58	31.25	189.97
1998	1572.11	485.56	142.39	160.44
1999	1105.18	606.04	40.02	338.61
2000	1024.05	178.23	55.21	83.39
2001	1466.87	585.09	0.10	378.67
2002	561.57	351.92	1.91	241.06
2003	1112.86	393.37	79.81	254.21
2004	1491.74	336.91	2.91	543.99
2005	1818.01	160.43	6.62	236.67

Appendix VII. Bias correction coefficients

	a	**b**
January	0.022	1.684
February	0.000	5.678
March	0.480	1.054
April	1.844	1.168
May	1.842	0.726
June	7.347	0.752
July	5.416	0.777
August	3.382	0.820
September	1.145	0.990
October	3.080	0.833
November	1.728	0.777
December	0.047	1.672

Appendix VIII. Bias corrected RCM data of precipitation for different scenarios

	2071-99 RCP 8.5	2071-99 RCP 4.5	2041-70 RCP 8.5	2041-70 RCP 4.5
January	0.65	4.10	1.19	5.16
February	0.39	2.34	1.08	5.66
March	2.32	3.78	4.13	7.64
April	38.71	53.83	51.54	66.36
May	149.69	195.83	155.95	165.31
June	204.30	224.23	205.29	208.08
July	407.37	460.36	414.43	377.76
August	383.09	388.92	381.58	353.73
September	332.29	248.23	309.48	231.44
October	152.75	144.93	164.19	196.01
November	111.79	187.95	161.18	193.46
December	16.18	41.79	29.46	40.44

Appendix IX. Bias corrected RCM data of maximum temperature for different scenarios

	2041-70 RCP 4.5	2041-70 RCP 8.5	2071-99 RCP 4.5	2071-99 RCP 8.5
January	32.43	32.93	31.61	34.87
February	34.20	34.74	33.38	37.12
March	36.48	37.10	36.32	39.79
April	38.12	38.83	38.20	41.40
May	37.35	37.61	36.15	40.01
June	35.38	35.96	34.46	38.75
July	34.16	34.38	33.27	37.56
August	33.52	33.74	33.54	36.09
September	33.84	34.27	33.72	36.19
October	33.49	34.00	33.13	36.34
November	33.04	33.39	32.41	34.97
December	32.03	32.51	31.62	34.27

Appendix X. Bias corrected RCM data of minimum temperature for different scenarios

	2071-99 RCP 8.5	2071-99 RCP 4.5	2041-70 RCP 8.5	2041-70 RCP 4.5
January	22.52	20.23	21.43	20.24
February	24.41	21.41	22.77	21.39
March	28.02	24.50	26.25	25.10
April	29.89	26.46	28.23	27.12
May	30.36	26.76	28.55	27.54
June	29.86	26.06	27.87	26.96
July	29.29	25.66	27.48	26.50
August	28.95	25.31	27.09	26.18
September	28.94	25.32	27.08	26.16
October	28.31	24.87	26.55	25.77
November	26.75	23.34	24.95	23.97
December	24.27	21.19	22.53	21.80

Appendix XI. Details of land use classes in SWAT

SWAT-Land use	Land use code	Area (Sq.km)	Percentage of total Area
Forest-Evergreen	FRSE	310.8	6.59
Rubber	RUBR	270.3	5.73
Agricultural-close grown	AGRC	1769.5	37.53
Agricultural-row crops	AGRR	27.9	0.59
Range-Brush	RNGB	21.5	0.46
Residential	URBN	63.2	1.34
Rice	RICE	1572.6	33.35
Barren	BARR	65.5	1.39
Coconut	COCO	334.4	7.09
Water	WATR	21.1	0.45
Range-Grasses	RNGE	8.2	0.17
Forest-Deciduous	FRSD	3.7	0.08
Wetlands-Forested	WETF	246.5	5.23

Appendix XII. Details of slope classes in SWAT

Slope class	Area (Sq.km)	Percentage of total Area
0 to 5	2724.41	57.78
5 to 10	1143.23	24.24
10 to 20	405.48	8.6
20 to 25	16.13	0.34
>25	426.07	9.04

Appendix XIII. Details of soil classes in SWAT

Soil series	Area (Sq.km)	Percentage of total
Mountaneous	117.82	2.5
Nadukani	41.51	0.88
Mungilmada	367.13	7.79
MannurSree	473.87	10.05
Anakkatty	116.93	2.48
Kottamala	82.14	1.74
Karinganthodu	1221.17	25.9
Agali	11.15	0.24
MannurKanji	192.44	4.08
Ayyanthole	121.35	2.57
Mannamkulam	123.41	2.62
Irumpiliyam	133.36	2.83
THALAKKAD	7.30	0.15
THUYYAM	5.23	0.11
Excessively	39.30	0.83
Shallow well drai	140.89	2.99
Uthrampallam	38.15	0.81
Very deep	56.86	1.21
Kozhinjampara	269.26	5.71
Elappully	2.17	0.05
Karakurisi	1.88	0.04
Shallow	129.49	2.75
Very shallow	485.30	10.29
Koottala Kozhu	283.22	6.01
Velappaya	109.06	2.31
Bhavaninagar	103.53	2.2
KoottalaVela	15.94	0.34
Vadavannur	25.45	0.54

Appendix XIV. List of major WRS: VCB/checkdam constructed in Kunthipuzha subbasin during 2007-2013

Sl.No.	Work done
1	Bund cum regulator culvert connecting Ayilakkad Dubaipadi to Alam Dweep in Edappal Panchayath
2	VCB across Naduvattom Valiya thode and protecting works to Chembikkal canal in Kuttippuram Panchayath.
3	Palathingal VCB across Thrippalur thode in Thavanur Panchayath.
4	Chelayipuram Athikkachira regulator cum bund in Edappal
5	Checkdam across Choriyode river at Kundukandam in Pallikurup in Karakurissi Panchayath
6	Check dam across Kunthipuzha at Arattukadavu upstream of Kunthipuzha bridge in Mannarkkad Municipality
7	Checkdam across Choriyode river at Nechulli in Thachampara Panchayath
8	Check dam across Thuppanad river D/s of Thuppanad Bridge at Thuppanad in Karimba Panchayath
9	Check dam across Nellipuzha river at Modhikkal in Kumaramputhur Panchayath
10	Check dam across Machamthodu at Chandanakunnu in Thachampara
11	Check dam across Thuppanad river in Cheenikadavu in Kadambazhipuram in Palakkad district
12	Check dam across Thuppanad river in Cholapadam in Kadambazhipuram in Palakkad district
13	Check dam across Kunthipuzha river in Changaleerikadavu,Pothozhikavuin, Mannarkkad in Palakkad district
14	Edavazhathodu VCB, Kezhattur Panchayath
15	Thottapazhappadi check dam, Kezhattur Panchayath
16	Cherakkal VCB, Vettathur Panchayath
17	Pallikkuthu VCB, Vettathur Panchayath
18	Pottikkudu VCB, Vettathur Panchayath
19	VCB across Kannankadavu Thodu at Vavunna padam
20	VCB across Valiya thode at Kanhirakkal In Irimbilium Panchayath
21	Checkdam across Oniyil padam thodu in Valanchery Panchayath.
22	Checkdam across Varathur kayal thodu in Vattamkulam Panchayath
23	VCB cum bridge in Makkaraparambu Panchayath
24	VCB at Parambathu in Makkaraparambu Panchayath

25	Checkdam across Manali thodu in Alipparambu Panchayath
26	VCB at Puthenveedu in Mankada Panchayath
27	VCB at Nellipparambu in Thazhekode Panchayath
28	VCB at Mundenthodu in Thazhekode Panchayath
29	VCB at Murukkumkundu in Perinthalmanna Muncipality
30	VCB at Munnuruthodu in Perinthalmanna Muncipality
31	VCB at Chirayilthodu in Elamkulam Panchayath
32	Changanpetta cross bar in Elamkulam Panchayath
33	VCB at Thachunni in Elamkulam Panchayath
34	VCB at Valappuramthodu in Pulamanthole Panchayath
35	VCB at Panakkadu in Pulamanthole Panchayath
36	VCB at Palathumchira in Pulamanthole Panchayath
37	VCB at Choolackal in Moorkanadu Panchayath
38	VCB at Pallickal in Puzhakkattiri Panchayath
39	VCB at Chovvana in Puzhakkattiri Panchayath
40	VCB at Koottanchira in Angadippuram Panchayath
41	VCB at Oredum padam in Angadippuram Panchayath
42	VCB at Nalukanni in Angadippuram Panchayath
43	VCB at Moonnukudi thodu in Angadippuram Panchayath
44	Check dam at Thachampara in Palakkad District
45	Check dam at Oniyilpadam thodu in Valancherry Panchayath
46	Check dam at Edatharachola in Malapparambu, Pulamantholde Panchayath
47	Check dam at Varathur kayal thodu in Vattamkulam Panchayath
48	Check dam at Perumbuzha thodu in Edarikode Panchayath
49	Check dam at Pulamanthole, Pulamanthole Panchayath
50	Check dam at Cherupuzha, Kallingal kadavu in Angadippuram Panchayath
51	Check dam at Thottungal thodu in Edarikkode Panchayath
52	Edathi thodu checkdam , Alipparambu Panchayath
53	VCB cum bridge at Makkaraparambu, Makkaraparambu Panchayath

Appendix XV. Increase in area in the sub basins corresponding to 0.05%, 0.1% and 0.2% increase in area under water bodies

Sub no.	Subbasin Area (ha)	0.05% Area (ha)	0.1% Area (ha)	0.2% Area (ha)
1	18022.91	9.01	18.02	36.04
2	19739.54	9.87	19.74	39.47
3	815.82	0.41	0.82	1.63
4	16353.87	8.18	16.35	32.71
5	35288.64	17.64	35.29	70.58
6	10959.24	5.48	10.96	21.92
7	13013.24	6.51	13.01	26.03
8	11323.81	5.66	11.32	22.65
9	14796.16	7.40	14.80	29.59
10	15367.24	7.68	15.37	30.73
11	47.59	0.02	0.05	0.095
12	7508.13	3.75	7.51	15.02
13	12035.95	6.02	12.04	24.07
14	4710.53	2.36	4.71	9.42
15	3221.66	1.61	3.22	6.44
16	13450.05	6.73	13.45	26.9
17	2341.25	1.17	2.34	4.68
18	16366.62	8.18	16.37	32.73
19	52.69	0.03	0.05	0.11
20	957.74	0.48	0.96	1.92
21	18305.90	9.15	18.31	36.61
22	31091.39	15.55	31.09	62.18
23	9214.56	4.61	9.21	18.43
24	11373.95	5.69	11.37	22.75
25	3545.44	1.77	3.55	7.09
26	21297.26	10.65	21.30	42.59
27	19399.62	9.70	19.40	38.80
28	8983.41	4.49	8.98	17.97
29	36815.76	18.41	36.82	73.63
30	51255.00	25.63	51.25	102.51
31	12563.69	6.28	12.56	25.13
32	17801.96	8.90	17.80	35.60
33	13511.24	6.76	13.51	27.02

Appendix XVI. Annual streamflow simulated under different conditions

	2007	2008	2009	2010	2011
Simulated streamflow without WRS	4379.8	1905.5	2511.4	2833.7	3355.1
Streamflow with WRS (0.05%)	4338.9	1874.9	2428.2	2727.3	3324.9
Streamflow with WRS (0.1%)	4331.2	1748.7	2244.7	2356.3	3084.4
Streamflow with WRS (0.2%)	3920.6	1692.4	2203.8	2491.2	2989.5

Publications from the research work

Anu Varughese and Suma Nair. 2015. Impact of climate change on water resources. Proc. of the International conference on Climate Change and the Developing world, CMS college, Kottayam, 21-25 Jan, 2015.

Anu Varughese and Hajilal M.S. 2016. Comparison of Regional Climate models and prediction of future climate for Bharathapuzha river basin. Paper presented in 28th Kerala Science Congress held at University of Calicut, Malappuram from 28th to 30th Jan, 2016.

Anu Varughese and Hajilal M.S. 2016. Analysis of historical climate change trends in Bharathapuzha River Basin, Kerala, India. *Nature, Environment and Pollution Technology* (Acceptance received).

Anu Varughese and Hajilal M.S. 2016. Assessing long term climate trends of Bharathapuzha Basin, Kerala, India. International journal of Ecology and Environmental Sciences.42(2):119-124.

