EVALUATION OF IRRIGATION INDUCED HYDROLOGICAL CHANGES IN THE MALAPRABHA RIVER BASIN, KARNATAKA, INDIA

Thesis

Submitted in partial fulfilment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

by

USHA A

DEPARTMENT OF WATER RESOURCES AND OCEAN ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,

SURATHKAL, MANGALORE -575025

DECEMBER, 2021

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DECEMBER, 2021

DECLARATION

By the Ph.D. Research Scholar

I hereby *declare* that the Research Thesis entitled "**Evaluation of Irrigation induced Hydrological changes in the Malaprabha river basin, Karnataka, India**", which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in the **Department of Water resources and Ocean engineering** (Formerly Department of Applied Mechanics and Hydraulics), is a *bonafide report of the research work* carried out by me. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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Place: NITK-Surathkal

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CERTIFICATE

This is to *certify* that the Research Thesis entitled "**Evaluation of Irrigation induced Hydrological changes in the Malaprabha river basin, Karnataka, India**", submitted by USHA A. (Register Number: 155102AM15F11) as the record of the research work carried out by her, is *accepted as the Research Thesis submission* in partial fulfilment of the requirements for the award of degree of **Doctor of Philosophy**.

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ABSTRACT

Water and food are the two most essential needs for the survival of humankind. However, satisfying their increased demands for a growing human population remains a major challenge for several countries. The increasing demand for food can be fulfilled to a large extent by enhancement in agricultural productivity through the introduction of irrigation. Consequently, there has been a worldwide increase in irrigated agriculture during the past several decades. However, the introduction of large-scale irrigation in a region can bring about a wide variety of changes in the environmental, economic, and social domains. Since irrigation water withdrawals account for more than 70% of the total available water resources of the world, there is a potential for alteration of hydrological processes and regional climate patterns. Environmental impacts of irrigation in general and hydrological impacts in particular, which are usually detrimental in nature, have been a cause for concern given the rapid increase in irrigated agriculture across the world. Therefore, studies aimed at assessing irrigation impacts on regional hydrology are very essential to understand changes in the hydrological cycle and the magnitudes of water balance components. Improved understanding of such impacts will pave the way for developing plans for sustainable development and management of water resources.

The primary objective of the present research work was to analyze the impacts of large-scale irrigation on river-basin scale hydrological processes. Accordingly, the Malaprabha River basin located in a semi-arid Karnataka State, India in which an irrigation project was established in 1972, was selected for the study. The sequential methodology adopted to evaluate the hydrological effects of irrigation consisted of 1) Characterizing the river basin using historical observations of hydro-meteorological variables 2) Analysing the likely effects of irrigation on long-term trend and variability of hydro-meteorological variables 3) Analysing the historical growth of irrigated agriculture in the Malaprabha river basin using CROPWAT 4) Identify and evaluate the contributions of major drivers causing the stream-flow change in the river using the SWAT model and 5) Evaluating the

hydrological impacts of irrigation using plausible cropping pattern scenarios in the river basin.

With the obtained historical hydro-meteorological data (rainfall, rainy days, average temperature, stream flows, and groundwater levels), a preliminary analysis was carried out using box-whisker plots and Spatio-temporal maps over the Malaprabha river basin. The analysis revealed that the large part of the basin experiences annual average rainfall between 544 mm to 700 mm, which is a typical range for a semi-arid climate. Streamflow regime at downstream gauging stations was significantly affected by the Malaprabha irrigation project in the study area causing increased low flows (LFI upto 111%) during summer months and decreasing amount of peak flows (HFI upto 37.4%) during monsoon. Also, higher GWL fluctuations (10 to 20 mbgl) were observed in the downstream command area during all seasons. This defending the fact that excessive groundwater utilization for growing water-intensive crops in the immediate vicinity to the reservoir.

Trend analysis for the historical hydro-meteorological variables was carried out from 1960 to 2015 using nonparametric Singular Spectrum Analysis (SSA) and conventional Sen's slope Estimator (SE) methods. The results demonstrated the ability of SSA to capture the trajectory of nonlinear trends over the entire time series of hydro-meteorological variables. The traditional SE and MK methods, on the other hand, provide information on linear monotonic trends. The temporal variability of the data was analyzed using the Coefficient of Variation (CV) statistic. Variability study revealed that the presence of the reservoir has resulted in the occurrence of rainfall events with higher intensities in its vicinity. Also, wells located in irrigable command areas are subjected to greater variability. The trend analysis indicates non-significant decreasing rainfall and rainy days till the year 2000, but an increasing trend thereafter. A significant increasing trend in mean temperature was observed for all the stations and all the seasons of the basin with an average magnitude of 0.2º C per decade. The annual stream-flow trends for downstream gauging stations were subjected to variability as these are regulated flows and showed decreasing trends corresponding with the progression of irrigation in the command area. Groundwater levels of most of the wells in the upstream region showed increasing annual trends. The two wells located in close vicinity of the Malparabha dam towards the downstream side showed significantly decreasing trends. On the other hand, the wells in the downstream command area indicated a combination of significantly increasing and decreasing trends.

The analysis of the historical growth of irrigation in the Malaprabha command area revealed that the commissioning of the irrigation project has a significant role in the development of irrigated agriculture in the region. The contribution of canal supplies to irrigated agriculture was maximum until 1985-86 (61%) and decreased thereafter and the contribution of canal supplies to irrigated agriculture was maximum until 1985-86 (61%) and decreased thereafter. Also, the regions close to the reservoir appear to be fully benefitted by canal water supplies whereas regions located away from the reservoir seem to be benefitting from groundwater supplies. A shift from low water consuming crops to water-intensive crops is observed and the area under cash crops has increased significantly. Cropping-pattern violations, flood-irrigation, illegal water withdrawals, and poor maintenance of canal and associated structures are likely causing the current status. Overall, it appears from the performance analysis that the Malaprabha irrigation project has not been able to enforce the planned objectives and goals.

The SWAT hydrological model was applied to study the combined and isolated effects of Malaprabha reservoir, LULC change, and climate change for the decades 1980s, 1990s, and 2000s. The combined effect of changes in all three drivers caused an increase in annual stream-flow in the basin by 53% between the 1980s and 1990s and a decrease in stream-flow by 38% between 1990s and 2000s. The study reveals that in a tropical river basin the presence of an irrigation reservoir can significantly alter temporal variability of stream-flow which is further exacerbated by changes in LULC and climate. On the other hand, the analysis of irrigation effect on stream flows revealed that when irrigation is withdrawn, water availability in the basin was found to be improved significantly. Also, increased low-flows during the non-monsoon period and decreased flows during the

monsoon period have been noticed for irrigation conditions concerning no-irrigation conditions. The quantity of actual evapotranspiration (AET) in the study for existing irrigation conditions was increased by 4 to 26% concerning the no-irrigation scenario and 15% concerning the proposed irrigation scenario over the irrigated sub-basins.

The present study demonstrated a sequential methodology adopted to evaluate the hydrological effects of irrigation over the Malaprabha river basin through statistical analysis as well as using a hydrological model. The information provided by this study will be useful in solving water scarcity issues in the river basin through the development of effective management strategies to improve the efficiency of the Malaprabha project and promote the sustainable development of natural resources in the study area.

Key Words: *Irrigated agriculture, Hydrological impacts, Command area, Cropping pattern, Singular Spectrum analysis, Sen's slope, CROPWAT, Malaprabha river basin, SWAT model.*

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LIST OF ABBREVIATIONS

Abbreviation	Description
AAR	average annual rainfall
AGNPS	Agricultural Non-point Source model
CADA	Command Area Development Authority
CAM	Community Atmosphere Model
CGWB	Central Ground water Board
CLM	Community Land Model
CN	Curve Number
CV	Coefficient of Variation
CWC	Central Water Commission
CWR	Crop Water Requirement
$\overline{D}_A$	average annual number of rainy days
DBHM	distributed biosphere hydrological model
DEM	Digital Elevation Model
DES	Directorate of Economics and Statistics
DPR	Detailed Project Report
EMD	Empirical Mode Decomposition
ET	Evapotranspiration
ET_0	Reference Crop Evapotranspiration
ET_C	crop evapotranspiration
FAO	Food and Agricultural Organization
FDC	Flow Duration Curves
HFI	High flow index

HRU	Hydrologic Response Units
HY	Hilly climatic zone
IMD	India Meteorological Department
IQR	inter-quartile range
ISRO	Indian Space Research Organization
IWR	Irrigation Water Requirement
Kc	Crop Co-efficient
LFI	Low flow index
LH	Latin Hypercube
LIS	lift irrigation schemes
LULC	land use/land cover
M	Monsoon
M ha	Mega hectares
MAR	Modele Atmospheric Regional model
mbgl	meters below ground level)
MC-SSA	Monte-Carlo SSA
MK	Mann-Kendall Test
MLBC	Malaprabha Left Bank Canal
MLBCC	Malaprabha left bank canal construction
MODFLOW	Modular 3D flow model
MRBC	Malaprabha Right Bank Canal
MSL	Mean Sea Level
ND	Northern dry
NE	North East
NEXGDDP	NASA Earth Exchange Global Daily Downscaled Projections
NIH	National Institute Hydrology
NITK	National Institute of Technology Karnataka
NRSC	National Remote Sensing Centre
NSE	Nash-Sutcliffe Efficiency

NT	Northern transition
NW	North West
PBIAS	Percentage bias
PCA	Principal Component Analysis
P_{eff}	effective rainfall
POMKH	Post-monsoon Kharif
POMRB)	Post-monsoon Rabi
PREM)	Pre-monsoon
R^2	Coefficient of determination
$\bar{R}_A$	average annual rainfall
RAMS	Regional Atmospheric Modelling System
RG	rain gauge
RMSE	root mean square error
SCS	Soil Conservation Cervice
SE	South East
SE	Sen‘s slope Estimator
SNHT	Standard Normal Homogeneity Test
SRTM	Shuttle Radar Topography Mission
SSA	Singular Spectrum Analysis
SUFI-2	Sequential Uncertainty Fitting
SVD	singular value decomposition
SW	South West
SWAT	Soil and Water Assessment Tool
SWAT-CUP	SWAT- Calibration and Uncertainty procedures
USDA-ARS	United States Department of Agriculture- Agricultural Research Service
VIC	Variable Infiltration Capacity model
WEAP	Water Evaluation and Planning model
WRDO	Water Resources Development Organization

CHAPTER 1
INTRODUCTION

1.1 GENERAL

Water and food are the two most essential needs for the survival of humankind. However, satisfying their increased demands for a growing human population remains a major challenge for several countries. The increasing demand for food can be fulfilled to a large extent by enhancement in agricultural productivity through the introduction of irrigation. Consequently, there has been a worldwide increase in irrigated agriculture during the past several decades. However, the introduction of large-scale irrigation in a region can bring about a wide variety of changes in the environmental, economic, and social domains. Since irrigation water withdrawals account for more than 70% of the total available water resources of the world (Shiklamanov 1998), there is a potential for alteration of hydrological processes and regional climate patterns. Environmental impacts of irrigation in general and hydrological impacts in particular, which are usually detrimental in nature, have been a cause for concern given the rapid increase in irrigated agriculture across the world. Therefore, studies aimed at assessing irrigation impacts on regional hydrology are very essential to understand changes in the hydrological cycle and the magnitudes of water balance components. Improved understanding of such impacts will pave the way for developing plans for sustainable development and management of water resources.

1.2 IRRIGATION

Irrigation is generally defined as the process of artificial application of water to the land to supply moisture essential to effective plant growth (Shanan 1987). Seasonal rainfall fluctuations make rain-fed farming a risky venture. Irrigation reduces some of the uncertainties and thereby promotes increased production. In deserts and arid zones, irrigation enables the economic development of areas which otherwise would be unproductive and uninhabitable. Estimates indicate that about half of the increase in agricultural production in the previous decades has come from irrigated land, about one-third of the world's crops are grown on one-sixth of the cropped area which is irrigated, and the irrigated land is, on average, more than twice as productive as rain-fed land (Stockle 2001). Irrigation water withdrawal normally far exceeds the net irrigation water requirement because of water lost in its distribution from its source to the crops. According to FAO, statistics for 2016 indicate that the total amount of water withdrawals worldwide is 4001 km^3/year which includes municipal, industrial, and agricultural sectors which account for 12, 19, and 69% withdrawals respectively.

1.3 IRRIGATION IN INDIA

India is an agrarian country and agriculture is the most important contributor to the Indian economy. India has the highest land area (704 Mha) equipped for irrigation in the world (Figure 1.1). The ultimate irrigation potential of India has been estimated to be 139.5 Mha, comprising 58.5 Mha from major and medium schemes, 15 Mha from minor irrigation schemes, and 66 Mha from groundwater exploitation. India's irrigation potential has increased from 22.6 Mha in 1951 to about 139.5 Mha by the end of 2013. Figures. 1.2 and 1.3 show water withdrawals and variations of cultivated and irrigated areas of the country respectively. The total cultivated area increased from 162.4Mha in 1962 to 169.34Mha in 2014. The actual irrigated area extended from 24.88 to 66.103 Mha during the respective years. It can be observed that about 90% of total water withdrawals are for agricultural activities.

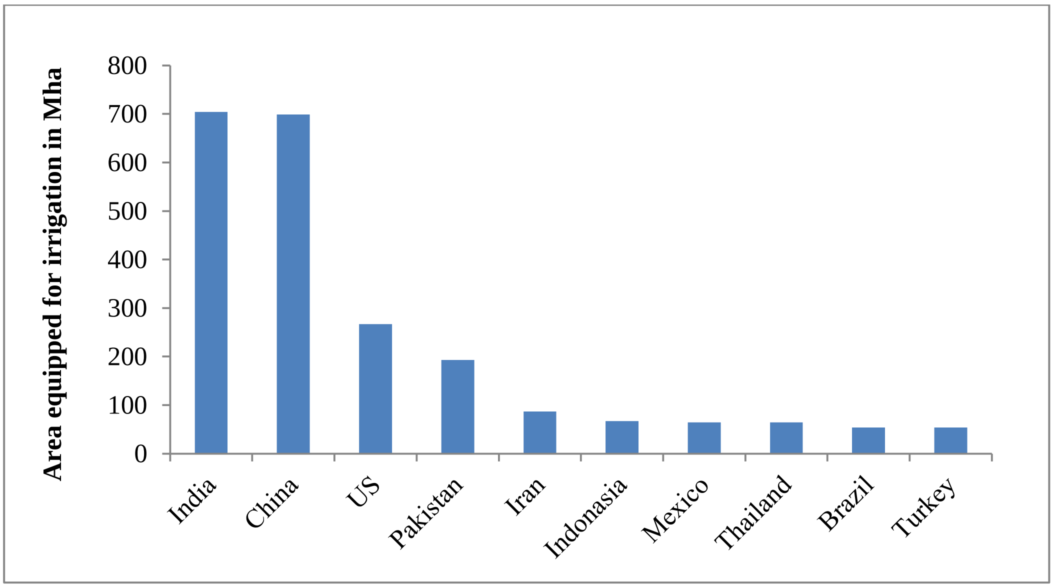
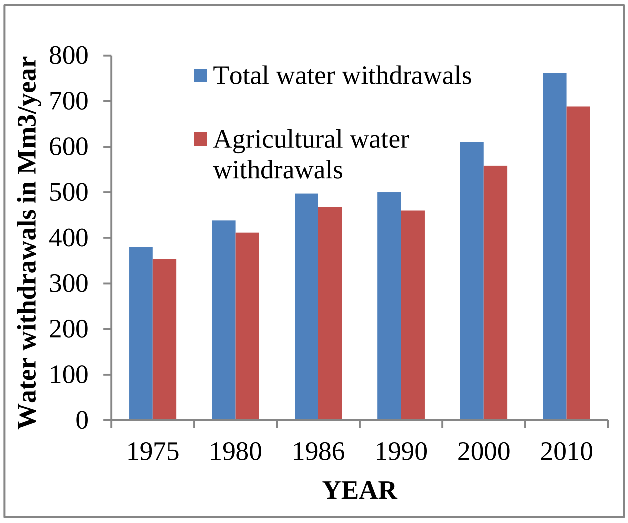


Figure 1.1: Top 10 Irrigated countries worldwide



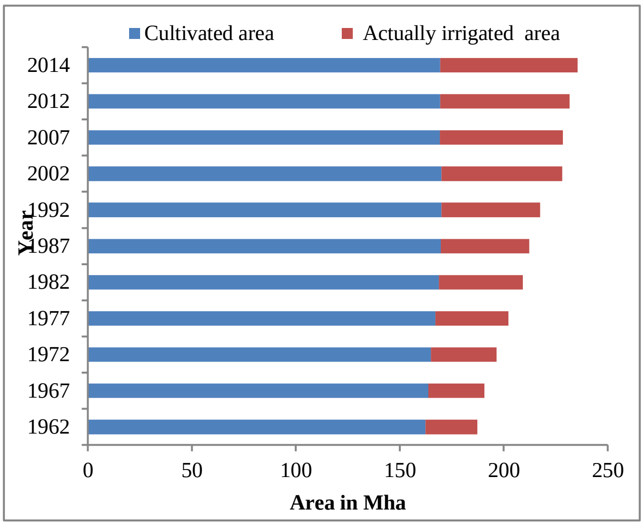


Figure 1.2: Water Withdrawals of India **Figure 1.3: Extend of Cultivated and Irrigated area *(Source*: FAO UN, AQUASTAT 2016*).***

1.4 ENVIRONMENTAL IMPACTS OF IRRIGATION

The benefits of irrigation have resulted in lower food prices, higher employment, and more rapid agricultural and economic development. The spread of irrigation has been a key factor behind the near tripling of global grain production since 1950 (Sekler et al. 1998). However, irrigation practice and water resource development can also cause hydrological, social, and environmental problems. The sustainability of irrigated agriculture is being questioned, both economically and environmentally. The increased expansion of irrigation has not been without its negative environmental effects. The following section enumerates different sources of environmental impacts associated with an irrigation scheme.

1.4.1 Construction of irrigation projects

An estimated 40,000 large dams and 800,000 small dams have been built and around 272 million hectares of land are under irrigation worldwide (Keiser et al. 2005). Large irrigation projects which impound or divert river water have the potential to cause major environmental disturbances, resulting from changes in the hydrology and limnology of river basins. Diversion of water through irrigation canals further reduces the water supply for downstream users, including municipalities, industries, and agriculture. A reduction in river base flows also decreases the dilution of municipal and industrial wastes added downstream, posing pollution and health hazards like malaria, bilharzia and river blindness, whose vectors proliferate in the irrigation water.

1.4.2 Impact on Hydrological flow regime

The consumptive nature of irrigation changes the local hydrological flow regime. Potential impacts of irrigation on water resources include changes to river flow rates, in particular low flows, and altering the groundwater levels as a result of abstraction and changes in recharge rates. Figure 1.4 depicts a conceptual diagram of flow through a river-supplied irrigation scheme.

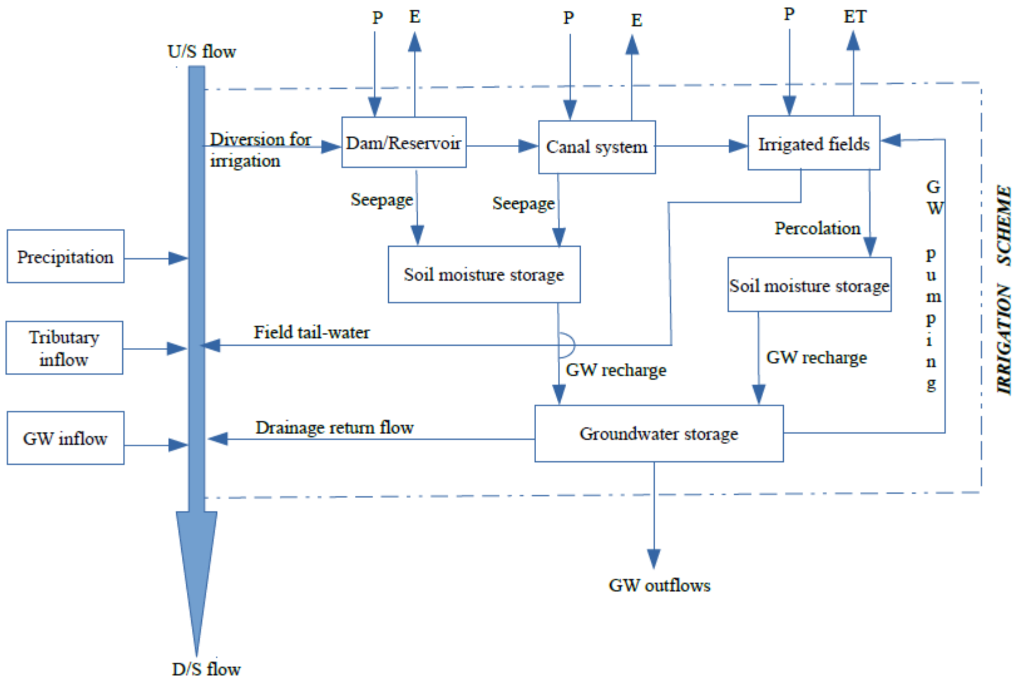


Figure 1.4: Conceptual diagram of irrigation scheme with return flow for a given reach of a river system. *(Source:* Utah State University Foundation 1969. FAO*).*

Changes to the low flow regime may have significant negative impacts on downstream users. As return flows contribute to low flows, the flows need to be high enough to ensure sufficient dilution of pollutants discharged from irrigation schemes and other sources such as industry and urban areas. Large changes to low flows will alter micro-habitats such as wetlands. The ecology of estuaries is sensitive to the salinity of the water which is determined by the low flows. Saline intrusion into the estuary will also affect drinking water supplies and fish catches.

Radically altered flood regimes may also have negative impacts. Floodwaters are important for fisheries both in rivers and particularly in estuaries. Floods trigger spawning and migration and carry nutrients to coastal waters. Controlled floods may result in a reduction of groundwater recharge via flood plains and a loss of seasonal or permanent wetlands. Finally, changes to the river morphology may result because of changes to the sediment carrying capacity of the floodwaters. This may be either a positive or negative impact.

1.4.3 Source of Water supply for irrigation projects

Irrigated agriculture depends on supplies from surface and groundwater. The environmental impact of an irrigation system depends on the nature of the water resource, the quality of the water, and how water is delivered to the irrigated land.

Over-extraction (withdrawing water in excess of the recharge rate) of groundwater can result in the lowering of the water table, land subsidence, decreased water quality, and salt-water intrusion in coastal areas. Withdrawing surface water implies changes to the natural hydrology of rivers and water streams, changes to water temperature, and also deeply affecting the aquatic ecosystems associated with these water bodies.

1.4.4 Agricultural management practices

The management of water application systems, as well as the suitability of related agronomic practices, has a dramatic influence on the environmental impact of irrigated agriculture. Poorly planned and executed agricultural practices such as flood irrigation, extensive monoculture, excessive use of fertilizers, insufficient drainage facilities, etc., leads to problems like salinization, water-logging, and downstream degradation of water quality by salts, agrochemicals, and toxic leachates. Low irrigation efficiencies (as low as 20 to 30%), poor water distribution, and maintenance system management are the main causes of the rise of the water table. Groundwater rising under capillary action will evaporate, leaving salts in the soil. The problem is of particular concern in arid and semi-arid areas with major salinity problems.

1.5 HYDROLOGICAL MODELLING

Given the complexity of the problem, recourse has to be taken to simulation whereby the various drivers which cause problems need to be identified and their impact on the system needs to be quantified in specific terms. Engineers commonly use hydrological modeling to answer this since a model is a mathematical description of the spatial processes of the hydrological cycle and is often used to estimate basin water resources as well as for impact assessment or for formulating policies of water resources management. Many hydrological models have been developed in the past and are also still being developed. They are used to determine the performance of watersheds under inevitable land-use changes, climate change, and increased climate variability. Hydrological models can be broadly classified as:

i. Hydrological models that can be either lumped or spatially distributed. Lumped models do not take into account spatial heterogeneity across the modeling domain. Rather, they simulate a spatially averaged hydrological system. Spatially distributed models allow for spatially varying precipitation, temperature, and other climatic variables, and the spatial occurrence of watershed characteristics such as soils, slope, and land cover types (Chow et al. 1988).

ii. Hydrological models that can be either single event (e.g. a rainstorm) or continuous simulation models. Continuous simulation models are designed to simulate water quantity and quality characteristics in the catchment over an extended period and provide an output representing longer-term average conditions.

iii. Hydrological models on a conceptual basis as being empirical or physically-based. Several models have been developed considering the different aspects mentioned above. Some of the popular distributed hydrological models developed are NITK model, Agricultural Non-point Source model (AGNPS) (Young et al. 1989), Water Evaluation and Planning model (WEAP) (Yates et al. 2005a, b), Modular 3D flow (MODFLOW) model (McDonald and Harbaugh 1984), Variable Infiltration Capacity model (VIC) (Liang et al. 1994) and Soil and Water Assessment Tool (SWAT)(

Arnold and Fohrer 2005). SWAT is being widely used internationally for water resources assessment due to its capability to model the basic interventions such as storage/diversion structures, land use, and agricultural management practices, pollutant tracking as well as the effects of climate change (Kumar Raju 2016).