IMPACT OF CLIMATE CHANGE ON WATER RESOURCES

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Abstract

Climate change is recognized as one of the most serious challenges mankind is facing today. It has a profound impact on the water cycle and water availability at the global, regional, basin, and local levels. Changes in temperature and precipitation alter the climatic conditions and subsequently hydrological and watershed processes in the long run. The effects of changes due to climatic variability on hydrological responses have been extensively carried out at watershed and river basin scales. IPCC observed that the global average air temperature near earth's surface rose by 0.74 ± 0.18^0C in the last century. This has also made significant effects on hydrological regimes. The outputs from the General Circulation Models are downscaled with the help of Regional Climate Models (RCMs) for projecting the output to a finer resolution. RCMs show significant improvements over the global models in depicting the surface climate over the Indian region. These high resolution climate change scenarios are used for the prediction of impact of climate change on water resources. Hydrologic models including Soil and Water Assessment Tool (SWAT) is made use of in making these predictions. The hydrologic cycle has been predicted to be more intense with likely occurrence of extreme events. These prediction models help in more accurate forecast of future climatological events. This in turn helps planners in management, adaptation and mitigation of the effects of climate change in all sectors affecting human population – *viz.* agriculture, water availability and management, energy, nutrition and health, natural resource conservation and management.

INTRODUCTION

The fresh water available for use is only about 2.7 per cent of the total water available on the earth. Of the fresh water available, 75.2 per cent lies frozen in polar regions and another 22.6 per cent is present as ground water. The rest is available in lakes, rivers, atmosphere, moisture, soil and vegetation. What is effectively available for consumption and other uses is a small proportion of the quantity available in rivers, lakes and ground water. The crisis about water resources development and management thus arises because most of the water is not available for use and secondly it is characterized by its highly uneven spatial distribution. Accordingly, the importance of water has been recognized and greater emphasis is being laid on its economic use and better management.

Climate change is recognized as one of the most serious challenges mankind is facing today. It is a major threat to present day society because of its adverse impacts on ecosystem, agricultural productivity, water resources, socio-economy and sustainability in a global as well as regional basis. It has a profound impact on the water cycle and water availability at the global, regional, basin, and local levels. Indeed, according to the recent Technical Report on Climate Change and Water from the Intergovernmental Panel on Climate Change (IPCC), "Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide ranging consequences on human societies and ecosystems" (Bates et al., 2008). Climate change will occur at local scales, but presently models used for projecting climate change due to future greenhouse gas emissions have an average global climate model resolution of 2.6˚ x 3.0˚.

It is believed and predicted that climate change will have a significant impact on water resources and hydrology. Any study related to this requires data at the river basin scale or even at station scale. Changes in temperature and precipitation alter the climatic conditions and subsequently hydrological and watershed processes in the long run. The effects of changes due to climatic variability on hydrological responses have been extensively carried out at watershed and river basin scales. Future climate scenario is best demonstrated by global climate models, the resolution of which is too coarse to capture regional and local climate scenario to simulate hydrological processes at basin scale. General Circulation Models (GCM) are the only reliable source for simulating future climate scenarios, but because of their coarse resolution they cannot be used directly for climate change studies and they do not provide a direct estimation of the hydrological response to climate change.

A. Climate scenarios, their purpose and methodology

Future greenhouse gas (GHG) emissions are the product of very complex dynamic systems, determined by driving forces such as demographic development, socio-economic development, and technological change. Their future evolution is highly uncertain. Scenarios are alternative images of how the future might unfold and are an appropriate tool with which to analyze how driving forces may influence future emission outcomes and to assess the associated uncertainties. They assist in climate change analysis, including climate modeling and the assessment of impacts, adaptation, and mitigation. The possibility that any single emissions path will occur as described in scenarios is highly uncertain.

The Special Report on Emissions Scenarios (SRES) establish different future world development possibilities in the 21st century, taking into consideration the possible changes in various factors in future including economic development, technological development, energy intensities, energy demand, and structure of energy use, resources availability, population change, and land-use change. The possibilities of changes in future developments are categorized mainly in the form of four major storylines quantified as four scenarios families namely A1, A2, B1 and B2. There are total of 40 different scenarios constructed across these four major scenario families. They cover a wide range of key “future” characteristics such as demographic change, economic development, and technological change. Based on this concept, a particular emission scenario is selected so that the impact study is done corresponding to that.

General circulation models (GCM’s)

In 1956, Norman Phillips developed a mathematical model which could realistically depict monthly and seasonal patterns in the troposphere, which became the first successful climate model. By early 1980s, the United States' National Center for Atmospheric Research had developed the Community Atmosphere Model; this model has been continuously refined into the 2000s. In 1996, efforts began to initialize and model soil and vegetation types, which led to more realistic forecasts. Coupled ocean-atmosphere climate models such as the Hadley Centre for Climate Prediction and Research's HadCM3 model are currently being used as inputs for climate change studies. The role of gravity waves was neglected within these models until the mid-1980s. Now, gravity waves are required within global climate models to simulate regional and global scale circulations accurately, though their broad spectrum makes their incorporation complicated.

Regional Climate Models (RCMs)

The nested regional climate modeling technique consists of using initial conditions, time-dependent lateral meteorological conditions and surface boundary conditions to drive high-resolution RCMs. The driving data is derived from GCMs (or analyses of observations) and can include GHG and aerosol forcing. A variation of this technique is also to force the large-scale component of the RCM solution throughout the entire domain. To date, this technique has been used only in one-way mode, i.e., with no feedback from the RCM simulation to the driving GCM. The basic strategy is, thus, to use the global model to simulate the response of the global circulation to large-scale forcings and the RCM to (a) account for sub-GCM grid scale forcings (e.g., complex topographical features and land cover inhomogeneity) in a physically-based way; and (b) enhance the simulation of atmospheric circulations and climatic variables at fine spatial scales.

The nested regional modelling technique essentially originated from numerical weather prediction, and the use of RCMs for climate application was pioneered by Giorgi (1990). RCMs are now used in a wide range of climate applications and can provide high resolution (up to 10 to 20 km or less) and multi-decadal simulations and are capable of describing climate feedback mechanisms acting at the regional scale. A number of widely used limited area modeling systems have been adapted to, or developed for, climate application. More recently, RCMs have begun to couple atmospheric models with other climate process models, such as hydrology, ocean, sea-ice, chemistry/aerosol and land-biosphere models.

Two main theoretical limitations of this technique are the effects of systematic errors in the driving fields provided by global models; and lack of two-way interactions between regional and global climate. Practically, for a given application, consideration needs to be given to the choice of physics parameterizations, model domain size and resolution, technique for assimilation of large-scale meteorological conditions, and internal variability due to non-linear dynamics not associated with the boundary forcing (Giorgi and Mearns, 1991). Depending on the domain size and resolution, RCM simulations can be computationally demanding, which has limited the length of many experiments to date. Finally, GCM fields are not routinely stored at high temporal frequency (6-hourly or higher), as required for RCM boundary conditions, and thus careful co-ordination between global and regional modelers is needed in order to perform RCM experiments.

Downscaling Future Climate Information

Downscaling is the general name for a procedure to take information known at large scales to make predictions at local scales. Downscaling climate data is a strategy for generating locally relevant data from Global Circulation Models (GCMs). The overarching strategy is to connect global scale predictions and regional dynamics to generate regionally specific forecasts. Downscaling can be done in several ways. Downscaling methods are developed to obtain local-scale surface weather from regional-scale atmospheric variables that are provided by GCMs. Downscaling, or translation across scales, is set of techniques that relate local and regional-scale climate variables to the larger scale atmospheric forcing (Hewitson and Crane, 1996). The downscaling approach was developed specifically to address present needs in global environmental change research, and the need for more detailed temporal and spatial information from Global Climate Models (GCM). The main objective of downscaling is to bridge the mismatch of spatial scale between the scale of global climate models and the resolution needed for impact assessments.

Two general categories exist for downscaling techniques: process based techniques focused on nested models, and empirical techniques using one form or another of transfer function between scales (Hewitson and Crane, 1996). Figure 1 depicts graphically the downscaling process where the GCM with a coarse resolution of 2.5^o X 3.75^o is downscaled to the 25 km basin scale. The high resolution topography, land cover, soil type covering the local domain from satellite data as static inputs and meteorological data such as temperature, wind speed, specific humidity etc. for lateral boundary conditions and initial condition from GCM are used to drive the RCM. With downscaling, a low resolution image is enhanced to a finer resolution using another higher resolution data product and a certain regression procedure.

Statistical downscaling is a method where a statistical relationship is established from observations between large scale variables, like atmospheric surface pressure, and a local variable, like the wind speed at a particular site. The relationship is then subsequently used on the GCM data to obtain the local variables from the GCM output. It can be classified into:

1. Weather classification schemes
2. Regression methods (multiple regression, artificial neural networks)
3. Weather generators

Dynamical downscaling is a method where output from the GCM is used to drive a regional, numerical model in higher spatial resolution, which therefore is able to simulate local conditions in greater detail. Dynamical downscaling requires running high-resolution climate models on a regional sub-domain, using observational data or lower-resolution climate model output as a boundary condition. These models use physical principles to reproduce local climates, but are computationally intensive. Statistical downscaling is a two-step process consisting of i) the development of statistical relationships between local climate variables (e.g., surface air temperature and precipitation) and large-scale predictors (e.g., pressure fields), and ii) the application of such relationships to the output of global climate model experiments to simulate local climate characteristics in the future.

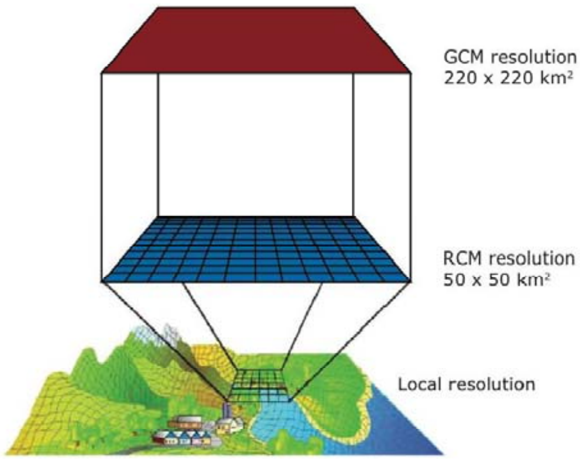

Fig. 1 Graphical representation of downscaling

Uncertainty in projected data and bias correction

Uncertainties (errors) are inherent in all projections of the future. In climate change, uncertainties are related to future path of emissions and limitation in climate models. Uncertainties must be taken into account when assessing the impacts, vulnerability and adaptation options. Bias is defined as the time independent component of the error. Bias arises because of several reasons. It has a high spatial component as well. Also, the biases in the output subsequently influence other hydrologic processes like evapotranspiration, runoff, snow accumulation and melt. Some form of pre-processing is necessary to remove biases present in the computed climate output fields before they can be used for impact assessment studies. Hydrological modeling depends on the choice of a bias correction method and the location of a watershed. Moreover, distribution-based methods are consistently better than mean-based methods.

B. Climate change and water resources

Temperature drives the hydrological cycle, influencing hydrological processes in a direct or indirect way. A warmer climate may lead to intensification of the hydrological cycle, resulting in higher rates of evaporation and increase of liquid precipitation. These processes, in association with a shifting pattern of precipitation, may affect the spatial and temporal distribution of runoff, soil moisture, groundwater reserves etc. and may increase the frequency of droughts and floods. The future climate change, though, will have its impact globally but likely to be felt severely in developing countries with agrarian economies, such as India. The population of the country has increased from 361 million in 1951 to 1130 million in July 2007. Accordingly, the per capita availability of water for the country as a whole has decreased from 5177 m^3/year in 1951 to 1654 m^3/year in 2007. Due to spatial variation of rainfall, the per capita water availability also varies from basin to basin. Surging population, increasing industrialization and associated demands for freshwater, food and energy would be climate scenarios. Increase in extreme climatic events will be of great consequence owing to the high vulnerability of the region to these changes. Indian Institute of Tropical Management (IITM) is active in studying long-term climate change from observed and proxy data as well as model diagnostics and assessment of climatic impacts, with a particular focus on the Indian summer monsoon. IITM used the Hadley Centre Regional Climate Models (RCMs) for the Indian subcontinent to model the potential impacts of climate change.