1.6 SCOPE OF THE STUDY

As there is an increasing trend to make irrigated agriculture accountable for its impact on the environment as well as to critically evaluate the water use in the agricultural sector compared with other competing uses, improving the environmental performance of irrigated agriculture is also important for its long-term sustainability.

The present work attempts to develop a methodology to evaluate the impacts of extensive irrigation water withdrawals on catchment-scale hydrological processes. The focus of the present research is to investigate the impacts of irrigation water withdrawals on the hydrology of the Malaprabha river basin, Karnataka State, India. Large-scale irrigation commenced in this river basin with the construction and operation of the Malaprabha project in 1972. The focus of the present study was to analyze available historical records of hydro-climatic variables, streamflow, and groundwater levels to detect changes in them due to irrigation activities. The study also intends to simulate the impact of irrigation on streamflow using the popular Soil and Water Assessment Tool (SWAT) hydrological model. Ground-based data on crops and also classified images of land use/land cover (LULC) and soil were used to provide inputs to the model. Hypothetical scenarios of changes in cropping patterns were used to simulate their likely impacts on the hydrology of the Malaprabha basin.

1.7 OBJECTIVES OF RESEARCH WORK

The objectives of the present research work are:

1. To characterize the hydrology of the Malaprabha river basin using historical data of relevant variables.
2. To analyze variability and trends in observed historical records of

hydro-meteorological variables and evaluate the likely effects of irrigation on such variability.

3. To analyze the growth of irrigated agriculture and quantify historical and current crop/irrigation water requirements in the command area of the Malaprabha irrigation project.
4. To evaluate the contributions of major drivers causing streamflow variations in the Malaprabha river basin using the SWAT hydrological model.
5. To analyze the impacts of irrigation water withdrawals (from surface and groundwater sources) and scenarios of changes in cropping patterns on hydrological processes using the SWAT model.

1.8 ORGANIZATION OF THE THESIS

The thesis comprises nine chapters and a list of references. A brief description of each chapter is presented herein.

Chapter 1 introduces the problem being considered for the study describes the importance of the study in India, the scope of the research work, and the main objectives of the study work.

Chapter 2 presents a critical review of literature pertaining to the impacts of irrigation on climate and hydrological processes along with the use of hydrological models in this regard.

Chapter 3 provides details of the study area and data products used in the study.

Chapter 4 provides an analysis of the hydrology of the Malaprabha river basin using historical data of relevant variables.

Chapter 5 includes trend and long-term variability analysis of historical records of hydro-meteorological variables and discusses the likely effects of irrigation on such variability.

Chapter 6 describes the growth of irrigated agriculture and quantifies historical and current crop/irrigation water requirements in the command area of the Malaprabha project.

Chapter 7 deals with the identification of major drivers causing stream-flow variations in the Malaprabha river basin using the SWAT hydrological model.

Chapter 8 analyses the impacts of irrigation along with changes in patterns of hydrological processes scenarios caused by changes in cropping patterns using the SWAT model.

Chapter 9 presents conclusions of the research along with limitations and discusses the scope for future research.

CHAPTER 2
LITERATURE REVIEW

2.1 General:

The introduction of irrigation in a region can bring about a wide variety of changes in the environmental, economic, and social domains. In particular, environmental impacts of irrigation, which are usually detrimental in nature, have been a cause for concern given the rapid increase in irrigated agriculture across the world. Therefore, a large number of previous studies have focused on the identification, characterization, and evaluation of impacts of irrigation on diverse aspects of the environment at different spatial and temporal scales. Among the various possible environmental impacts, changes brought about by irrigation in the natural water cycle and climate are probably most important given the widespread nature of these impacts.

The primary objective of the present study is to evaluate the impacts of irrigation water withdrawals on the hydrology of a tropical river basin located in India. In developing an appropriate methodology for performing such an evaluation, a comprehensive review of previous studies focusing on identification, characterization, and evaluation of impacts of irrigation on diverse environmental impacts, especially changes brought about by irrigation in the natural water cycle and climate was carried out and a report is presented in this chapter.

Several previous research studies have been undertaken to analyze the impacts of irrigation water withdrawals on hydrological processes at global, regional, and catchment scales. The most common approach adopted has been by incorporating an appropriate irrigation module into hydrological models which are either water balance models or land surface hydrology models. A comprehensive review of such studies is presented in this chapter. For the sake of clarity, the review has been classified into studies pertaining to 1) impacts of irrigation on climatic variables (precipitation and air temperature) 2) impacts on surface water hydrology in general, and streamflow in particular 3) impacts on groundwater hydrology. Major conclusions from the literature review and research gaps are been described at the end of the chapter.

2.2 Impacts of Irrigation on Climate

Studies on analyzing irrigation impacts on hydrology started around 1950. While the initial focus of such studies was on assessing the impacts of large-scale irrigation on local and regional climate patterns, subsequent studies focused on impacts on catchment and regional hydrologic processes.

2.2.1 Effect on Precipitation

Several researchers have proposed that excessive irrigation practice has an impact on rainfall (Stidd 1967; Joos 1969; Changnon 1973). Their results indicate that irrigation causes excess convective rainfall, mostly in the early part of the summer and more so in the irrigation period. An increased thunderstorm frequency has also been reported. Among other investigators, Schickendanz (1976), has provided strong statistical evidence for the existence of irrigation-produced rainfall excess in the Great Plains of the USA. He demonstrated that there is an increase in rainfall of 19-35% in and surrounding irrigated regions during crop growing stages of the summer irrigation period. Similarly, Barnston and Schickendanz (1984) suggested that 'any synoptic condition providing low-level convergence and uplift was found to be fundamental in allowing irrigation produced low-level moisture to increase cloud development and rainfall'. Their results showed that there is a 25% increase in rainfall over the regions associated with irrigation in the Great Plains during 1931-70. However, a study conducted by Lohar and Pal (1995) over southwest Bengal, India; has demonstrated that increased rainfall will not always depend on vegetation and soil moisture, but is also greatly influenced by mesoscale effects over certain specific areas. Segal et al. (1998) carried out conceptual and numerical model evaluations to provide preliminary insight into the possible impact of the change in irrigation over North America on summer rainfall associated with medium to large scale atmospheric systems. The simulated effect of irrigation on rainfall was found to be mostly non-local since the modifications to rainfall did not coincide with irrigation locations. They conclude that the overall change in land use has a larger impact on rainfall compared with the change solely related to changes in irrigation. de Ridder and Galle´e (1998) studied the effect of irrigation on convective rainfall over Southern Israel. They used a mesoscale atmospheric model, Modele Atmospheric Regional (MAR) to perform the numerical simulations. Results showed that irrigation has a potential to increase convective moisture in the climate. But they also suggested that along with increased irrigation, a decrease in sensible heat flux is responsible for the occurrence of convective rainfall. Moore and Rojstaczer (2001) analyzed the same effect over the Great Plains through statistical methods during 1950-97. The results of their study indicate that the influence of irrigation on precipitation affects synoptic conditions only as a second-order effect and they also found a non-linear response of irrigation-induced rainfall with an increase in irrigation.

From the past literature, it has been observed that most of the researchers have proved the significant existence of the impact on rainfall. However, a few studies have shown that there is rather than irrigation alone regional rainfall is influenced collectively by other factors such as mesoscale effects, a decrease in sensible heat flux, etc. (Lohar and Pal,1995; Moore and Rojstaczer 2001). Therefore, because of contrasting results obtained, there appears to be scope for analyzing the effect of irrigation on precipitation patterns at river basin/watershed scale in other hydroclimatic zones such as tropical regions of India.

2.2.2 Effect on Air Temperature

Air temperature is one of the important parameters affected by intense irrigation practice especially at a regional scale, as demonstrated by the following studies. Schickendanz (1976) observed temperature anomalies over regions of the Great Plains during the irrigated period of 1946-1970. Barnston and Schickedanz (1984), showed that at a smaller scale, irrigation lowers the daily surface temperature by 2^0C during dry and hot weather conditions and by 1^0C during damp, cooler conditions. Alpert and Mandel (1986), also found a decrease in diurnal wind and temperature due to enhanced irrigation over Israel. de Ridder and Galle´e (1998), through their numerical simulations over Southern Israel, found out that increased irrigation has a potential to decrease the diurnal amplitude of temperature. Adegoke et al. (2003) used the Colorado State University Regional Atmospheric Modelling System (RAMS, version 4.3) to analyze the effect over U.S high plains, Nebraska. The long-term surface data trend analysis indicated decreasing trend of mean and maximum temperature over the irrigated areas.

In addition to effects on local/regional scale, the following researchers assessed the ‘irrigation cooling’ effect at a global scale. Boucher (2004) analyzed the global-scale impact of irrigation using a GCM and found a surface cooling up to 0.8K. Lobell et.al. (2008) analyzed the effect using the Community Atmosphere Model (CAM3.3) and showed up to 10^0C reduction in temperature for the period 1978-1999 worldwide. This indicates that variation in temperature reduction depends on the areal extent of the irrigation and climate of the region. Mahmood et al. (2006) compared temperature trends in irrigated areas in Nebraska with those in nearby non-irrigated areas. They found an irrigation-induced cooling of 1 K in maximum temperatures during the growing season over irrigated areas. Similarly, Bonfils and Lobell (2007) found that irrigation decreased summertime maximum temperatures in heavily irrigated areas by 2–3 K over California’s Central Valley. Kueppers et al. (2007) investigated the irrigation cooling effect over California and found that the conversion of natural vegetation to irrigated crops cooled irrigated areas by 3.7 K in August and 1.6 K year-round. Averaged over all of California, they found that irrigation (along with other land cover changes) decreased August temperatures by 0.4 K. Haddeland et al. (2006) found qualitatively similar, but smaller temperature decreases over the Colorado and Mekong river basins due to irrigation. Sacks et al., (2009) used the Community Atmosphere Model (CAM) coupled with the Community Land Model (CLM) and compared the global simulations with and without irrigation. They found that irrigation alters climate significantly in some regions such as Northern mid-latitudes, central and south-east United States, portions of south-east China and portions of southern and south-east Asia with an annual cooling of 0.5 K. However, they noted negligible effect on global average near-surface temperatures. Based on these results it can be deduced that irrigation has a negligible effect on near-surface temperature at the global scale whereas at regional scales its effect is significant.

2.3 Irrigation impact on surface water hydrology

As was pointed out in Chapter 1, large-scale irrigation can significantly alter the run-off regime of a catchment by way of increased flood flows reduced low flows and a temporal shift in the timing of run-off events. Other hydrological components likely to be affected by irrigation are evapotranspiration (ET), soil moisture, and groundwater recharge.

The majority of previous studies have focused on evaluating the impacts of irrigation on run-off and latent heat flux (evapotranspiration). For example, de Rosnay et al., (2003) incorporated an irrigation scheme into the ORCHIDEE land surface model and simulated impacts of irrigation withdrawals on surface water fluxes over the Indian peninsula. Their simulations indicated that annual streamflow decreased by 9.25%, 17%, and 43.2% at the outlets of Godavari, Krishna, and Indus river basins respectively. Also, annual mean latent heat fluxes increased by 9.5% over all the river basins. However, the irrigation scheme incorporated did not consider water storage in dams and conveyance systems which may have led to overestimation of run-off values. To overcome this limitation, Haddland et al., (2006) developed a more realistic irrigation scheme that is based on simulated soil moisture deficit and included the effect of water storage in reservoirs. The irrigation scheme was incorporated into the Variable Infiltration Capacity (VIC) land surface model and applied over Colorado (USA) and Mekong (South-east Asia) river basins with varying climatic conditions. Model simulations over 20 years considering with and without irrigation situations showed that relative effects of irrigation on annual streamflow and evapotranspiration were more significant in the arid Colorado River basin than the humid Mekong river basin. While a decrease in mean annual streamflow of 37% in the Colorado basin and 2.3% in the Mekong basin was noted, an increase in latent heat flux (evapotranspiration) of 4.7% (Colorado) and 2.1% (Mekong) were simulated. Although the irrigation scheme considered in this study was more realistic than that of de Rosnay et al., (2003), this study assumed sprinkler irrigation system for both the river basins and also did not consider water diversions and transport systems which induced the main source of uncertainty in the model simulations. This work has been continued further by Tatsumi and Yamashiki (2015) who applied the improved VIC model over the Mekong river basin. Along with a 32% decrease in total monthly run-off, they noted a 1.4% increase in average total ET over the simulation period (1979-2000). The model performance was found to be good with average Nash-Sutcliffe Efficiency (NSE) of 0.82 and percentage bias (PBIAS) ranging between -6.74 and 15.25. However, this study also did not consider water diversions and transport systems.

Tang et al., (2007) investigated the effects of anthropogenic heterogeneity (irrigation withdrawals) on runoff over the Yellow river (semi-arid) basin, China. They developed an irrigation scheme based on simulated soil moisture and available water and incorporated the scheme into a distributed biosphere hydrological model (DBHM). Simulations performed for the period 1983-2000 suggested that irrigation leads to increased evapotranspiration by $3.3Wm^{-2}$ and decreased run-off by 41%. The effect of reservoir storage and water distribution through canals was not considered in the study which led to overestimation of irrigation water requirements and underestimation of evapotranspiration values. Reshmi et al., (2008) carried out a comprehensive analysis of the streamflow response to land-use change in the Malaprabha catchment, Karnataka, India using the SWAT hydrological model. A scenario-based analysis of land-use change revealed that conversion and intensification of rain-fed agriculture into irrigated agriculture in the catchment was the main cause for the reduction in river run-off. Kienzle and Schmidt (2008) introduced an irrigation scheme into the ACRU model which consisted of a reservoir, irrigation supply, and demand, return flows, and land-use change impacts along with irrigation distribution system (manually controlled unlined canals, open water races). The model was applied to the Manuherikia catchment, Otago, New Zealand to derive the first estimates of irrigation impacts on regional hydrology. They showed that while irrigation increases water demands on account of increased ET, it also reduces mean annual catchment water yields by 37% loss with inefficient irrigation practices and by 30% even with the most water-efficient irrigation infrastructure. Based on a seasonal analysis, they noticed that irrigation affects low flows more significantly than peak flows.

Apart from streamflow and ET, irrigation can also have a significant effect on groundwater recharge and soil moisture, processes which are significantly influenced by land use (Tang et al., 2007; Micheal et al 2013; Sorooshian et al.2014). Micheal et al (2013) showed an increase of groundwater recharge rate under irrigated fields by 70% relative to non-irrigated fields in a small prairie watershed in Canada.

Sorooshian et al., (2014) employed a regional climatic model (RCM) to investigate the effects of irrigation on land hydrological processes over California, USA. The novelty of their work stems from the use of a realistic scheme in which irrigation is applied depending on soil moisture depletion level or minimum solar radiation input or minimum soil temperature. Based on simulations carried out at different time scales, they assessed induced variations in ET, soil moisture, surface and subsurface run-off, and groundwater recharge. Model results were compared to reference data obtained from a variety of sources – an offline land surface model, in-situ observations, and remote sensing data. A major finding from this study was that irrigation-induced ET shows a decreasing trend which they attribute to a reduction in net radiation. While noting that surface run-off was a negligible component of the water balance especially during the irrigation season, results indicated that groundwater recharge constituted about 18% of irrigation application. Despite achieving reasonably accurate simulations of hydrological components, they recommend modeling studies to be taken up at field scale for the more realistic representation of differences in crop responses to water stress.

From the review of previous studies, it is evident that due to differences in model physics and adopted irrigation scheme, the magnitude and spatial patterns of irrigation volumes simulated by models can differ substantially and may potentially influence the simulated effects of irrigation on land surface water budget and energy fluxes and regional/local climate. In view of this, an uncertainty analysis of the Community Land Model simulations was performed by Leng et.al, (2013) over the conterminous United States using two different input datasets of global irrigated area maps produced by Siebert et al. (2005) and Ozdogan and Gutman (2008). Results showed that simulations obtained with the Siebert et al. (2005) map were relatively more uncertain. Therefore, Leng et al., (2013) conclude that a non-realistic representation of water sources for irrigation and management conditions can lead to erroneous results. Consequently, many researchers tried to improve the representation of irrigated and other managed lands by incorporating satellite observations (Ozdogan et.al. 2010: Pokhrel et al., 2012) into LSMs.

Concerning the impact of irrigation on run-off, most studies only report variability in annual run-off. An exception is the study by Kienzle and Schmidt (2008) wherein variabilities in seasonal, peak and low flows have been reported. Such detailed information is essential for planning and management of agriculture, irrigation, and hydropower production and also in the allocation of water across various uses (Reshmi et al., 2008).

2.3.1 Impact of Irrigation structures on Streamflows

Dams and reservoirs form an integral part of a surface irrigation system. There are more than 45,000 large dams (greater than 15m high), capable of holding back more than 6,500 km^3 of water, or approximately 15% of the total annual river run-off globally (Nilsson et al., 2005) and 35% of which are designed for irrigation purposes only (Haddland et al., 2006). Hence, irrigation impacts streamflow regimes indirectly as well.

However, studies focusing on assessing the impacts of irrigation take into account the buffering effect caused by reservoirs thereby introducing uncertainties in the model simulations. The significant effects on river flow due to the construction of a dam and the formation of storage reservoir were studied by numerous researchers. For example, Schreider et al., (2002) showed that due to the construction of small farm dams in Australia, small but detectable changes can occur in the daily discharges. Magilligan et al., (2003) estimated that the peak discharges occurring every two years have decreased by 60% for several river basins in the United States on account of large storages. Batalla et al., (2004) investigated hydrological changes in the Ebro river basin (NE Spain). They compared pre and post-dam river flows and suggested that the effects of a given reservoir on downstream flow regime depend on its capacity and reservoir operational rules. Studies by Syvitski et al. 2005; Magilligan and Nislow 2005 have shown that reservoirs have profound impacts on river hydrology, primarily through changes in the timing, magnitude, and frequency of low and high flows, ultimately producing a hydrologic regime differing significantly from pre-impoundment natural flow regime. Bouwer et al., (2006) presented a method to differentiate between the effects of man-made hydrological developments (construction of dams) and climate variability over the Krishna river basin. They found that water consumption due to the construction of dams caused monthly run-off variability 3 times higher (61%) than climate variability (6 to 15%). Also, they noticed seasonal variability of river flows decreasing in monsoon due to storage in reservoir and increasing in post-monsoon due to return flows from agricultural fields to rivers as base flow. Yang et al., (2008) obtained similar results in their study performed over the middle and lower yellow river, China. Poff et al., (2007) stated that extensive construction of dams has greatly dampened seasonal and inter-annual river discharge variability. Reservoir operation reduces the rate of information production of the flow series by avoiding extreme hydrologic events and makes the flow series more regular and self-similar (Huang et al., 2015). Vogl and Lopes (2009) compared naturalized and anthropogenically impacted mean monthly and annual river flow regimes in Brazos River, Texas. They identified a decrease in the frequency of high flow events (in spring and winter) and increased summer flows. In the Chao Phraya River basin (Thailand), a comparison of the annual and monthly flow regimes downstream from the reservoirs before and after reservoir development showed a constant increase in low flow and a drastic decrease in high flow (Tebakari et al., 2012). At the middle reaches of the Irtysh River, (an international river flowing through China, Kazakhstan, and Russia), the impact of the reservoirs at the upper reaches is significant and the main factor leading to an abrupt decrease in annual run-off and its interannual variability and concentration (Huang et al., 2012). Sun and Feng (2013) carried out a multi-stage analysis of hydrologic alterations in the yellow river, China. Their results indicated that the dam operations efficiently achieved flood control, but it could not handle extremely low flows, during droughts and the water consumption by agriculture was the main cause of water shortage under an arid climate of the river basin. Huang et al., (2015) analyzed the downstream flow variability at monthly and hourly scales over Qingy River, China. Their results indicated that, on a monthly scale, reservoirs impound flood water for the dry season and at an hourly scale, reservoirs retain flood pulse and control the outflow. Consequently, reservoirs reduce variation and concentration of the run-off distribution within a year and a day.

The studies described above have utilized daily and monthly flow data to assess the hydrological regime alteration by comparing the pre-dam and post-dam flow regimes and revealed the hydrological alterations at the inter-annual and intra-annual time scales (i.e., hourly, daily, weekly, monthly and seasonal). This kind of temporal flow analysis would improve the understanding of hydrological fluctuations that occur as a result of massive human interference in a complex river system and provide practical guidance for policymakers to help them manage the basin's water resources more effectively. However, these studies have not considered the impact of land-use change and water withdrawals, which has a significant effect on downstream flows, and this accounts for major uncertainty in the results obtained. An exception to this is Doll et al., (2009) who carried out a global-scale analysis of river flow alterations due to irrigation water withdrawals and reservoirs. They found a decrease in the long-term average global discharge into oceans and internal sinks by 2.7% due to water withdrawals and 0.8% due to the storage effect of dams. Mainly due to irrigation, the low flow quantile Q_{90} decreased by more than 10% on one-sixth and one-quarter of the global land area and Q_{90} increased significantly on only 5% of the land area downstream of the reservoir. The hydrological model (WaterGAP) overestimated the irrigation water use due to the limitation in global data of the irrigated area. Consequently, they recommend that the study has to be executed in the river basin scale for a realistic representation of irrigated areas and appropriate simulations.

2.4 Irrigation impacts on groundwater hydrology

Groundwater is often used as an additional water source in regions with frequent water stress and large aquifer systems and is the main source of irrigation in arid and semi-arid regions. Globally, the area equipped for irrigation is about 301 Mha of which 38% is equipped for irrigation with groundwater (Siebert et al., 2010). Also at regional scales, a major portion of groundwater abstractions is utilized for irrigated agriculture (Rodell et al., 2009; Wada et al., 2010; Reshmidevi and Nageshkumar, 2014). Large scale abstractions of groundwater may result in lowering the water table, land subsidence, decreased water quality, and salt-water intrusion in coastal areas and also affect the aquifer storage and river flows. However, very few studies have analyzed the impact of irrigation on groundwater flow behavior.

The previous studies have mainly focused on evaluating the impact of irrigation on groundwater fluctuations and streamflow interactions. For example, Rodell et al., (2009) carried out a regional assessment of the rate of groundwater depletion over India, using remote sensing techniques. They found that groundwater depletion at a rate of 4.0± 1.0 cm yr^{-1} over the states of Rajasthan, Punjab, and Haryana (including Delhi) and that unsustainable consumption of groundwater for irrigation was the main cause for groundwater depletion. Wada et al.,(2010*)* provided a global overview of groundwater depletion for the year 2000. They evaluated total groundwater withdrawals based on different sectoral demands and applied a global hydrological model (PCR-GLOBWB) to assess the groundwater recharge component. They found that irrigation utilized a major portion of groundwater, which is non-renewable in nature and has a significant effect on groundwater depletion. The global estimates also suggested that northwest parts of India are experiencing severe water table decline, supporting the results of Rodell et al., (2009).

Kustu et al., (2010) explored the influence of large-scale irrigation pumping on spatial and seasonal patterns of streamflow regimes in the US High plains using extensive observational data. Trend (Mann-Kendall test) and step (Student's t-test) time series analysis of hydrological components such as precipitation, groundwater levels, and streamflow over the study area during intensive irrigation development period (1940-1980) were carried out. The results showed decreasing trends of annual and dry season stream flows and increasing trends of several low-flow days. The results indicate that extensive irrigation pumping caused stream flow reduction more severely. Doll et al., (2012) performed a first global-scale analysis of the impact of water withdrawals on water storage variations using the global hydrological model WaterGAP. They found that 42% of total groundwater withdrawals are utilized for irrigation purpose during the simulation period (1998-2002) and seasonal aquifer water storage variability is high under irrigation dominated regions, which in turn affect the seasonal stream-flow variability. These studies identified the effect of irrigation withdrawals on stream flows and water storage at global and large river basin scales. However, the impact of land-use change, irrigation application, and return flow to stream flows and aquifer interactions were not analyzed, which affects the reliability of simulations and water availability at a local scale.