River basins in India

River basin is considered as the basic hydrologic unit for planning and development of water resources. There are 12 major river basins with catchment area of 20000 km^2 and above. The total catchment area of these rivers is 25.3 lakh km^2. All major river basins and many medium river basins are inter-state in nature which cover about 81% of the geographical area of the country (fig.2).

Climate change impact assessment on water resources

Studies have assessed that an enhanced surface warming over the Indian subcontinent by the end of the next century would result in more runoff in the northeast and central plains during the monsoon, with no substantial change during the winter season. The results, however, are not statistically significant. The possible changes in the climate of northwest India (Thar Desert) due to greenhouse warming have also been examined.

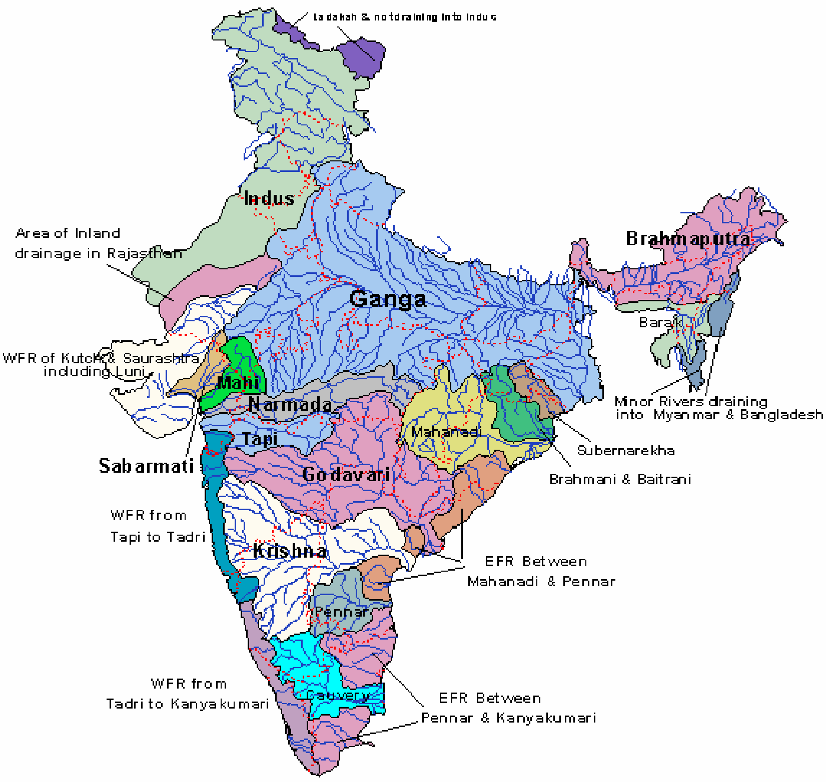

Fig.2 Major river basins of India

The results pointed to a pronounced warming and associated enhancement in the evaporation rate without any significant change in the precipitation over the region over the next 100 years. This may lead to an enhanced aridity over the Thar Desert and could have major implications for the hydrology and water resources in this region. Impact of climate change on Indian hydrology has also been assessed by using a set of statistical estimates for the parameters describing the relationship between changes in global climatic variables and those in local climatic characteristics. It has been observed that an increase in mean annual surface air temperature has resulted in increasing precipitation totals over the whole of India, especially along the western coast of the subcontinent (Divya and Mehrotra, 1995). The impact assessment is done under the following subheads:

a. Sea Level Rise

Melting of glaciers and polar ice sheets and heating up of oceans due to global warming is expected to reduce the size and extent of the polar ice caps and raise the average sea level. The Greenland and West Antarctic ice sheets face substantial melting if the global average temperature rises more than 2° to 7°F (1 to 4°C) relative to the period 1990-2000, eventually contributing to an additional sea-level rise of 13 to 20 feet (4 to 6 meters) or more. This would result in the inundation of low-lying coastal areas, including parts of many major cities. Regions especially at risk are low-lying areas of North America, Latin America, Africa, populous coastal cities of Europe, crowded delta regions of Asia that face flood risks from both large rivers and ocean storms, and many small islands whose very existence is threatened by rising seas.

Sea-level rise exposes coasts to higher risks of flooding and erosion, which would be exacerbated by growing population, increased human infrastructure within flood-prone areas, and human activities that increase erosion or local subsidence. Land will be lost due to inundation and erosion, increased flooding, and salt-water intrusion. These, in turn, would adversely affect coastal agriculture, freshwater resources, fisheries and aquaculture, human settlements, and health.

Mangroves and coastal wetlands (which are a home to birds, mammals, crustaceans and fishes, as well as valuable breeding habitat) are very sensitive to sea level rise, as their location is closely linked to the existing sea level. Any flooding of mangroves will cause the wiping out of many species, an example being the famous Bengal tiger in the Sundarbans, as predicted by the World Wide Fund for Nature.

b. Hydrological Impact Assessment under Indian conditions

Hydrological modelling is done to assess the impacts of future climate on the catchment water cycle. The water cycle, which includes surface and groundwater resources, is driven by two main forcing variables: climate and watershed development (land use and hydrological structures). Arc SWAT has been used by most of the researchers as the hydrological modelling tool for individual catchments. It is an ArcGIS - ArcView extension that has a graphical user input interface to the SWAT (Soil and Water Assessment Tool) model. The SWAT model is a process-based continuous hydrological model that can be used to assess the impacts of land use and hydrological structures on stream flows. SWAT use data on spatial variability in land use, soil and climate to capture human induced land and water management practices in a given catchment. The main model components are: climate, hydrology, erosion, plant growth, nutrients, pesticides, land management, channel and reservoir routing. Hydrological assessment done in different parts of India is discussed below.

Assessment done in the Musi Catchment, India

The hydrology of the catchment was modelled using the SWAT hydrologic model (Nune *et.al*.,2013). The model was set up for the entire Musi catchment in the Krishna Basin for which the model calibration and validation was carried out at the Osman Sagar and Himayat Sagar gauging stations. Monthly and annual inflows were used to carry out the model calibration. The model calibration and validation yielded Nash-Sutcliffe coefficients ranging between 0.65 and 0.75, which indicate a good model performance. The downscaled climate data was then used as forcing data in the model to carry out simulations for all three versions of the climate projection data ((Q0, Q1 and Q14). Analysis of flows at different time slices shows that stream flows decline in the near future (2011-40) and then an increasing trend towards the end of the century. Under the Q1 scenario, annual stream flows show a systematic decline over the period of analysis. The Q14 scenario shows an increase in stream flows over the next few decades followed by a decline towards the end of the century. Potential evapotranspiration is predicted to increase for all the climate scenarios.

A study on streamflow at the watershed scale in Chaliyar River Basin

Using the hydrologic model Soil and Water Assessment Tool (SWAT) a study was conducted in a part of the Chaliyar River Basin in Kerala, India by Raneesh *et al.*, 2010. Outputs from two scenarios, A2 and B2 are used in the RCM to predict future scenarios. The climate variables generated are rainfall and temperature. These are then input to the physically based hydrological model, SWAT to estimate the effect of climate change on streamflow. Goodness-of-fit measures such as the Nash–Sutcliffe efficiency and coefficient of correlation (R^2) are evaluated to assess the performance of the model. These values are found to be reasonably high, suggesting that model performance is reasonably good. It is predicted that annual streamflows in the river basin would significantly reduce in both the scenarios considered in this study. Results of the study indicate that hydrology of the basin is very sensitive to projected climate changes.

Climate change impact assessment of streamflow in Mahanadi

Impact of climate change on hydrology was assessed by Ghosh *et. al.*, 2010. The paper discusses recent studies carried out for climate change impact assessment and adaptation for Mahanadi river basin. The flow duration curves for monsoon stream flows using Conditional Random Field (CRF) downscaling model. High flows increase in most scenarios for 2045-65, but the number of scenarios showing an increase in high flows also decreases by 2075-2095. It is suggested that Uncertainity modeling of climate change impacts on water availability needs to be utilized in risk assessment and planning of mitigation measures for reservoir systems. Results from hydrological impact assessment studies can thus enable policy makers to identify adaptation and mitigation strategies that are robust to future uncertainities.

Hydrologic response to climate change in Baitarni river basin

Climate change sensitivity showed an increasing streamflow to independent increase in rainfall and decreasing streamflow to decreased rainfall and increased temperature in the basin (Mitra and Mishra, 2014). The increased atmospheric CO_2 concentrations, independently, showed an increase in streamflow. As a possibility it is said that the water availability at the Baitarni river basin is expected to increase in future under linear increase in rainfall since historic and expected increasing rainfall trend persisting in future. The predicted future scenarios developed by SWAT model gave the normalized daily rainfall distribution and was unable to catch the expected extreme rainfall conditions. The study suggests to analyse the hydrologic conditions of individual river basin under the expected climate change using trend extrapolation approach as well as by utilizing the outputs of global climate models (GCMs) and Regional Climate Models (RCMs) for more confident estimates.

Impact of climate change and land use change on the water resources in Pune

The hydrologic model SWAT (Soil and Water Assessment Tool) was used to study the impact of climate change and past land use change on water resources in Pune (Wagner *et. al.*, 2013) . The study aims at analyzing the impact of global change on the water balance components in the meso-scale Mula and Mutha Rivers catchment upstream of the city of Pune, India. To analyze climate change impacts regional climate model data based on IPCC emission scenario A1B was used by employing a downscaling method that rearranges historically measured data. The hydrologic model was run with the rearranged scenario weather data and model results were analyzed for the scenario period from 2020 to 2099. Past land use changes between 1989 and 2009 were identified with the help of three multi-temporal land use classifications, which were based on multi-spectral satellite data. Two model runs were performed and compared using the land use classifications of 1989 and 2009. Climate change leads to a slight increase of evapotranspiration. Particularly in the rainy season and in the first months of the dry season higher evapotranspiration can be observed. Towards the end of the scenario period low water storages in the major dams of the catchment at the beginning of the dry season indicate severe impacts on water availability. The impacts of land use changes balance out on the catchment scale and are hence more obvious at the sub-basin scale, where e.g., urbanization results in increased runoff and decreased evapotranspiration.

What future projections on climate change predict?

The available models and assessments done both in India and worldwide point out that climate change will have a drastic effect on the different resources that we are so used to. Gosain et al. (2003) have used distributed hydrological modeling to quantify the impact of climate change on the water resources of the country. The SWAT (Soil and Water Assessment Tool) was used to carry out the hydrologic modeling of various river basins in the country. The study first determines the present water availability in space and time without incorporating manmade interventions like dams, diversions etc. The same framework is then used to predict the impact of climate change on the availability of water resources with the assumption that the land use shall not change over time. They report that the GHG scenario may deteriorate the conditions in terms of severity of droughts and intensity of floods in many parts of the country, but there is also a likelihood of general reduction in the quantity of the available runoff in the GHG scenario.

Surface air temperature shows comparable increasing trends by as much as 3 to 4° C towards the end of the 21st century. The rainfall scenarios are dependent on climate scenarios. There is no clear evidence of any substantial change in the year-to-year variability of rainfall over the next century. Increased temperatures and increased seasonal variability in precipitation are expected to result in increased recession of glaciers and increasing danger from glacial lake outburst floods. A reduction in average flow of snow-fed rivers, coupled with an increase in peak flows and sediment yield, would have major impacts on hydropower generation, urban water supply, and agriculture. Increased population and increasing demand in the agricultural, industrial, and hydropower sectors will put additional stress on water resources. Pressure on the drier river basins and those subject to low seasonal flows will be most acute.

Scarcity of Water Resources

Climate change would also lead to a reduction in the availability of freshwater. Hundreds of millions of people face water shortage that will worsen as the global temperatures rise. At maximum risk are the current drought-affected regions, areas with heavily used water resources, and areas that get their water from glaciers. The IPCC expects many Latin American glaciers to disappear entirely over the next couple of decades, and water resource competition to increase in western North America when decreased snow pack in the mountains reduces summer river flow. Several of the African lakes, such as Victoria, Malawi and Chad, will experience shrinking lake area and basins, further exacerbated by over extraction and mismanagement. Many rivers that derive their water from melting glaciers or snow will have earlier peak runoff in spring and an overall increase in runoff, at least in the short term. Such a temporary increase in water flow would not always be welcome; for example, melting glaciers in the Himalayas would increase flooding and rockslide risks, while flash flood risks could increase in Northern, Central, and Eastern Europe. The supply of water is very likely to increase at higher latitudes due to glacial melting while it is likely to decrease over the mid-latitudes and dry tropics, which are already water-stressed areas. Such shifts in water availability would drastically affect agriculture, which in the tropics is significantly dependent on the rains. It would also affect the energy sector as hydropower generation would be affected. Industries that require large quantities of water (e.g paper and pharmaceutical industry) would also be challenged.

Conclusion

In the Indian water resources scenario, it is essential to understand the impact of global climate change on water resources. It is also important to have an understanding of the intensity and frequency of hydrologic extremes of floods and droughts which may occur in the future. Climate change estimates on regional or local spatial scales are burdened with a considerable amount of uncertainty, coming from several sources. Moreover, due to significant spatial and temporal hydrologic variations in the country, downscaling procedures for climate related hydrologic forecasts need to be developed. Research works integrating the atmospheric and hydrologic models to understand the climatic influence on hydrologic extremes are needed. These forecasts should be incorporated into the framework of developmental policy. This will help to plan and execute intense action towards water conservation and provision of water resources, in order to mitigate the ill effects of climate change, so that a large community is not affected. The climate change predictions at a regional level must be taken into account for a holistic development plan of any region. The engineers, administrators and scientists working in this line must be updated with the latest technologies. The engineers, administrators and scientists working in this line must be updated with the latest technologies and must work hand in hand for the benefit of the Nation.

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Final Acceptance Letter

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To,

AnuVarughese, Hajilal M.S and George B.A
Department of Irrigation and Drainage Engineering, Kelappaji College of Agricultural Engineering and Technology,
Kerala Agricultural University, Tavanur, 679573, Kerala

Dear Sir/Madam

We are happy to inform you that your paper entitled **"Analysis of historical climate change trends in Bharathapuzha River Basin, Kerala, India"** has been accepted for publication in the scientific journal Nature Environment and Pollution Technology (p-ISSN 0972-6268; e-ISSN 2395-3454). The paper is likely to come in Vol. 16, No. 1 (March), Year 2017.
Thanking you,

Yours sincerely,

Pradeep

P. K. Goel
Editor

Analysis of historical climate change trends in Bharathapuzha River Basin, Kerala, India

Anu Varughese[1,]*,Hajilal M.S[2] and George B.A[3]

Abstract: Climate change is considered as a global phenomenon, but investigations at the regional level is essential to understand the changes induced, and to suggest suitable adaptation strategies. This study is mainly concerned with the variation of temperature and rainfall in a river basin which lies in the tropical climate of India. Observed temperature and rainfall data were compared with the gridded data prepared by Indian Meteorological Department (IMD) and was found comparable. The trend analysis of mean, maximum and minimum temperatures during 1951-2013 showed a significant warming trend with Mann-Kendall test statistic values of 4.63, 5.52and 3.63 respectively. The increase in mean, maximum and minimum temperatures during the period was at the rate of 0.07°C/decade, 0.14°C/decade and 0.04°C/decade respectively. Trend analysis of gridded rainfall data for the period 1971-2005 showed statistically significant decreasing trend, at the rate of 15 mm/year. Mann-Kendall and t-test gave a statistical significance at a level of a=0.1 and a=0.05 respectively. Trend analysis of seasonal rainfall indicated that there was no significant trend in rainfall except during the south-west monsoon period. Appropriate mitigation measures need to be undertaken for controlling future scarcity of water considering the increasing temperature trends and decreasing rainfall pattern.

Key words: Mann-Kendall, trend analysis, Bharathapuzha, rainfall, temperature, climate change

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1. Introduction

Climate change, rapidly increasing population and depletion of natural resources have become global challenges which influence the socio-economic well-being of the people. Agricultural production and water resources availability are affected by changes in rainfall and temperature. Several researchers have studied the variability and trends in temperature and rainfall across the globe to understand the severity of climate change. An increase of 0.89°C (0.69-1.08°C) in the global land and ocean temperature combined was reported during the period 1901-2010 (IPCC, 2013). Many researchers worldwide (Longobardi and Villani 2010; Mondal *et al*. 2012; Dash et al. 2013) have contributed to the study of climate change based on the analysis of long term climate data. Study of the temperature regimes and changes in general rainfall pattern at local level is needed for understanding the regional scenarios. Increasing trends in maximum temperature have been reported from various parts of the world (Kothawale *et al*. 2010 Keggenhoff *et al*. 2014; Lu *et al*. 2014 and Opiyo *et al.* 2014).In the proper planning of regional water resources it is essential to study the trend of past rainfall (Ziv *et al*. 2013; Keggenhoff *et al.* 2014; Nyatuame *et al.* 2014; Thomas *et al*. 2014).

In the Indian context, the spatial and temporal pattern of monsoon rainfall is strongly affected by the changes in the air and ocean temperatures (Jagadeesh and Anupama, 2014; Goswami *et al*., 2006). Agriculture and other related sectors of India (George *et al.* 2002) and especially Kerala depends mainly on the monsoon rainfall, viz. South-West (June-Oct) and the North-East (Oct-Nov). In addition to agriculture and related sectors, electricity generation (hydroelectric), industries and various other activities depend on the monsoon rains. Proper planning of strategies needed to mitigate the extreme events can be done based on the results of the trend analysis.

Though Kerala, the southernmost state of India is blessed with an annual average rainfall of 3107 mm (India-Wris 2015), the flow in the rivers during summer has become meagre. The variations of different climatological parameters are highly location specific and hence studies need to be done in the regional level. It has been reported that there is severe drought and shortage of water in the basin (CWRDM,2004). So this paper aims to understand the temporal variability of temperature and rainfall as well as to study the occurrence of drought in the Bharathapuzha river basin in Kerala. The results of the study will help in developing management strategies which bridge the gap between the water needs and the possible supply.

2. Study Area

The Bharathapuzha river basin which lies between 10°25'-11°25'N and 75° 50'- 76°55'E, is the second longest basin in Kerala with a length of around 209 km (Figure 1. It extends over an area of 6186 square kilometres spread over the two states of India, namely Kerala and Tamil Nadu with an aerial extent of 71% and 29% respectively. The river originates from the Anamudi Peak having a height of 2695 m above MSL in Devikulam Taluk, Idukki District, Kerala to the southern portion of Western Ghats and flows west through the Palakkad gap and finally drains into the Arabian sea at Ponnani, Malappuram district, Kerala. Sand mining and unsustainable exploitation of natural resources have caused a dying state of the river during the summer season.

3. Data and Methodology

Gridded data of rainfall (0.5^o x 0.5^o) and temperature (1^o x 1^o) prepared by the Indian Meteorological Department (IMD) for the Indian region have been used in the study. The gridded data on rainfall was prepared based on 1803 rain gauge stations with a minimum data availability of 90% for the period 1951-2008. Shepard (1968) method was used for data interpolation. The weighted sum of the observations at the surrounding rain gauge stations falling within the predefined radius of influence is considered. The entire data of Indian region has been interpolated into 35 x 32 grid cells.

The daily gridded interpolated rainfall data for the area was taken from the data of the Indian region. It was compared with the direct observation for the grid where rain gauge data was available (Alathur) for the period 1976-97. This comparison was done based on the coefficient of determination (R^2) between the gridded and observed data. The range of R^2 values obtained was 0.53-0.99 which showed moderate to very strong correlation between the two sets of data. Rainfall analysis was carried out for all the seasons as well as the whole year separately for each station. The statistical parameters mean, maximum, minimum, standard deviation and coefficient of variation for rainfall data have been computed for seasonal and annual periods. Gridded data of mean, maximum and minimum temperature were also analysed to study the temporal changes in temperature.

3.1 Trend Analysis

The magnitude of trend was determined using regression analysis (parametric test) and using Mann-Kendall test (non-parametric method). Both these methods assume a linear trend in the time series. Time is taken as the independent variable and rainfall/temperature as the dependent variable for the regression analysis. The linear trend value represented by the slope of the simple least-square regression line provided the rate of increase/decrease in the variable. The trend analysis was carried out for the temperature (mean, maximum and minimum) and rainfall data using the Mann-Kendall test as well as using t-test.

3.1.1 Mann-Kendall test

The Mann-Kendall test is a non-parametric statistical procedure which is well suited for identifying trends in data over long time periods (Mann 1945; Burn et al. 2004;Thomas et al. 2014). The Mann-Kendall statistic 'S' measures the trend in the data and

$$S = \sum_{k=1}^{n-1} \sum_{j=i+1}^{n} sgn(xj - xk) \qquad \text{----------(1)}$$

the positive values indicate an increasing trend, whereas negative values indicate a decrease in value over time. There are n data points and xi, xj, xk represents data points at time i,j and k respectively. The strength of trend is proportional to the magnitude of 'S' (i.e., large magnitudes indicate a strong trend).

The null hypothesis is that there is no trend (H_0) in the time series. Using the Kendall probability table and by assessing the 'S' result along with the number of samples 'n' we get the probability of rejecting the null hypothesis for a given level of significance.

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} \text{for } S > 0 \\ 0 \qquad S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} \text{for } S < 0 \end{cases} \qquad \text{-----------(2)}$$

'Z' follows a normal distribution and if the 'Z' value is positive and the computed probability is greater than the level of significance, there is an increasing trend. If the 'Z' value is negative and the computed probability is greater than the level of significance, there is a decreasing trend.

4. Results and Discussion

4.1 Analysis of temporal trends in temperature

The monthly gridded temperature data was first compared with the observed data and the R^2 values obtained showed satisfactory correlation between the two. The R^2 values showed moderate to very strong correlation between the two data sets and it varies from 0.53 to 0.82 for maximum temperature and 0.25 to 0.90 for minimum temperature.

The changes in temperature affect the hydrologic cycle and hence in the climate change studies of river basins, the trend in temperature is important. The statistical characteristics of the mean, maximum and minimum annual temperature in the Bharathapuzha basin obtained from the gridded data (1°x1°) of IMD for the period 1951-2013 are presented in Table1.Mean monthly maximum temperature was recorded for the month April (31.4°C) and the minimum temperature was recorded for the month of January (16.8°C).

Month-wise variation of mean temperature and maximum temperature are plotted in Fig.1. The region experiences maximum temperature during March-April and minimum during December-January. The temporal variation of mean temperature during 1951-2013 is shown in Figure 2. There is an increasing linear trend which implies that there is a positive linear relationship between annual averages of mean temperature and time. This warming up is at the rate of 0.069°C/decade. Similar increasing trend in mean annual temperatures have been reported from various parts of India (Arora *et al.* 2005; Bhutiyani *et al.* 2007; Thomas et al. 2014). While comparing the trend of maximum temperature from various parts of India, Rathore *et al.*, 2013 reported maximum rate of increase in Himachal Pradesh (0.06°C per year).

The temporal variation of mean maximum temperature with time was also studied by plotting trend lines as well as using the Mann-Kendall test and t-test. Variation of maximum and minimum temperature with time during the period 1951-2013 is plotted in Fig. 3 and 4 respectively. The trend is shown by the linear regression line whose equation and R^2 values are also given in the figure. There is an increasing trend in maximum temperature with an increase of 0.14°C/decade and there is an increase of 0.68°C during the period 1951-2013. Studies conducted by Kothawale *et al.* (2010) also revealed that the annual mean (average of maximum and minimum), maximum and minimum temperatures showed significant warming trends of 0.51, 0.72 and 0.27°C respectively over 100 years during 1901–2007. The results of the Mann-Kendall test and the t-test (Tables 2 and 3) also confirmed the results obtained from the linear regression analysis. At an annual scale the Mann-Kendall test of maximum temperature resulted in an increasing trend at 1% level of significance. The data set is divided into two (1951-1981 & 1982-2013) and t-test was conducted to test the significance of these two data sets. The mean of maximum temperature for the periods 1951-1981 and 1982-2013 were estimated as 28.17°C and 28.71°C and the t-test results showed that the two data sets are significantly different. Similar analysis was conducted for average temperature and minimum temperature and the means were found statistically different.

4.2 Studies of trends in rainfall

4.2.1 Comparison of observed and gridded rainfall data

The gridded data was compared with the observed data and the R^2 values obtained showed satisfactory correlation between the two. R^2 values ranged between 0.53 and 0.99 which showed moderate to very strong correlation between the data.