Addressing this uncertainty, Zeng and Cai (2014) analyzed the regional scale conjunctive effects of irrigation pumping and return flows on natural stream-flow over the Republic river basin, USA. The SWAT model was modified by linking the base flow component to aquifer storage to simulate the complex effect of groundwater pumping and irrigation return flow on streamflow, and to understand the impact of irrigated agricultural development on streamflow change. The simulations (40 years) showed that irrigation not only depleted stream-flow (0.177 to 0.154m^3 s^{-1}) but also increased sub-surface flows (0.311 to 0.362m^3 s^{-1}). This indicates, ignoring irrigation return flow would overestimate stream depletion by aquifer pumping. They also observed that groundwater-fed irrigation has altered surface and groundwater interactions. On the other hand, Reshmidevi and Nageshkumar (2014) integrated SWAT with a separate water balance component to calculate the deep aquifer water table. They modeled the impact of extensive irrigation on groundwater resources in the Malaprabha catchment of India, which exhibited a very severe water table decline in the lower plain, with some areas showing around 60 m depletion over eight years. Although these researchers have calibrated the modified SWAT model using observed stream flows or ET, the verifications of groundwater modeling were still qualitative or semi-quantitative. Kirby et al., (2015) analyzed the impact of irrigation development on regional groundwater resources in Bangladesh. They developed monthly water balances for the main regions of Bangladesh to investigate historic trends in water use and availability and possible future trends under changed management. Their results show that the fall in pre-monsoon groundwater levels was greatly influenced by irrigation withdrawals and post-monsoon groundwater levels by annual rainfall variability.

It is evident that groundwater contributes significantly to irrigation and affects the hydrological processes. It is essential to consider the source while analyzing the impact of irrigation water withdrawal. Also, a well-distributed integrated modeling system is essential to represent the interactions of surface and groundwater resources.

2.5 SUMMARY

The present literature review is concerned with approaches to evaluate the impacts of extensive irrigation on climate and hydrology at global, regional, and local scales. From the review of published literature, the following salient points may be deduced concerning the present state-of-the-art with regard to the selected topic of research:

- The most widely used approach to evaluate the impact of large-scale irrigation on climate variables is through statistical analysis of the historical observations of variables at different temporal and spatial scales. Results have revealed that extensive irrigation has the potential to increase convective moisture and reduce diurnal temperature variations over irrigated areas.
- The most widely used approach to evaluate the hydrological impact of irrigation is through implementing an appropriate irrigation scheme into a hydrological model. While most previous model simulations have indicated that extensive irrigation can alter the regional/local scale hydrology of a river basin, the magnitude and direction of effects are region-specific and cannot be generalized. Also, the impacts of irrigation were found to be more critical than those brought about by land-use change and climate change.
- The general conclusion of most studies is that extensive irrigation results in an increase in evapotranspiration, soil moisture, and groundwater recharge. On the other hand, irrigation water withdrawals tend to not only reduce but also cause temporal shifts in stream flows, groundwater levels, and groundwater storage. However, the magnitude of such changes varies with the extent of irrigation area, climatic conditions of the area, and irrigation management methods adopted.

2.6 RESEARCH GAP

The hydrological impacts of irrigation can be analyzed only through consideration of realistic irrigation schemes in the hydrological models. Incorporation of irrigation scheme will lead to better representation of managed land and hence improve predictions in a model. However, a non-realistic representation of water sources for irrigation and management conditions leads to erroneous results.

- The major source of uncertainty involved in the model simulations in a majority of the studies seems to be the inability of hydrological models to incorporate combined operations of reservoir storage and release, distribution of water, and irrigation practice. Thus, accurate representation of the irrigation scheme in the hydrological model along with all the irrigation operations is necessary to obtain realistic results.
- Assessment of long-term anthropogenic impacts on agro-ecosystems requires comprehensive modeling capabilities to simulate water interactions between the surface and groundwater domains. Integrated hydrological models capable of simulating dynamic interactions of surface and groundwater, along with abilities to predict future land-use change and management practices, need to be considered for better results.
- Very few studies have addressed the irrigation effect on subsurface hydrological processes like soil moisture, deep percolation, and subsurface flows, and soil moisture is assumed at saturation condition. There is a need for more research in this regard.
- In agricultural countries like India, where surface and groundwater contribution for irrigation is very significant, studies considering both sources (surface and groundwater) of water withdrawals for irrigation are essential.

CHAPTER 3
STUDY AREA AND DATA SOURCES

3.1 GENERAL

Krishna River is the second largest river in peninsular India. The river originates as the Upper Krishna River in the Western Ghats of Maharashtra and Karnataka, drains the Deccan plateau, and discharges into the Bay of Bengal. It ranks as the fifth largest river system in India in terms of annual discharge and drainage area. The principal tributaries of river Krishna are Bhima, Ghataprabha, Malaprabha, Muneru, Musi, Palleru, and Tungabhadra (Figure 3.1). The climate of the river basin is predominantly semi-arid with a small humid region in the Western Ghats. Krishna river basin is subjected to intensive irrigation activities (around 668 dams) since 1945. The major part of the basin is covered with agricultural land accounting for 75.86% of the total area. Also, annual discharge from the river to oceans has significantly decreased (56 km^3 during 1901-1960 to 13 km^3 from 1994 to 2003) since 1960-2003 due to irrigation expansion (Biggs et.al 2007).

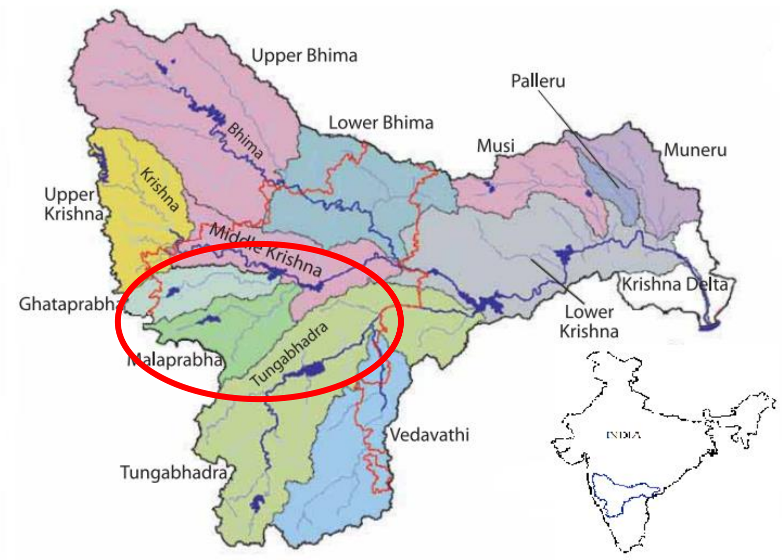


Figure 3.1 Map of the Krishna River basin

(Source: Closing of the Krishna Basin: Irrigation, Streamflow Depletion, and Macro-scale Hydrology, IWMI report).

Among the tributaries of the river, Malaprabha is subjected to large-scale irrigation with the construction and operation of the Malaprabha irrigation project in 1972 and significant amounts of surface and groundwater contribution to irrigation have been noticed (Reshmi et. al. 2008, Reshmidevi and Nageshkumar 2014) in the river basin. Due to irrigation expansion and unsustainable land-use practices, the basin is experiencing water stress across all sectors. It is for these reasons that the Malaprabha river basin was selected for the present study.

3.2 DESCRIPTION OF THE STUDY AREA

Malaprabha River is a right bank tributary of river Krishna and flows through the State of Karnataka. The river originates from the Chorla Ghats, a section of Western Ghats, at an elevation of about 792 m above MSL (Mean Sea Level) in Belagavi district, Karnataka. The river traverses eastwards almost 306 km before merging with the Krishna River at Kudalasangama in Bagalkot district at an elevation of 488m above MSL. Bennihalla, Hirehalla, and Tas Nadi are the principal tributaries of the river. The basin area up to its confluence with the Krishna River is 11,549 km^2. The extent of the Malaprabha river basin considered in the present study extends between $74^0$10' and $76^0$5' E longitudes, and $15^0$0' and $16^0$15' N latitudes and encompasses an area of 11,400 km^2 at Huvanuru gauging station (Figure 3.2) and includes parts of Belagavi, Bagalkot, Dharwad and Gadag districts of north Karnataka.

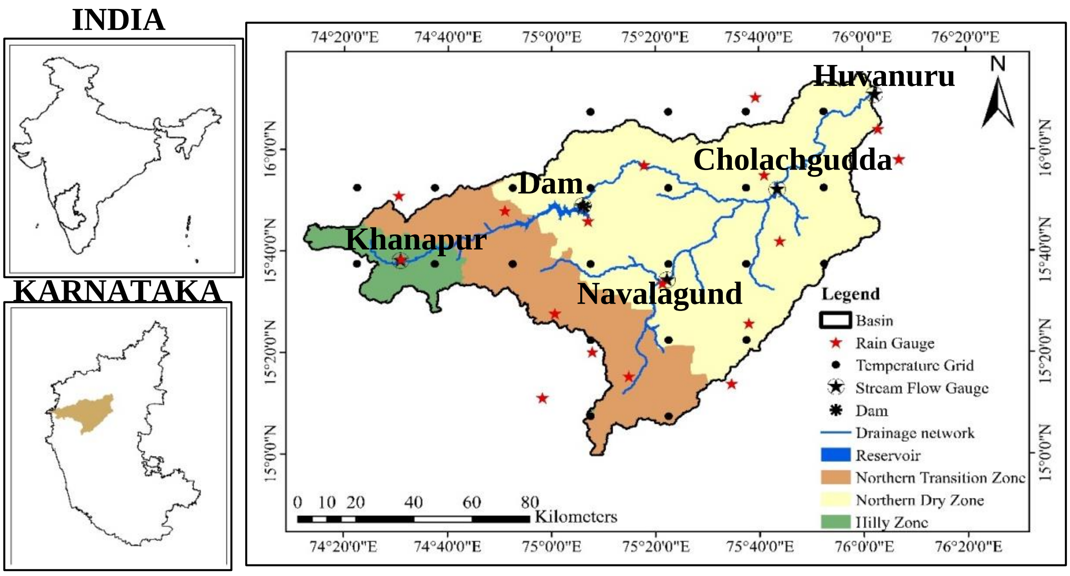


Figure 3.2 Location of rainfall, temperature, and streamflow gauging stations in the Malaprabha River Basin

The basin comprises three agro-climatic zones namely, Hilly (HY), Northern transition (NT), and Northern dry (ND). The Hilly zone comprising the Western Ghats occurs over a small area towards the west of the basin. The Northern dry zone is the largest and encompasses the region towards the east. A small portion of the basin between these two zones falls under the Northern transition zone. Climatology of the area varies from tropical humid (with average annual rainfall more than 1800 mm) in the upper catchment to semi-arid (with average annual rainfall close to 500 mm) in the lower catchment. A large part of the basin experiences a semi-arid climate with monsoon rainfall (June to October) contributing about 66% of total annual rainfall. The average annual rainfall (AAR) of the basin over the last 56 (1960-2015) years is 751 mm but significant inter-annual variability exists. For instance, the basin received the highest annual rainfall of 1132 mm in the year 2009 and the lowest annual rainfall of 442 mm was received in 2003. The unpredictable monsoonal rainfall, droughts, and famines are part of the life of people in the region. The mean monthly maximum temperature ranges from 30^0C to 36^0C and the mean monthly minimum temperature ranges from 16^0C to 22^0C.

There are two broad groups of soil cover in the catchment, red and black varieties. The black soil occupies 45% of the area out of which 38% is deep and 7% is shallow to moderately deep. The red soil is found in 33% of the area. Patches of a mixture of red and black soil are found in 16% of the area. The rest of the catchment is a conglomeration of rocky outcrops, river courses, etc. (DPR, 2008). Agriculture is the dominant land use in the basin and it is the main occupation of about 85% of the population in the region. The study area covers three major aquifer systems (Figure 3.4) namely, banded gneissic complex (BGC), schist, and basalt. Also, minor patches of limestone and laterite (CGWB 2012) exist. A significant amount of groundwater exploration for irrigation has been noticed in the river basin over the last two decades.