Table 1 Statistical summary of monthly averages of maximum temperature, mean temperature and minimum temperature during 1951-2013

	Maximum temperature (^oC)			Mean temperature (^oC)			Minimum temperature (^oC)		
	Mean	**SD**	**CV(%)**	**Mean**	**SD**	**CV(%)**	**Mean**	**SD**	**CV(%)**
January	28.0	0.54	1.92	22.4	0.60	2.68	16.7	0.66	3.92
February	29.4	0.59	2.00	23.6	0.51	2.18	17.8	0.68	3.80
March	31.1	0.85	2.74	25.3	0.61	2.41	19.5	0.50	2.55
April	31.4	0.92	2.92	26.2	0.86	3.29	21.0	0.47	2.25
May	30.4	0.91	3.00	25.8	1.21	4.68	21.0	0.51	2.44
June	27.7	0.75	2.71	24.0	1.06	4.40	20.1	0.41	2.02
July	26.6	0.72	2.69	23.2	0.68	2.95	19.6	0.28	1.40
August	26.7	0.51	1.92	23.3	0.53	2.29	19.7	0.29	1.47
September	27.6	0.60	2.17	23.7	0.47	1.99	19.7	0.27	1.38
October	27.6	0.58	2.10	23.6	0.46	1.96	19.5	0.35	1.79
November	27.2	0.50	1.85	23.0	0.34	1.46	18.8	0.55	2.93
December	27.3	0.57	2.07	22.4	0.47	2.10	17.6	0.69	3.93

Table 2 Mann-Kendall test results for climatic variables of Bharathapuzha basin

Variable	S-value	Z-value	Result
Maximum temperature	931	5.52	Statistically significant trend (at a<0.01)
Mean Temperature	782	4.63	Statistically significant trend (at a<0.01)
Minimum temperature	121	3.63	Statistically significant trend (at a=0.01)

Table 3 Results of t-test for climatic variables of Bharathapuzha river basin

	1951-1981	1982-2013	Results
Mean of Max.Temp.	28.17	28.72	Mean of 1951-81 and 1982-2013 is significantly different at a<0.01
Mean of Avg.Temp.	23.74	24.03	Mean of 1951-81 and 1982-2013 is significantly different at a<0.01
Mean of Mini.Temp.	19.15	19.37	Mean of 1951-81 and 1982-2013 is significantly different at a<0.01

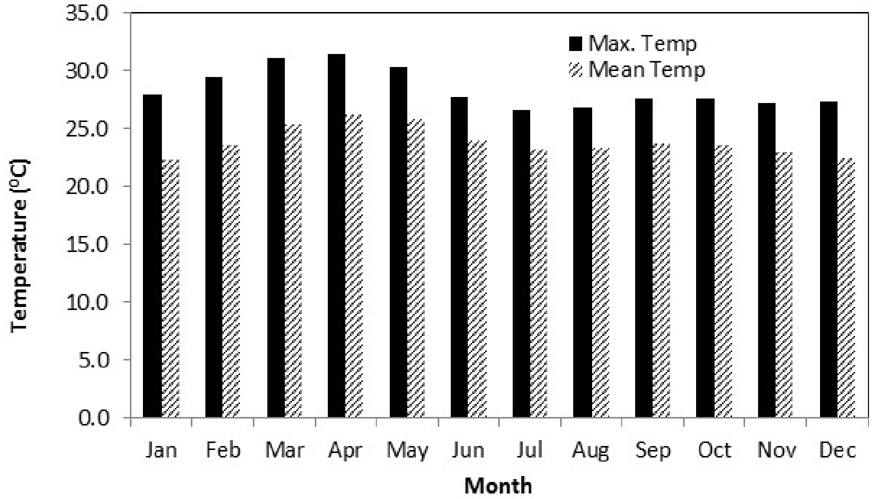

Figure 1 Month-wise variation of mean and maximum temperature

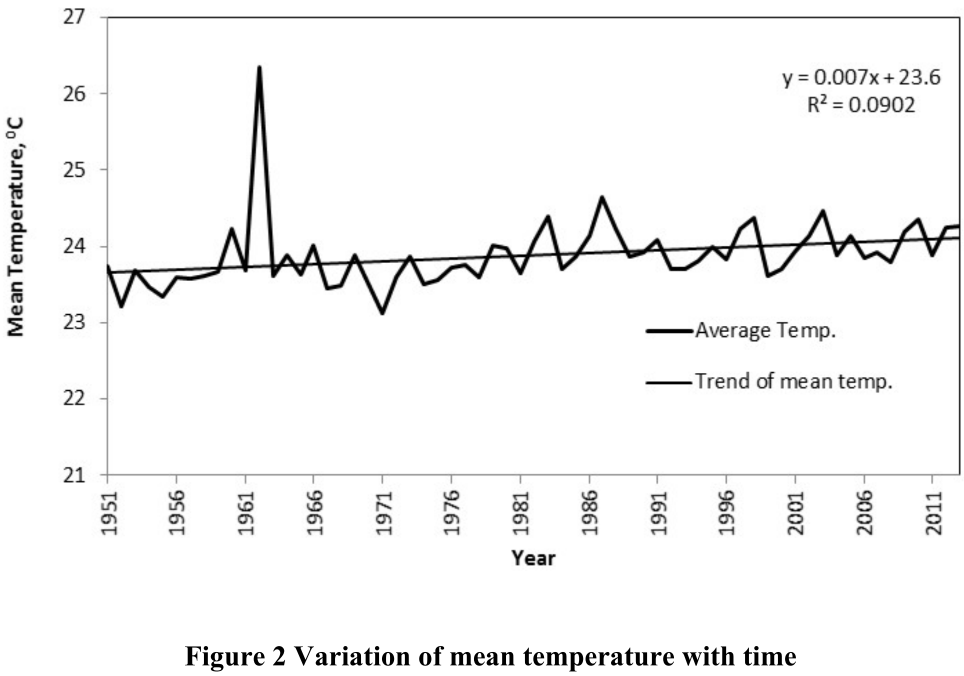

Figure 2 Variation of mean temperature with time

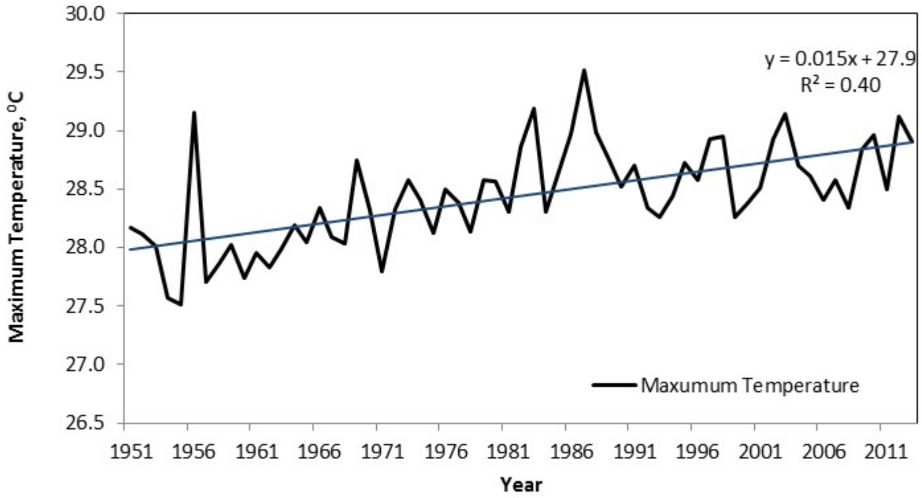

Figure 3 Variation of maximum temperature with time

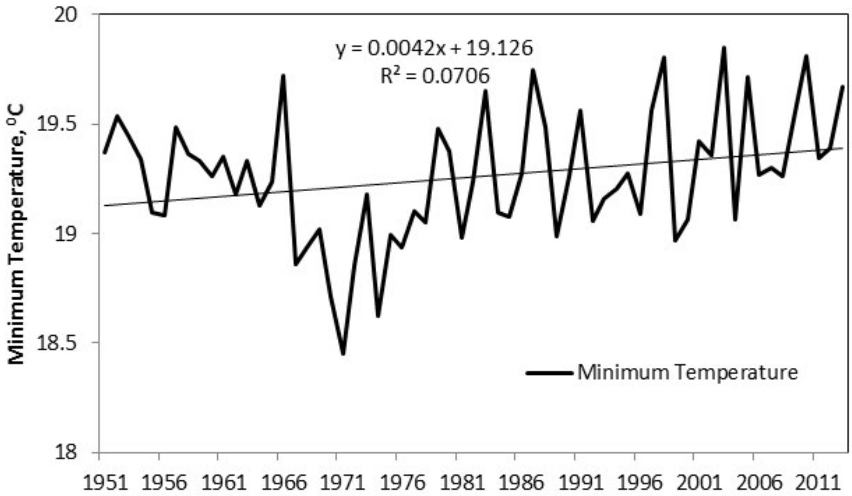

Figure 4 Variation of minimum temperature with time

Hence the gridded data was used for analyzing the temporal and seasonal changes in rainfall. The statistical characteristics of rainfall in the Bharathapuzha basin obtained from the gridded data (0.5°x0.5°) of IMD for the period 1971-2005 are presented in Table4. About 60% of rainfall occurs in the months of June, July and August. Maximum average monthly rainfall was received during July and minimum was recorded in January.

4.2.2 Temporal variation of rainfall

The temporal variation of rainfall during 1971-2005 is shown in Figure 5. The trend line is fitted with a linear equation, with a coefficient of determination (R^2) value of 0.118. There is a decreasing trend in rainfall and a decrease of 15 mm/year is noted in case of average annual rainfall during this period. The results of the Mann-Kendall test and linear regression analysis (Table 5) also showed a statistically significant decline in rainfall at99% and 95% confidence level. Analysis of climatological data for 140 years (1871-2007) over Kerala (Krishnakumar et al.2009) in India indicated cyclic trend in annual rainfall, whereas during the past 60 years (1950-2010) there was a decreasing trend in annual and southwest monsoon rainfall whereas in certain locations the rainfall trends were uncertain.

4.2.3 Seasonal trend in rainfall

While analysing the average monthly variation of rainfall during the period 1971 to 2005it is seen that maximum rainfall occurred during the month of July (515.5 mm) and minimum during January (2.5 mm). Around 60% of the average annual rainfall occurred during the months of June, July and August. For assessing the trend of rainfall based during four major rain giving seasons (Ananthakrishnan *et al*. 1979), annual rainfall was divided into south-west monsoon (June–September), north-east monsoon (October–November), pre-monsoon months or summer rains (March–May), and winter rains (December–February). Rainfall trend during the four seasons is shown in Figure 6.

Mann-Kendall test done to test the trend of seasonal rainfall indicated that there is a significant decreasing trend in case of south-west monsoon in the region during 1971-2005. In all the other seasons (North-East, summer and winter) there is no significant trend in rainfall. Krishnakumar *et al*. 2009 analysed the seasonal trend of rainfall in Kerala state as a whole during the period 1871 to 2005 and found that there was significant decreasing trend in the south-west monsoon and increase in post monsoon season whereas rainfall during summer and winter had insignificant decreasing

Table 4 Statistical summary of monthly averages of rainfall during 1971-2005

	Mean (mm)	**Std_dev**	**CV(%)**
January	2.5	8.6	3.4
February	6.8	24.5	3.6
March	14.8	24.1	1.6
April	73.7	57.2	0.8
May	135.8	89.1	0.6
June	473.6	236.0	0.5
July	515.5	182.5	0.4
August	341.0	123.4	0.4
September	169.6	114.3	0.7
October	226.5	106.9	0.5
November	118.8	98.7	0.8
December	24.8	47.9	1.9

Table 5 Mann-Kendall and linear regression results for rainfall

	Test statistic	Critical values			Result
		(Statistical Table)			
		a=0.1	a=0.05	a=0.01	
Mann-Kendall	-1.70	1.65	1.96	2.58	Statistically significant decreasing trend at a=0.1
Linear regression	-2.11	1.69	2.04	2.74	Statistically significant decreasing trend at a=0.05

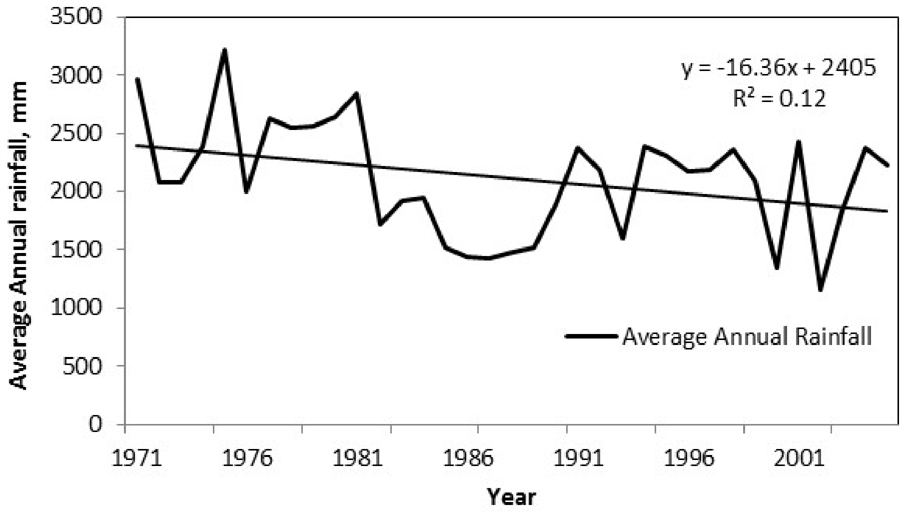

Figure 5 Temporal variation of rainfall

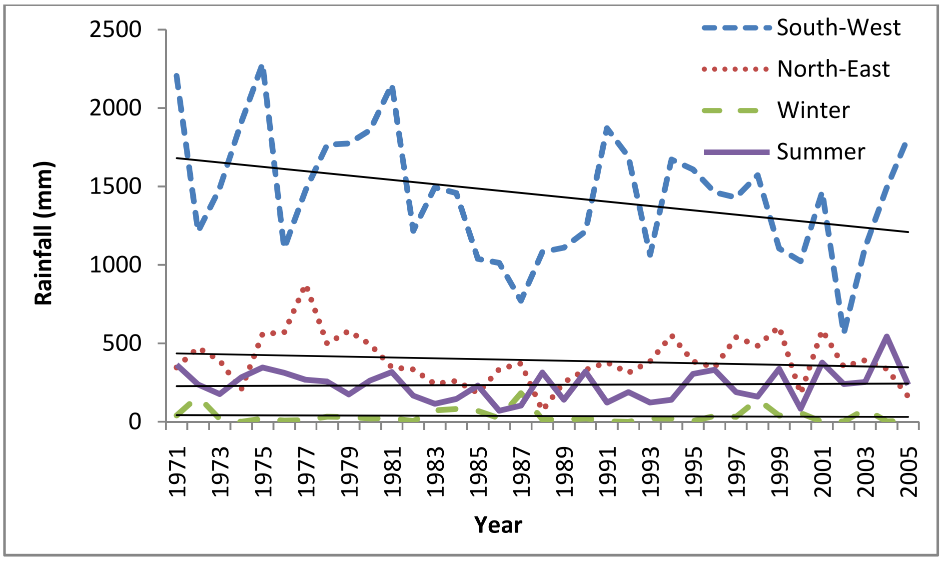

Figure 6 Seasonal trend of rainfall in Bharathapuzha basin

trend. A better understanding of the trends or variations in temperature and rainfall of an area will thus be helpful for evaluating the uncertainties associated with the management of water resources.

The regional scale variations in rainfall over India have been studied by many researchers with the analysis of annual and seasonal series of rainfall. Rathore *et al.* 2013 reported that in case of monthly rainfall spatially coherent increasing trends were observed in Feb, May and June while in Jan, March, July and September there was decreasing trends in most states of India. Increase in extreme rainfall events have been reported from various parts of the country (Thomas *et al*. 2014, Goswami *et al.* 2006, Rajeevan *et al.* 2008), whereas varying trends in different seasons for the same area was also reported (Krishnakumar *et al*. 2009; Manikandan and Tamilmani 2012; Thomas *et al*. 2014).

Summary and conclusion

This study analysed changes in temperature and precipitation in the Bharathapuzha river basin based on the gridded data provided by IMD. The trend in daily rainfall, mean, maximum and minimum temperature were analysed considering those as indicative of climate change phenomenon and that which influences the catchment hydrology. The gridded data was compared with the observed data for the grids and corresponding time period and R^2 values showed moderate to strong correlation between the two data sets.

The trend analysis of mean temperature during 1951-2013 showed an increasing trend which indicate that there is a positive linear relationship between annual averages of mean temperature and time and that the rate of increase is in the rate of 0.0069°C/year. The maximum temperatures during this period also showed a similar trend. The results were confirmed using the Mann-Kendall test and t-test. The z-values obtained for mean temperature and maximum temperature was 4.632 and 5.516 respectively which shows that the variation is statistically significant at 95% level of significance

The trend in rainfall in the region was also analyzed. The trend in average rainfall showed statistically significant decreasing trend and the decrease is at the rate of 15 mm/year during 1971-2005. Mann-Kendall test gave a statistical significance at a=0.1. In the t-test also, statistical significance was at a=0.1. In case of rainfall, seasonal trend was also analysed. Significant increasing trend occurs in case of south-west monsoon in the area during 1971-2005. In all the other cases (North-East, summer and winter) there is no significant trend in rainfall at 99% level of significance.

Bharathapuzha basin is the major drinking water source for most of the villages in the Palakkad, Thrissur and Malappuram districts of Kerala. The river is the main water source for several minor irrigation schemes. An expert committee appointed by the Government of Kerala to investigate into the problems of Bharathapuzha reported that the system is seriously affected by unsustainable exploitation of its surface and groundwater resources, particularly during the lean period. A drastic increase in urban areas, deforestation, sand mining and decrease in natural vegetation in the area might have caused increase in temperature and decrease in rainfall over the area. This study will give an insight to the hydrologists and planners in arriving at potential solutions which can bring down the ill effects of climate change and variability in the study area.

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Assessing Long-Term Climate Trends of Bharathapuzha Basin, Kerala, India

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ABSTRACT

Hydrologic models are widely used as important tools in climate change impact studies. For operationalising the hydrologic models need proper bias correction in the climate data. This study aims at finding out the best suitable climate model by comparing downscaled re-analysis data on precipitation and temperature from five regional climate models (RCM's) derived from different Global Climate Models (GCM's) with observed data of Bharathapuzha river basin, Kerala, on the basis of the four statistical parameters (standard deviation, correlation coefficient, coefficient of variation and centered root mean square difference). The GFDL-CM3 RCM compared better with the observed data and hence, was used for further data analysis. Bias in precipitation was corrected using power transformation which corrects the mean and coefficient of variation (CV) of the observations. Since temperature is approximately normally distributed, it was corrected by fitting it to the mean and standard deviation of the observations. Comparison of the post-processed climate data to observed climate data was carried out. It is predicted that there may be a decrease of 4% to 7% in average annual rainfall during 2041-70 compared to the present day average values, whereas the decrease may be up to 10% to 15% during 2071-99. Based on the results obtained, the annual maximum and minimum temperatures are expected to increase in the future. The results obtained can be utilised in formulating future water resources management plans and for assessing the impact of climate change in the area using hydrologic models.

Key Words: CORDEX; Bias Correction; Regional Climate Model; RCP'

INTRODUCTION

The hydrology of an area is affected by the climate change effects, which will eventually influence the life of the people living there. The use of hydrologic models as important tools for climate change impact studies has become popular (Terrink et al. 2010, Raneesh and Thampi 2011 and Bocchiolla et al. 2011). To assess and simulate such potential hydrological climate change impacts, these hydrologic models require reliable meteorological variables for current and future climate conditions (Teutschbein et al. 2011). Climate change occurs at local scales, but the Global Climate Models (GCM's) predict changes occurring at a global scale. Changes in temperature and precipitation alter the climatic conditions and subsequently hydrological and watershed processes in the long run. The effects of changes due to climatic variability on hydrological responses have been extensively carried out at a watershed and river basin scales (Jha et al. 2004, Terrink et al. 2010, Hurkmans et al. 2010, Teng et al. 2015). Information at local scale is essential for assessing the impact of climate change on natural systems especially hydrologic systems and to formulate adaptation and mitigation strategies. Sensitivity of regional hydrology to variable climatic conditions was explained by Neiman and Elathir (2005). The ensemble of Regional Climate Model (RCM) simulations need to be used along with bias correction methods (Deque et al. 2007,Giorgi 2006, Teutschbein and Seibert 2010). The availability of such information at the regional or local scale is one of the major issues that climate scientists are facing.

A high resolution regional simulation model has been developed by the World Climate Research Programme (WCRP) and is made available to the scientific community, through the CORDEX (Co-ordinated Regional Downscaling Experiment) program (Giorgi et al. 2009). The simulations over South Asian region (CORDEX-SA) are available for different models and are available at the data portal of Centre for Climate Change Research of Indian Institute of Tropical Meteorology (IITM), Pune, India (Patwardhan et al. 2014). These models are of approximately 50 km × 50 km horizontal resolution and have been derived using the lateral boundary conditions from Coupled Model Intercomparison Project Phase 5 (CMIP5). CORDEX-SA provides the multi-model outputs for different scenario conditions and gives a range of uncertainty of model simulations. The present study was carried out using these multi-model simulations.

Population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy are the major anthropogenic factors which drive the greenhouse gas emissions. Four different Representative Concentration Pathways (RCPs) which describe 21st century emissions have been defined (IPCC 2014). The four scenarios are a low so-called peak-and-decay scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one with very high emissions scenario (RCP8.5). RCP 4.5 represents a stabilisation scenario, where the total radiative forcing is stabilised before 2100 and RCP 8.5 is characterised by increasing greenhouse gas emissions over time.

Uncertainties exist in the projected climate change data and these uncertainties must be taken into account when assessing the impacts, vulnerability and adaptation options. Many things pertaining to the working of the climate system are not clearly understood yet, and hence uncertainties arise because of the incorrect or incomplete description of key processes and feedbacks in the model. A problem with the use of regional climate model output directly for hydrological purposes is that there is significant variation between the computed precipitation and temperature from the observed precipitation and temperature (Frei et al. 2003). Bias is defined as the time independent component of the error and it arises because of several reasons. Also, the biases in the output subsequently influence other hydrologic processes and the errors in bias corrected precipitation are typically amplified in modelled runoff (Teng et al. 2015). Some form of pre-processing is needed to remove biases present in the computed climate output fields before they are used for impact assessment studies (Christensen et al. 2008, Dobor et al. 2015).

Though the state of Kerala is blessed with an annual average rainfall of 3000 mm, the flow in the rivers during summer has become meagre. The variations of different climatological parameters are highly location specific and hence studies need to be done in the regional level. Bharathapuzha basin in Kerala is representative of many river basins of India which face severe drought and dearth of water (CWRDM, 2004). Hence an attempt was done for studying the temperature and rainfall variability in future based on predicted scenarios for the Bharathapuzha river basin in Kerala.

MATERIALS AND METHODS

Study Area

Bharathapuzha is the second longest river in Kerala, lies between 10° 25' - 11° 25' N and 75° 50' - 76° 55' E, and is about 209 km long (Bijukumar et al. 2013). The geographical area of the river basin is around 6186 km^2 spread across two states of India, namely Kerala and Tamil Nadu with a share of 71% and 29% respectively. The river originates from the Annamalai hills in Western Ghats near Pollachi in Tamil Nadu and discharges into the Arabian sea at Ponnani. The climate of the basin is humid tropical climate (Guhathakurta and Rajeevan 2007).

Meteorological data including daily precipitation and maximum and minimum temperatures were collected from the observatories located in the area, for the period 1971-2005. This period was taken as the reference period. Two future scenarios were considered for the periods 2041-70 and 2071-99 in this study.

The outputs of Regional Climate Models (RCMs) were compared and an appropriate RCM was selected. Observed data of Bharathapuzha river basin on precipitation and temperature during the reference period and historical data from 5 regional climate models (RCA4, CCAM (CCSM4), CCAM (CNRM), CCAM (GFDL-CM3) and CCAM (MPI) derived from the GCM's EC-EARTH, CCSM4, CNRM-CM5, GFDL-CM3 and MPI-ESM-LR respectively, were compared. The similarity of the data sets with the observed data was evaluated on the basis of four statistical parameters (standard deviation, correlation coefficient, coefficient of variation and centred root mean square difference). Two emission scenarios pathways selected for the study, RCP 4.5 and RCP 8.5 roughly correspond to the Special Report on Emission Scenarios (SRES) B1 and A1F1 respectively by 2100.