3.3 MALAPRABHA IRRIGATION PROJECT

The Malaprabha irrigation project was commissioned in the year 1972 to provide irrigation facilities to several talukas of the basin which suffered from severe droughts and scarcity conditions in the past (Madar 1993). The dam was constructed at a place called Navilutheertha (15° 49’ N Latitude and 75° 6’ E Longitudes) in Saundatti taluk, Belagavi district. The reservoir so formed is named ‘Renuka Sagar Reservoir’ (Figure 3.2). The dam has a gross storage capacity of 1070 MCM and a live storage capacity of 830 MCM and the average annual inflow for the period 1973 to 2015 is 1044 MCM. The project also provides drinking water for Hubli and Dharwad cities which are close by. The catchment area up to the Malaprabha dam is 2564 km^2. The project was planned to create a total irrigation potential of 1,96,132 ha in the Malaprabha command area through two main canals namely Malaprabha Right Bank Canal (MRBC-1,21,392 ha), Malaprabha Left Bank Canal (MLBC-47,769 ha), and 11 foreshore lift irrigation schemes (LIS-26,971 ha) (DPR-2008) (Figure 3.3). The mean annual rainfall in the command area is 591 mm for the period 1965 to 2015. Black cotton soil covers the major portion of the irrigated area under the reservoir command area. Cereals, pulses, oilseeds, and sugar cane are the major crops grown in the study area. In addition to the cultivation of water-intensive crops, many areas are cultivated more than once a year with the help of irrigation. Irrigated area in the Malaprabha command area increased in extent from 4.7% during 1975-76 to 37% of the total cultivable land in 2013-14.

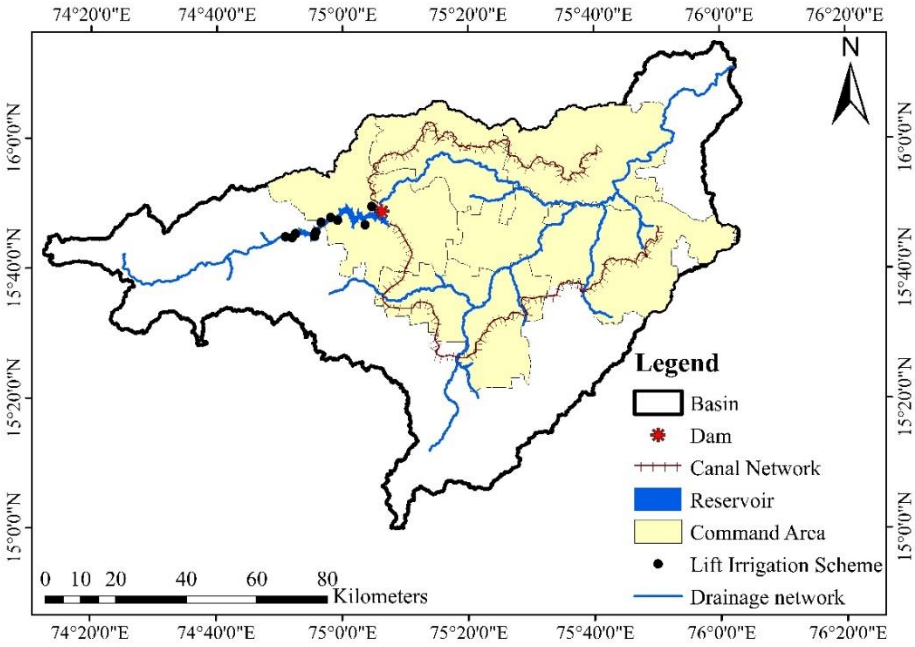


Figure 3.3: Location map showing details of Malaprabha Irrigation Project

3.4 DATA SOURCES AND COMPILATION

Data used in this study was collected from various organizations and agencies, while some data were downloaded from internet sources (Table 3.1). The data collected for this study include topography, hydro-meteorological data, soils, groundwater levels, LULC, and agriculture-related data such as crop types, cultivated area, irrigated area, and reservoir releases for irrigation. A detailed description of the data used in the present study follows.

3.4.1 Hydro-Meteorological Data

Daily rainfall data of 17 rain gauge stations located in the basin (Figure 3.2) for the period 1960 - 2015 (56 years) was collected from the Directorate of Economics and Statistics (DES), Government of Karnataka. Daily maximum and minimum temperature data of 0.25^0 resolution, from 1960 - 2015 (56 years) was procured from the NASA Earth Exchange Global Daily Downscaled Projections (NEXGDDP) data sets (Thrasher et. al. 2013, Thilakarathne and Sridhar 2017). To develop NEX-GDDP data sets, initially, the Bias-Correction Spatial Disaggregation (BCSD) method was employed to downscale CMIP5 GCMs. Later, these data sets were bias-corrected using the Quantile mapping technique with the aid of climatic data sets of Global Meteorological Forcing Dataset (GMFD). Further spatial disaggregation methods were applied to get a finer resolution (0.25^0 X 0.25^0) of NEX-GDDP data sets (Thilakarathne and Sridhar 2017). The temperature dataset used in the study is obtained from the ACCESS1-0 model of NEX-GDDP. The advantages of NEX-GDDP over India were also explored by Jain et al. 2019 and Kumar et.al. 2020. Twenty-three grid points of temperature which cover the Malaprabha River basin were considered (Figure 3.2). Comparison of temperatures for selected grid points with ground-based observations yielded values of correlation coefficient in the range 0.78 to 0.83 indicating reasonably accurate estimates.

The daily streamflow records for four gauging stations (Figure 3.2) in the Malaprabha river basin were obtained from Central Water Commission (CWC) India Water Resource Information System (https://www.indiawris.nrsc.gov.in/wris.html) and from the Water Resources Development Organization WRDO, Govt. of Karnataka, India. However, runoff analysis was carried out at only three gauging stations (Khanapur, Cholachgudda, and Huvanuru) considering the length of data available. Monthly reservoir level data, outflow discharge from dam data, canal releases from the reservoir for irrigation were obtained from National Institute Hydrology (NIH) and Executive Engineer, Malaprabha left bank canal construction (MLBCC) Department, Division II, Navilutheertha, Belagavi.

In the study, seasonal groundwater level data for wells situated in and around the study area were obtained from the Central Ground Water Board (CGWB), Government of India. Wells with less than 20 years of data were excluded from the study. Finally, groundwater-level data from 45 wells (Figure 3.4), spanning not less than 20 years, were considered for the analysis.

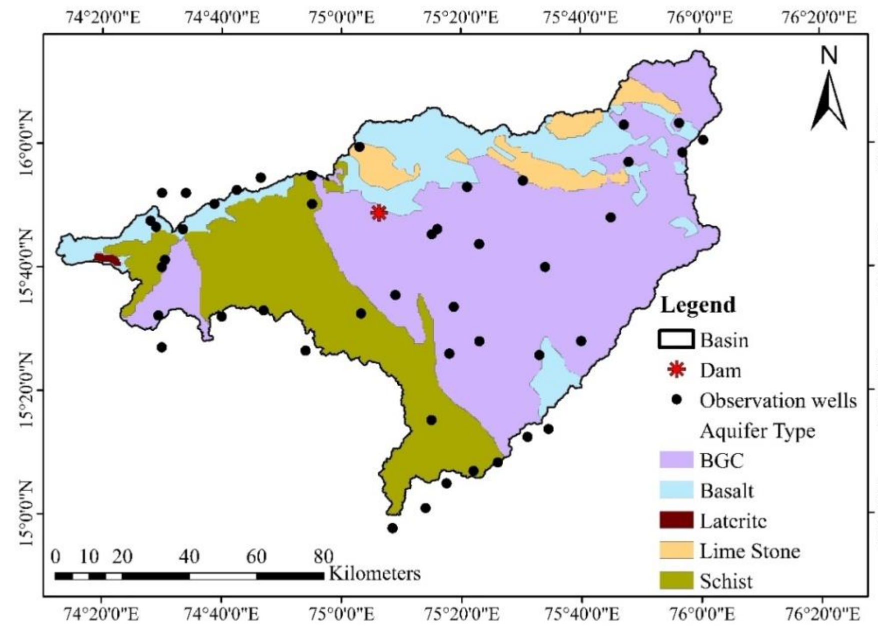


Figure 3.4 Location of CGWB observation wells overlaid on aquifer map of Malaprabha river basin

3.4.2 Agricultural data: The data pertaining to irrigated agriculture, sources of irrigation, and cropping patterns in the Malaprabha river basin were obtained from the District at a glance yearbook and published doctoral theses (Table 3.1).

3.4.3 Topographic Data

Topographic data were obtained in the form of a Digital Elevation Model (DEM) at 30 m resolution from the Shuttle Radar Topography Mission (SRTM). The SRTM 30 m resolution DEM data was used in this study (Figure 3.5). DEM was used to delineate the basin and sub-basins and calculate sub-basins parameters such as slope and slope length.

3.4.4 Soil:

Soil map of 1:50,000 scale along with the associated physical properties database is obtained from the Food and Agricultural Organization of the United Nations, FAO (Figure 3.6).

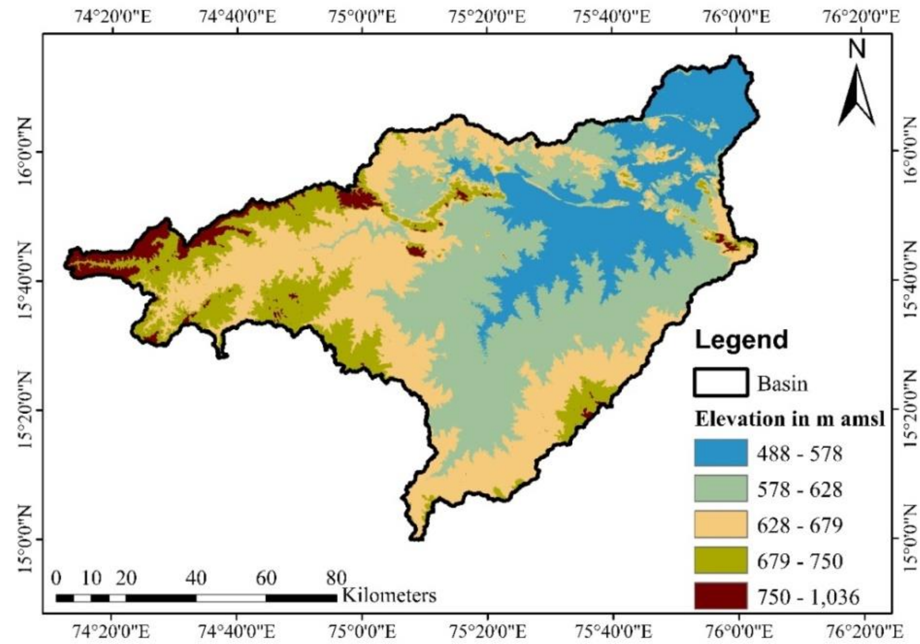


Figure 3.5 Digital Elevation Model (DEM) of the Malaprabha River Basin

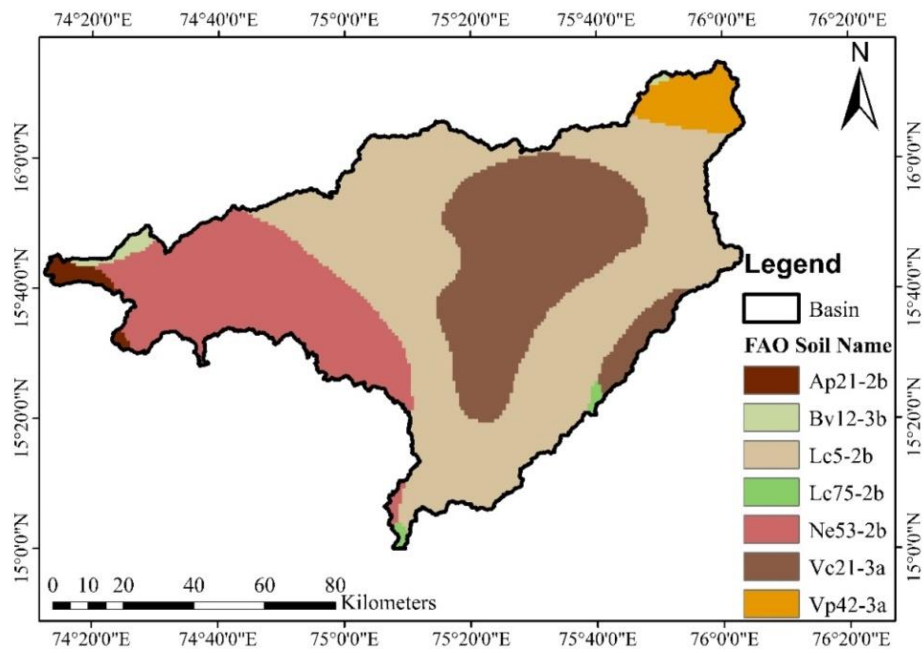


Figure 3.6 Soil map of Malaprabha River basin

3.4.5 Land Use / Land Cover

The decadal LULC maps for the years 1985, 1995, and 2005 at 100 m resolution from the Indian Space Research Organization (ISRO) (Roy et al., 2016) were used in this study (Figure 3.7) to analyze land-use changes and their impact on stream-flows. Also, the LULC image from NRSC for the year 2005-06 is obtained for the impact study of irrigation on hydrological processes.