Precipitation and temperature are the key drivers for the hydrological regimes and hence, both were bias corrected. In the simplest formulations of bias correction, only the changes in a specific statistical aspect (mean value or the variance) of the computed field are used. Leander and Buishand (2007) found that a relatively simple non-linear correction, adjusting both the biases in the mean and its variability, leads to better reproduction of observed extreme daily and multi-daily precipitation amounts than the commonly used linear scaling correction. This power law transformation method which corrects for the coefficient of variation (CV) and the mean of the precipitation values was used in this study to correct for bias in precipitation data. The most important statistics (coefficient of variation, mean and standard deviation of the model data) were matched with corresponding quantities computed from the observed values. The daily precipitation P is transformed to a corrected value P^* using

$$P^* = aP^b \qquad (1)$$

where a and b are constants.

Correction for temperature involves shifting and scaling to adjust the mean and the variance. The corrected daily temperature T* is given by:

$$T^* = \bar{T}_{obs} + \frac{\sigma(T_{obs})}{\sigma(T_{mod})}(T_{mod} - \bar{T}_{obs}) + (\bar{T}_{obs} - \bar{T}_{mod})$$

where T_{mod} is the uncorrected daily temperature from GFDL-CM3 model and T_{obs} is the observed daily temperature. The average over the considered period is denoted by an overbar in the equation and σ the standard deviation. The bias corrected data for both scenarios and the two future scenario periods were compared with the observed data.

RESULTS AND DISCUSSION

Comparison of Predicted Data with Observed Data

Observed data of Bharathapuzha river basin on precipitation and temperature during the reference period and historical data from the 5 regional climate models were compared. The results of comparison of the observed data to the historical data of five models on the basis of the four statistical parameters (Standard deviation, Correlation coefficient, coefficient of variation and centered root mean square difference) is given in Table 1.

Bias Correction of Predicted Data

Even though the RCM GFDL-CM3 showed a good ability to simulate the present climate over the basin, the presence of uncertainties on the future climate because of systematic bias needs to be corrected. The method reported by Leander and Buishand was used for bias correction. The bias correction coefficients a and b obtained for different months is plotted in Figure 1.

Table 1. Statistical comparison of different model estimates with observed data

	EC-Earth	CCSM4	CNRM	GFDL-CM3	MPI	Observed
Precipitation						
Standard deviation	49.69	56.50	58.52	73.43	56.87	181.46
Correlation coefficient	0.24	0.68	0.74	0.76	0.78	
Coeff. of variation	0.44	0.58	0.62	0.66	0.59	1.03
Centered RMSE	3.86	1.75	1.88	1.57	1.71	
Maximum Temperature						
Standard deviation	2.92	2.47	2.62	2.32	2. 50	2.39
Correlation coefficient	-0.14	0.72	0.69	0.76	0.73	
Coeff. of variation	0.10	0.09	0.10	0.09	0.09	0.07
Centered RMSE	3.86	1.75	1.88	1.57	1.71	
Minimum Temperature						
Standard deviation	1.52	1.72	1.82	1.71	1.82	1.09
Correlation coefficient	0.49	0.77	0.78	0.82	0.81	
Coeff. of variation	0.09	0.08	0.09	0.08	0.09	0.05
Centered RMSE	1.31	1.07	1.13	0.99	1.08	

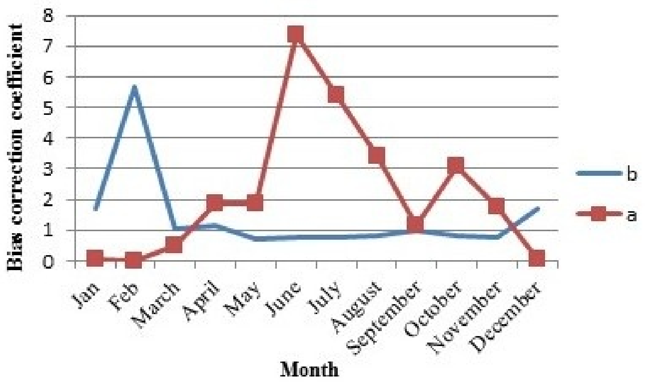

Figure 1. Comparison of transformation coefficients obtained during different months

The coefficient values determined by this method for each month were used to correct the precipitation and temperature data for the future periods. The model data for two emission scenarios RCP4.5 and RCP8.5 and two scenario periods 2041-70 and 2071-99 were corrected using this method. A marked improvement was achieved with nonlinear transformation, adjusting the mean as well as coefficient of variation of daily precipitation.

Impact on Precipitation

The monthly variation of the bias corrected data of precipitation for the two emission scenarios RCP4.5 and RCP8.5 for the periods 2041-70 and 2071-99 is shown in Figure 2. There is a consistent decrease in rainfall during all months except May, August, September, November and December for the two emission scenarios and for both future periods. After studying the rainfall trend during the southwest monsoon, it is observed that rainfall during the months of June and July showed a decrease whereas there was increase in rainfall during the months of August and September. A seasonal shift in the rainfall pattern is observed with a significant decrease in southwest monsoon (June to September) rainfall where as an increase in rainfall is observed during the northeast (October to November) monsoon period.

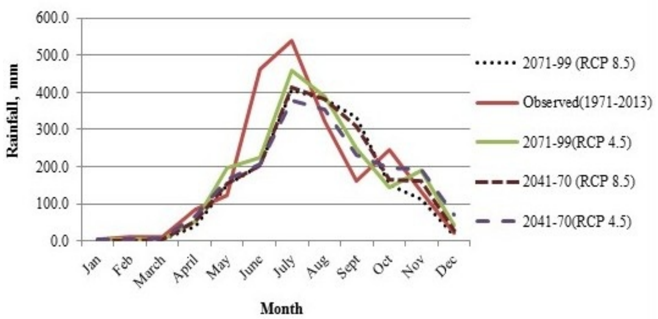

Figure 2. Comparison of present and bias corrected future scenario precipitation over Bharathapuzha basin

Based on the predictions done, there may be a decrease of 4% and 7% in average annual rainfall in the basin during 2041-70 under RCP4.5 and RCP8.5 respectively. It is also predicted that there may be a decrease of up to 10% and 15% in annual rainfall during 2071-99 during RCP4.5 and RCP8.5 respectively along with the seasonal shift.

Rainfall decline is more predominant in the months of June and July but not so in August and September. This decreasing trend in southwest monsoon rainfall in Kerala has been reported by other researchers (Guha-thakurta and Rajeevan 2007, Patwardhan et al. 2014, Raneesh and Thampi 2013).

Impact on Temperature

The monthly variation of the bias corrected data of maximum and minimum temperature for the two emission scenarios RCP4.5 and RCP8.5 for the periods 2041-70 and 2071-99 is shown in Figures 3 and 4 respectively. The annual maximum temperature in the basin may increase by 3-5 ºC (with an increase percentage of 8% to 9%) during 2041-70 under both scenarios. The increase in temperature under RCP4.5 during 2071-99 is almost to the same range, where as in the RCP8.5 scenario the increase was to the range of 4-8 ºC (8% to 15%) in the years 2071-99.

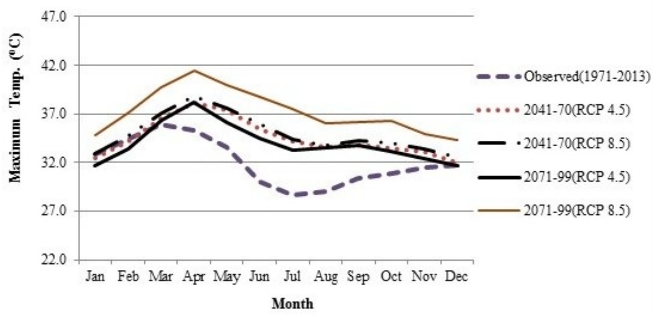

Figure 3. Comparison of present and bias corrected future scenario maximum temperature in Bharathapuzha basin

A similar increasing trend in temperature was also noted in the case of minimum temperature. The annual minimum temperature in the basin may also increase by

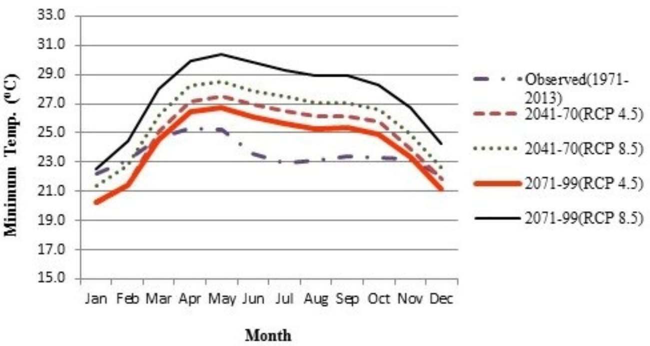

Figure 4. Comparison of present and bias corrected future scenario minimum temperature over Bharathapuzha basin

5% to 8% during 2041-70 under both RCPs, whereas the increase during 2071-99 under RCP8.5 may be up to 15%. The results obtained can be utilised in formulating future water resources management plans and for assessing the impact of climate change in the area using hydrologic models.

CONCLUSION

The probable changes of surface climate over Bharathapuzha river basin based on CORDEX simulations were analysed. Downscaled re-analysis data on precipitation and temperature from five regional climate models (RCM's) derived from different Global Climate Models (GCM's) were compared with observed data based on statistical parameters. GFDL-CM3 RCM compared better with the observed data and hence, future predicted data of the model was used for further data analysis after doing bias correction. The monthly variation of the bias corrected data of precipitation for the two emission scenarios (RCP4.5 and RCP8.5) for the periods 2041-70 and 2071-99 were compared with observed data, it is seen that there may be a consistent decrease in rainfall during all months except May, August, September, November and December. It is also predicted that there may be a decrease of 4% to 7% in average annual rainfall during 2041-70 whereas the decrease may be up to a tone of 10% to 15% during 2071-99. A seasonal shift in the rainfall pattern is observed with a significant decrease in southwest monsoon rainfall where as an increase in rainfall is observed during the northeast monsoon period. The annual maximum and minimum temperature in the basin is also predicted to increase in future under both scenarios. Results of simulation can be utilised in future for climate change impact assessment of hydrologic models in the area.

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COMPARISON OF REGIONAL CLIMATE MODELS AND PREDICTION OF FUTURE CLIMATE FOR BHARATHAPUZHA RIVER BASIN

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A changing climate can certainly perturb the hydrology of an area and thereby the life of the people living there. To assess and simulate such potential hydrological climate change impacts, hydrologic models require reliable meteorological variables for current and future climate conditions. Climate change will occur at local scales, but presently the Global Climate Models (GCM's) used for projecting climate change due to future greenhouse gas emissions have an average global climate model resolution of 2.6˚ x 3.0˚. Changes in temperature and precipitation alter the climatic conditions and subsequently hydrological and watershed processes in the long run. The effects of changes due to climatic variability on hydrological responses have been extensively carried out at watershed and river basin scales. Information at local scale is essential for assessing the impact of climate change on natural systems especially hydrologic systems and to formulate adaptation and mitigation strategies. The availability of such information at the regional or local scale is one of the major issues that climate scientists are facing.

High resolution regional model simulations have been made available recently to the scientific community, through the CORDEX (Co-ordinated Regional Downscaling Experiment) program under the auspices of the World Climate Research Programme (WCRP). The simulations over South Asian region (CORDEX-SA) are available for different models and have been archived at the data portal of Centre for Climate Change Research (CCCR) of Indian Institute of Tropical Meteorology (IITM), Pune, India. These models are of latitude/longitude approximately 50 km × 50 km horizontal resolution and have been derived using the lateral boundary conditions from Coupled Model Intercomparison Project Phase 5 (CMIP5). CORDEX-SA provides the multi-model outputs for different scenario conditions and gives a range of uncertainty of model simulations. The present study was carried out using these multi-model simulations.

The Representative Concentration Pathways (RCP's) are used for climate modelling and research. Four greenhouse gas concentration trajectories were adopted by IPCC for its fifth Assessment Report (AR5) in 2014. A "historical" run forced by observed atmospheric composition changes (reflecting both anthropogenic and natural sources), and three RCPs consistent with a high emissions scenario (RCP8.5), a midrange mitigation emissions scenario (RCP4.5) and a low so-called peak-and-decay scenario, RCP2.6. RCP 4.5 represents a stabilisation scenario, where the total radiative forcing is stabilised before 2100 and RCP 8.5 is characterised by increasing greenhouse gas emissions over time.

Uncertainties exist in the projected climate change data and these uncertainties must be taken into account when assessing the impacts, vulnerability and adaptation options. Many things pertaining to the working of the climate system are not clearly understood yet, and hence uncertainties arise because of the incorrect or incomplete description of key processes and feedbacks in the model. Climate varies on time scales due to natural interactions between the atmosphere, ocean and land, and this natural variability is expected to continue into the future. A problem with the use of regional climate model output directly for hydrological purposes is that the computed precipitation and temperature differs systematically from the observed precipitation and temperature. Bias is defined as the time independent component of the error and it arises because of several reasons. Also, the biases in the output subsequently influence other hydrologic processes like evapotranspiration, runoff, snow accumulation and melt. Some form of pre-processing is necessary to remove biases present in the computed climate output fields before they can be used for impact assessment studies. Biases (errors) present in the computed climate output fields must be removed before they can be used for impact assessment studies.

Though the state of Kerala is blessed with an annual average rainfall of 3000 mm, the flow in the rivers during summer has become meagre. The variations of different climatological parameters are highly location specific and hence studies need to be done in the regional level. There is a need to study the trend in the temperature and rainfall in the Bharathapuzha basin since there is severe drought and dearth of water in the basin. Hence an attempt was done for studying the temperature and rainfall variability in future based on predicted scenarios for the Bharathapuzha river basin in Kerala.

The Bharathapuzha river basin which lies between 10° 25’ - 11° 25’ N and 75° 50’ - 76° 55’E is the second longest basin in Kerala with a length of around 209 km. It extends over an area of 6186 square kilometres spread over the two states of India, namely Kerala and Tamil Nadu with an aerial extent of 71% and 29% respectively. The river is the major source of water for Thrissur, Palakkad and Malappuram districts of Kerala and Coimbatore and Tiruppur districts of Tamil Nadu.

In the current study, the comparison of output of Regional Climate Models (RCM’s) and the selection of an appropriate RCM model is done. Observed data of Bharathapuzha river basin on precipitation and temperature during the reference period and historical data from 5 regional climate models (RCA4, CCAM (CCSM4), CCAM(CNRM), CCAM(GFDL-CM3) and CCAM(MPI) derived from the GCM’s EC-EARTH, CCSM4, CNRM-CM5, GFDL-CM3 and MPI-ESM-LR respectively were compared. The similarity of the data sets with the observed data was evaluated on the basis of four statistical parameters (Standard deviation, Correlation coefficient, coefficient of variation and centred root mean square difference). The data analysis focuses on the period 1971-2005 as the reference period and two scenario periods 2041-70 and 2071-99. Two emission scenarios pathways selected for the study, RCP 4.5 and RCP 8.5 roughly corresponds to the Special Report on Emission Scenarios (SRES) B1 and A1F1 respectively by 2100.

Precipitation and temperature are the key drivers for the hydrological regimes and hence both were bias corrected. In the simplest formulations of bias correction, only the changes in a specific statistical aspect (mean value or the variance) of the computed field are used. Leander and Buishand (2007) found that a relatively simple non-linear correction, adjusting both the biases in the mean and its variability, leads to better reproduction of observed extreme daily and multi-daily precipitation amounts than the commonly used linear scaling correction. This power law transformation method which corrects for the coefficient of variation (CV) and the mean of the precipitation values was used in this study to correct for bias in precipitation data. The most important statistics (coefficient of variation, mean and standard deviation of the model data) were matched with corresponding quantities computed from the observed values. The daily precipitation P is transformed to a corrected value P^* using

$$P^* = aP^b \qquad (1)$$

where a and b are constants.

Correction for temperature involves shifting and scaling to adjust the mean and the variance. The corrected daily temperature T* is given by:

$$T^* = \bar{T}_{obs} + \frac{\sigma(T_{obs})}{\sigma(T_{mod})}(T_{mod} - \bar{T}_{obs}) + (\bar{T}_{obs} - \bar{T}_{mod}) \qquad (2)$$

where T_{mod} is the uncorrected daily temperature from GFDL-CM3 model and T_{obs} is the observed daily temperature. In this equation an overbar denotes the average over the considered period and σ the standard deviation. The bias corrected data for both scenarios and the two future scenario periods were compared with the observed data.

The results of comparison of the observed data to the historical data of five models on the basis of the four statistical parameters (Standard deviation, Correlation coefficient, coefficient of variation and centred root mean square difference) calculated is given in table 1. On the basis of these parameters, the GFDL-CM3 gave better comparison with the observed data. Hence the model was used for further analysis.

The RCM GFDL-CM3 shows a good ability to simulate the present climate over the basin. Even then, presence of uncertainties on the future climate because of systematic bias needs to be corrected. Bias correction for precipitation and temperature was done using the method explained by Leander and Buishand.

Table 1. Statistical comparison of different model estimates with observed data

	EC-	**CCSM4**	**CNRM**	**GFDL-**	**MPI**	**Observed**
Precipitation						
Standard deviation	49.69	56.50	58.52	73.43	56.87	181.46
Correlation	0.24	0.68	0.74	0.76	0.78	
Coeff. of variation	0.44	0.58	0.62	0.66	0.59	1.03
Centred RMSE	3.86	1.75	1.88	1.57	1.71	
Maximum Temperature						
Standard deviation	2.92	2.47	2.62	2.32	2. 50	2.39
Correlation	-0.14	0.72	0.69	0.76	0.73	
Coeff. of variation	0.10	0.09	0.10	0.09	0.09	0.07
Centred RMSE	3.86	1.75	1.88	1.57	1.71	
Minimum Temperature						
Standard deviation	1.52	1.72	1.82	1.71	1.82	1.09
Correlation	0.49	0.77	0.78	0.82	0.81	
Coeff. of variation	0.09	0.08	0.09	0.08	0.09	0.05
Centred RMSE	1.31	1.07	1.13	0.99	1.08	

The coefficient values determined by this method for each month were used to correct the precipitation and temperature data for the future periods. The model data for two emission scenarios RCP4.5 and RCP8.5 and two scenario periods 2041-70 and 2071-99 were corrected using this method. A marked improvement was achieved with nonlinear transformation, adjusting the mean as well as coefficient of variation of daily precipitation.

The monthly variation of the bias corrected data of precipitation for the two emission scenarios RCP4.5 and RCP8.5 for the periods 2041-70 and 2071-99 is shown in figure 1. There is a consistent decrease in rainfall during all months except May, August, September, November and December for the two emission scenarios and for both future periods. After studying the rainfall trend during the southwest monsoon, it is observed that rainfall during the months of June and July showed a decrease whereas there was increase in rainfall during the months of August and September. A seasonal shift in the rainfall pattern is observed with a significant decrease in southwest monsoon rainfall where as an increase in rainfall is observed during the northeast monsoon period.

Rainfall decline is more predominant in the months of June and July but not so in August and September. The decreasing variability in southwest monsoon rainfall over Kerala is supported by other researchers (Raneesh et al., 2013, Patwardhan et al., 2014).

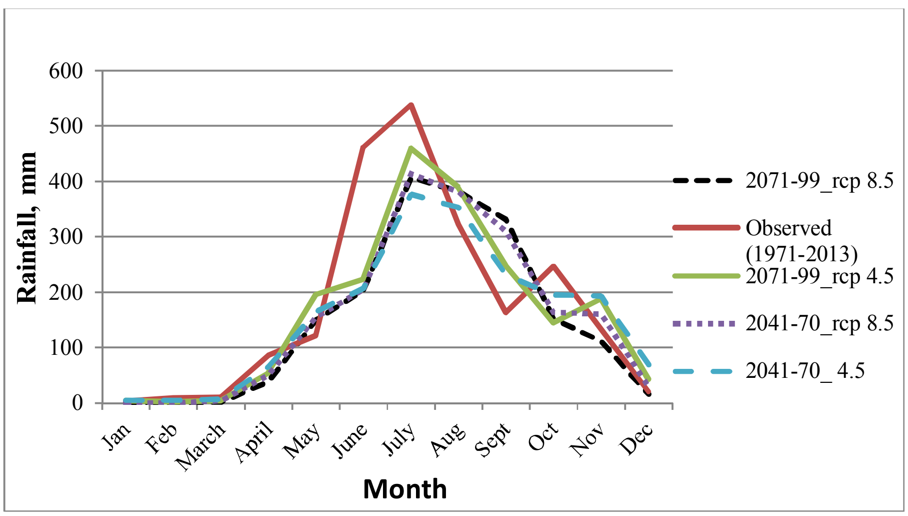

Fig.1 Comparison of present and bias corrected future scenario precipitation over Bharathapuzha basin

The monthly variation of the bias corrected data of maximum temperature and minimum temperature for the two emission scenarios RCP4.5 and RCP8.5 for the periods 2041-70 and 2071-99 is shown in figures 2 and 3 respectively.

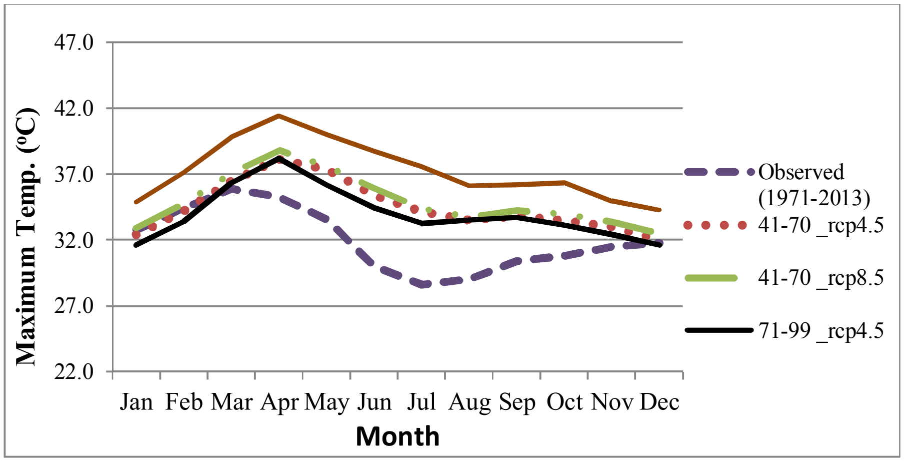

Fig.2 Comparison of present and bias corrected future scenario maximum temperature in Bharathapuzha basin

The increase in maximum temperature over observed temperature in RCP4.5 scenario was in the range of 3-5ºC, whereas in the RCP8.5 scenario the increase was to the range of 3-8ºC in the years 2017-99. A similar trend in with increase in temperature was also noted in the case of minimum temperature also.

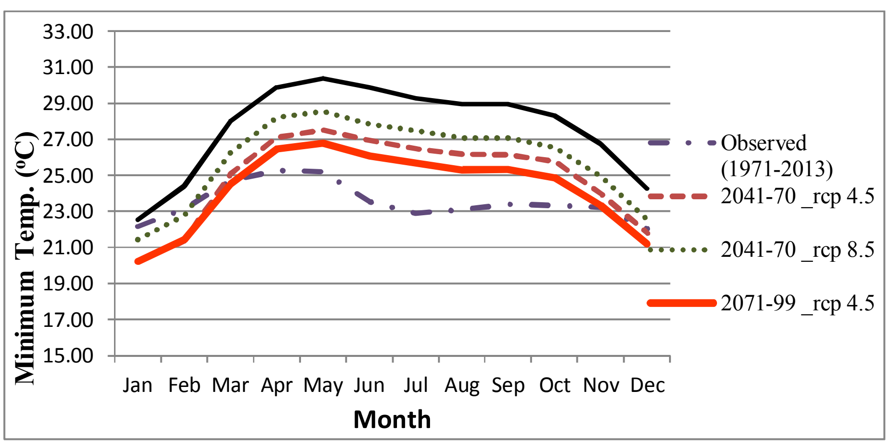

Fig.3 Comparison of present and bias corrected future scenario minimum temperature over Bharathapuzha basin

In this study the potential changes of the surface climate over Bharathapuzha river basin based on grid values at 0.44ºx 0.44º resolution CORDEX simulation was analysed. The estimation of systematic errors of 5 RCM's engaged in CORDEX project were analysed by comparing statistical parameters such as standard deviation, correlation coefficient, coefficient of variation and centered root mean square error (RMSE) over the study area. Bias correction was performed to ensure that the important statistics (standard deviation, mean and coefficient of variation) of the downscaled output matched the corresponding statistics of the observed data. Bias correction coefficients thus derived was used to correct the meteorological data on temperature and precipitation obtained from CORDEX for the future periods (2041-71and 2071-99). A marked improvement was observed by the non-linear transformation used. Results of simulation can be used in future as input for climate change impact assessment of hydrologic models.

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