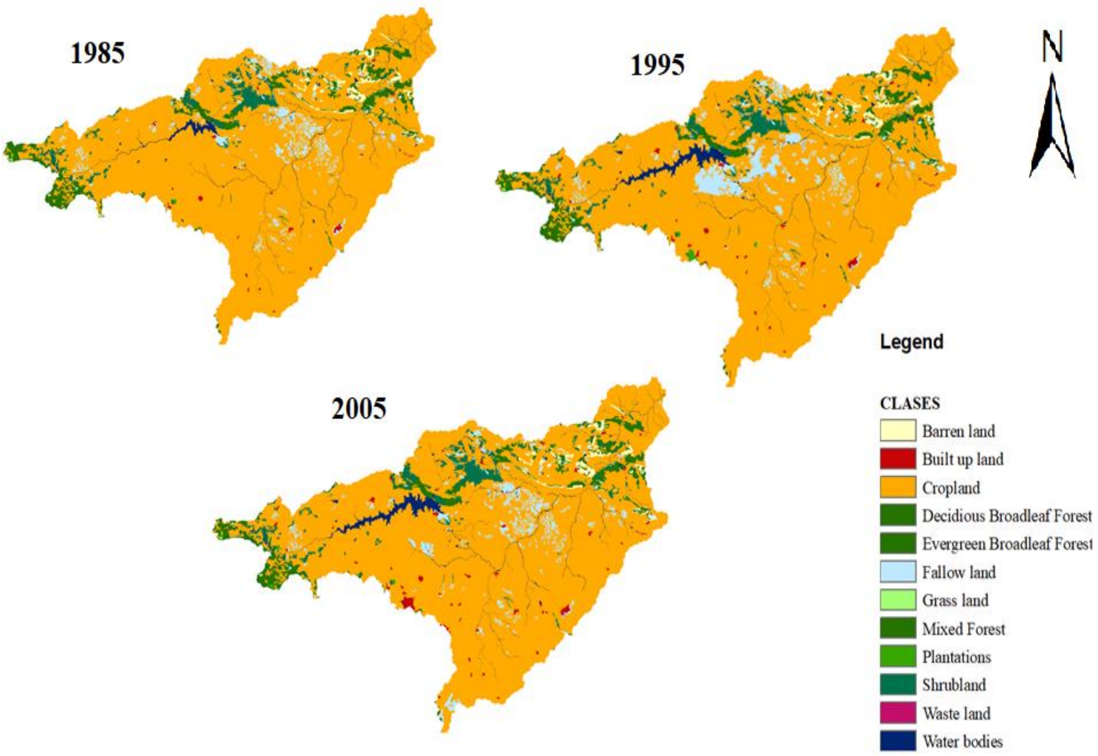


Figure 3.7: Decadal LULC maps for the years 1985, 1995, and 2005 at 100 m resolution from the Indian Space Research Organization (ISRO) *(Roy et al., 2016)*

Table 3.1: Datasets procured for the study

Sl.No	Data Type	Period	Resolution	Source
1	Rainfall	1960-2015	17 RG stations Daily	Directorate of Economics and Statistics (DES), Government of Karnataka
2	Maximum and Minimum temperatures	1960-2015	23 grids ($0.25^0 \times 0.25^0$) Daily	NASA Earth Exchange Global Daily Downscaled Projections -NEX-GDDP (ACCESS1-0 model)
3	Groundwater level	1996-2015	45 wells Seasonal	Central Ground Water Board (CGWB), Government of India.
4	Stream flows	1960-2006	4 gauging stations Daily	Central Water Commission (CWC), Government of India and Water Resources Development Organisation (WRDO), Government of Karnataka.
5	Reservoir and Canal water releases	1972-2015	Daily	Executive Engineer, Malaprabha left bank canal construction (MLBCC) Department, Division II, Navilutheertha, Belgaum.
6	Land Use -Land Cover (LULC)	1985,1995, 2005	100m decadal	ISRO
		2005-06	62m	NRSC
7	Agricultural data (Cultivated area, Irrigated area, Crop area and Sources of irrigation in Malaprabha command area)	1965-2015	Taluk wise Decadal	District at a glance reports, Government of Karnataka and Published values from Madar 1993, S.L. Chitragar 2018, doctoral thesis from the Department of Agriculture and Geography, University of Dharwad, Karnataka
8	Topography Digital Elevation Model		30m	SRTM
9	Soil map		1:25,000	Food and Agricultural Organisation (FAO)

CHAPTER 4
PRELIMINARY ANALYSIS OF HYDROMETEOROLOGICAL VARIABLES

4.1 GENERAL:

The preliminary analysis of observed hydro-meteorological data is essential to characterize the hydrology of a river basin. Also, an understanding of the long-term variability of hydro-meteorological variables is important from the viewpoint of characterizing likely future trends.

In this section, the temporal and spatial characterization of historical observations of hydro-meteorological variables such as rainfall, air temperature, groundwater levels, and stream flows about the Malaprabha river basin is described. Rainfall and runoff are complex hydrological phenomenon to understand due to the tremendous spatial variability of catchment characteristics and precipitation patterns (Singh et.al. 2010). Changes in the temporal, spatial, and seasonal distribution of rainfall influence the spatial and temporal distribution of runoff, soil moisture, and groundwater reserves (Kumar et.al. 2017). Thus, relationships between rainfall and streamflow were also characterized.

The data procured from different sources (Table 3.1) were tested for consistency and missing records. The data were checked for consistency using double mass curve analysis and data homogeneity was checked using the Standard Normal Homogeneity Test (SNHT) (Alexandersson 1986; Alexandersson and Moberg 1997a). Linear interpolation and the nearest neighbor method were used to fill in missing data. The Thiessen polygon method was used to calculate the basin average values of meteorological variables. The seasonal classification of the variables was carried out as per the India Meteorological Department (IMD) norms, i.e., pre-monsoon (March to May), monsoon (June to September), post-monsoon (October to December), and winter (January to February). The Malaprabha basin was further classified into four divisions – North East (NE), South East (SE), South West (SW), and North West (NW) to enable the identification of spatial patterns in the variables.

4.2 BOX-WHISKER PLOTS

Statistical characterization of the recorded datasets during the historical period was carried out using box-whisker plots. Such plots are commonly used to provide a concise graphical representation of several statistical properties of a given dataset such as central tendency, dispersion, skewness, asymmetry, and extremes through computation of quantiles/percentiles of the ranked data (e.g., Tukey 1977; Massart et al. 2005; Banacos 2011). The height of the box is proportional to the inter-quartile range (IQR) which is defined as the difference between the upper quartile (75th percentile) and the lower quartile (25th percentile). Since the box encompasses the middle 50% of the ranked data, its height provides a direct measure of the dispersion in the dataset. The median (50th percentile) plotted as a line, divides the box into either two equal or unequal parts and thereby provides a measure of central tendency and skewness in the data. The two whiskers drawn as vertical lines extending from both the edges of the box represent the range of the ranked dataset extending from ±1.5 times IQR from the upper and lower quartiles respectively. The observations in the dataset which fall beyond the range of the whiskers are referred to as outliers or extreme values and are represented as dotted symbols in the below figures. Also represented as a dot inside the box is the mean value of the data which in comparison with the median provides a measure of the skewness or asymmetry introduced on account of the extreme values.

4.3 RAINFALL

Daily rainfall data of 17 rain gauge (RG) stations located in the basin (Figure 4.1) for the period 1960-2015 (56 years) was collected from the Directorate of Economics and Statistics (DES), Government of Karnataka. Among the characteristics of rainfall, magnitude and intensity are considered critical in hydrological studies. However, since rainfall intensity can be calculated only with observations from self-recording rain gauges, number of rainy days is often used as an approximate surrogate when data from only non-recording gauges are available. Therefore, in this study rainfall magnitudes and also number of rainy days were analyzed. Using IMD criteria, rainy days in which daily rainfall depth ≥ 2.5 mm were identified.

Table 4.1 provides details of the location, elevation, average annual rainfall ($\bar{R}_A$) and the average annual number of rainy days ($\bar{D}_A$) for the selected RG stations. The station ids in Table 4.1 are assigned based on the four divisions of the Malaprabha river basin, and it can be seen that the number of stations in the NE, SE, SW and NW divisions are 6, 3, 4 and 4 respectively.

Table 4.1 Coordinates, elevations, average annual rainfall ($\bar{R}_A$) and the average annual number of rainy days ($\bar{D}_A$) for the selected rain gauge stations

Station Id	Agro-climatic zone	RG Station	Longitude (E)	Latitude (N)	Elevation (m)	$\bar{R}_A$ (mm)	$\bar{D}_A$ (days)
NE1	ND	Badami	75^0 40' 60"	15^0 55' 0"	566	597	40
NE2	ND	Bagalkot	75^0 39' 20.7"	16^0 10' 21.7"	541	587	37
NE3	ND	Hungund	76^0 3' 0"	16^0 4' 0"	533	695	44
NE4	ND	Ilkal	76^0 7' 0"	15^0 58' 0"	565	651	41
NE5	ND	Ramdurga	75^0 17' 50.9"	15^0 57' 0"	573	544	37
NE6	ND	Rona	75^0 43' 58.6"	15^0 41' 58.4"	581	695	43
SE1	ND	Navalgunda	75^0 21' 20.3"	15^0 33' 37.7"	579	605	41
SE2	ND	Gadag	75^0 37' 58.9"	15^0 25' 47"	657	681	46
SE3	ND	Shirahatti	75^0 34' 37.7"	15^0 13' 52.6"	667	717	48
SW1	NT	Hubli	75^0 7' 48.9"	15^0 20' 11.1"	614	722	56
SW2	NT	Dharwad	75^0 0' 36.8"	15^0 27' 44.1"	722	829	60
SW3	HY	Kalghatgi	74^0 58' 14"	15^0 11' 6.8"	551	959	71
SW4	NT	Kundagol	75^0 14' 51.1"	15^0 15' 19.1"	644	654	51
NW1	ND	Soundatti	75^0 6' 59.7"	15^0 45' 56.9"	662	547	39
NW2	NT	Bailahongala	74^0 51' 0"	15^0 48' 0"	687	646	49
NW3	NT	Belgaum	74^0 30' 31.9"	15^0 50' 56.2"	753	1240	76
NW4	HY	Khanapur	74^0 31' 1.3"	15^0 38' 26.4"	672	1891	87

Average annual rainfall ($\bar{R}_A$) values for the 17 rain gauge stations were computed for the 56 years 1960-2015 (Table 4.1). The spatial distribution of $\bar{R}_A$ over the Malaprabha river basin is depicted in Figure 4.1. Significant spatial variability in $\bar{R}_A$ is evident ranging from 544 mm in the eastern part of the basin to 1891 mm in the Western Ghats mountains to the west. A large part of the basin experiences $\bar{R}_A$ between 544 mm to 700 mm, which is a typical range for a semi-arid climate. A transitional zone from a humid climate in the Western Ghats to the semi-arid zone can be seen towards the eastern part of the basin. Average annual rainy days ($\bar{D}_A$) for the period of record were computed for each station (Table 4.1) and Figure 4.2 depicts the spatial distribution of $\bar{D}_A$ over the study area. $\bar{D}_A$ was found to vary from 37 days for the Bagalkot (NE2) and Ramadurga (NE5) stations located to the north of the basin to 87 days for the Khanapur station (NW4) located in the Western Ghats region (Figure 4.2). Figure 4.3 shows that an exponential equation ($y = 265.55\ e^{0.0207x}$, $R^2 = 0.9115$) best explains the relationship between $\bar{R}_A$ and $\bar{D}_A$ for the 17 rain gauge stations located in the study area. The exponential nature of the relationship is on account of the transitional nature of the climate in the basin and the occurrence of more intense rainfall events in the humid zone.

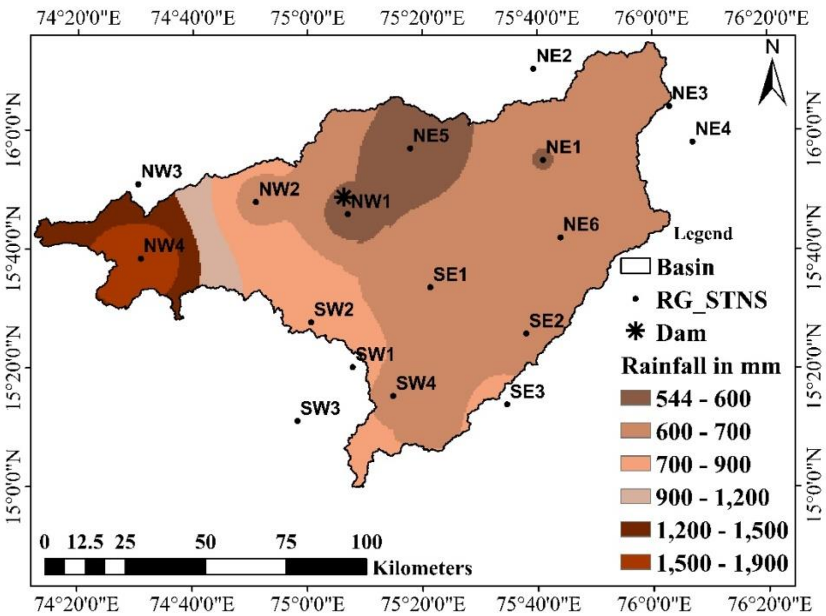


Figure 4.1: Spatial distribution of average annual rainfall ($\bar{R}_A$) over the Malaprabha river basin

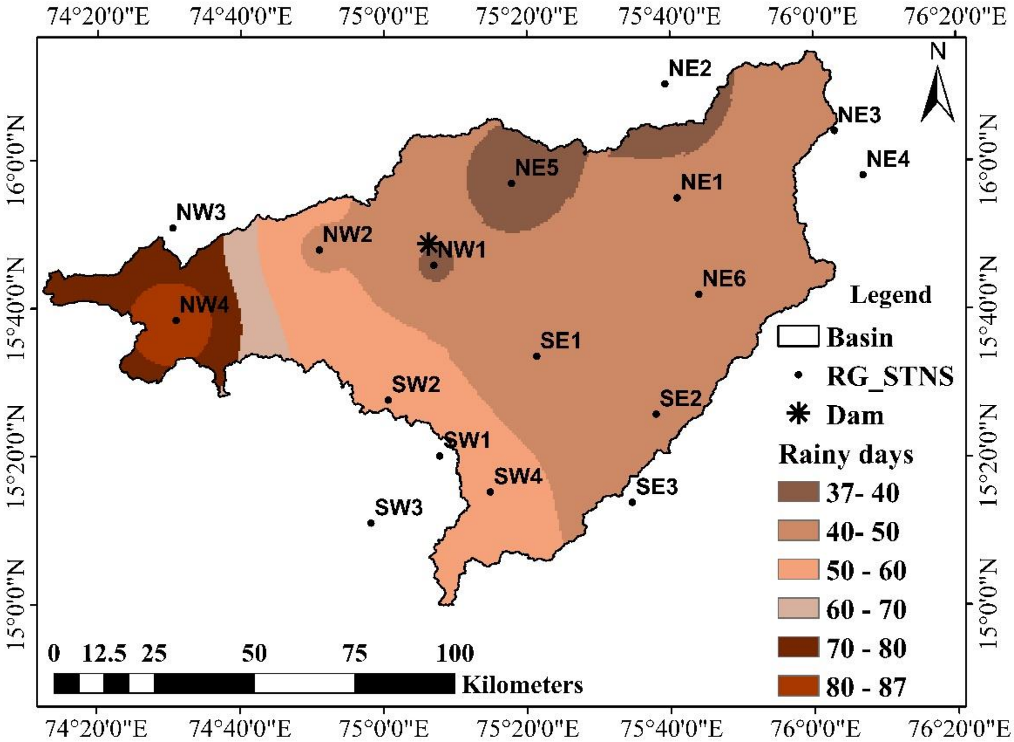


Figure 4.2: Spatial distribution of average annual rainy days ($\overline{D}_A$) over the Malaprabha river basin

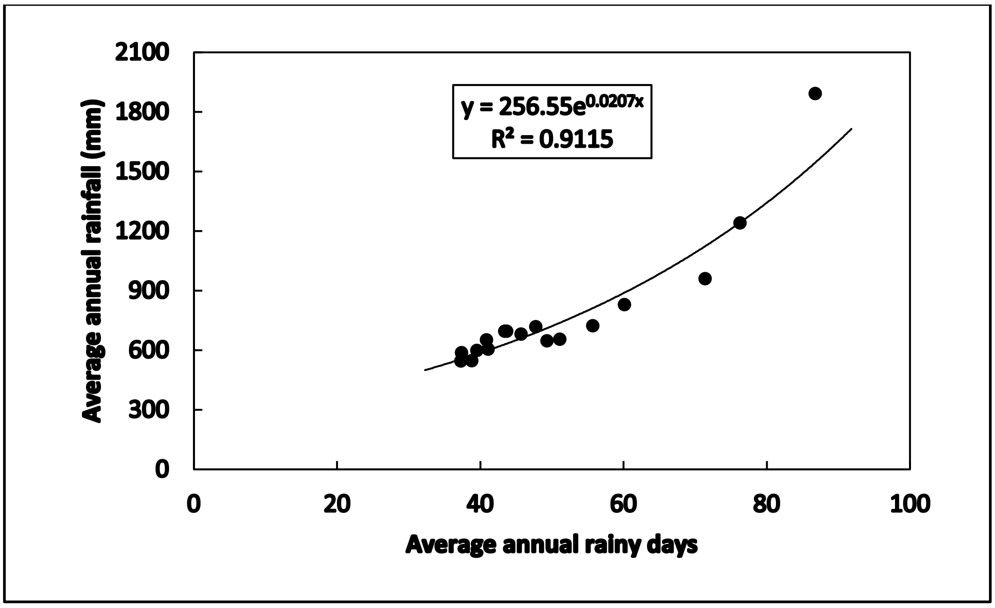


Figure 4.3: Relationship between average annual rainfall ($\overline{R}_A$) and average annual rainy days ($\overline{D}_A$) for rain gauge stations in the Malaprabha river basin

Daily rainfall data for each station were aggregated to annual totals (R_A) and also into totals for 4 seasons in a year as per the IMD classification - pre-monsoon (R_{PR}), monsoon (R_M), post-monsoon (R_{PM}), and winter (R_W). Likewise, rainy days were identified at each station for the period of record and annual rainy days (D_A) and number of rainy days in pre-monsoon (D_{PR}), monsoon (D_M), post-monsoon (D_{PM}), and winter (D_W) seasons were computed. Examination of data for the period 1960-2015 indicated that the contributions of pre-monsoon, monsoon, and post-monsoon season rainfalls to the annual totals ranged between 5.28-19.13%, 57.04-86.88%, and 7.74-24.03% respectively for the 17 selected rain gauge stations. Similarly, the contributions of pre-monsoon, monsoon, and post-monsoon season rainy days to the annual rainy days ranged between 8.06-18.33%, 62.08-81.61%, and 10.16-20.26% respectively. However, the contributions of rainfall and number of rainy days during the winter season to the corresponding annual totals were less than 1% for all the stations.

4.3.1 Station-wise box-whisker plots of R_A and D_A

Figure 4.4 shows station-wise box-whisker plots for annual rainfall totals (R_A) examination of which reveals several aspects of the spatiotemporal distribution of rainfall in the study region. Considering the stations located in the north-eastern division (NE1 to NE6), it can be seen from Figure 4.4 that the heights of the boxes indicate relatively low inter-annual variability of rainfall and skewness in the data appears small as indicated by the almost equal lengths of both whiskers and the fact that the means and the medians are equal to each other. The station Rona (NE6) seems to be an exception where the variability appears to be slightly higher and also skewed towards higher rainfall values. Stations SE1 to SE3 also exhibit similar characteristics probably on account of the fact that all these stations (NE1 to SE3) are located in the Northern Dry (ND) agro-climatic zone. Figure 4.4 indicates that in this zone, 50% of annual rainfall totals lie between 400 – 700 mm with a mean value of about 600 mm. Stations SW1 to SW4 are located in the Northern Transition (NT) agro-climatic zone and while exhibiting reasonably low variabilities, record slightly higher mean annual rainfall values in comparison to the stations in the ND zone. Stations Soundatti (NW1) and Ramadurga (NE5) which are located in the ND zone records the lowest mean/median annual rainfall amongst all the stations considered in this study. On the other hand, station NW3 (NT zone) and NW4 located in the Hilly zone (HY) exhibit relatively large IQR and mean/median values compared to the other stations. In particular the Khanapur station (NW4) has the largest IQR, largest mean/median and highest extreme values during the period of record probably on account of being located in the mountainous zone. Outliers exist in the datasets of many stations and except in one case (station SW3) they are all high extremes which result in the mean annual rainfall being greater than the median.

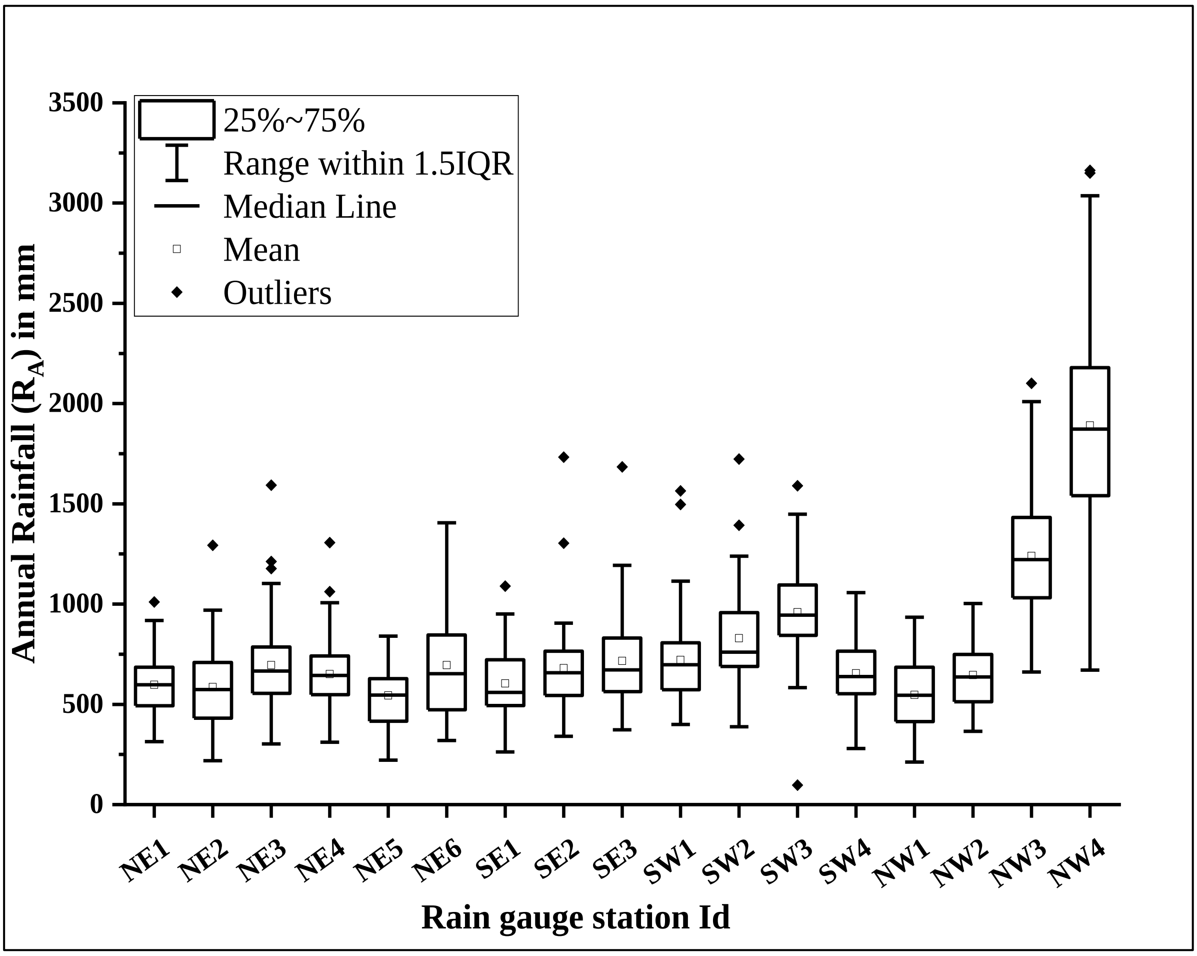


Figure 4.4: Station-wise box-whisker plots for annual rainfall during 1960-2015 in the Malaprabha river basin

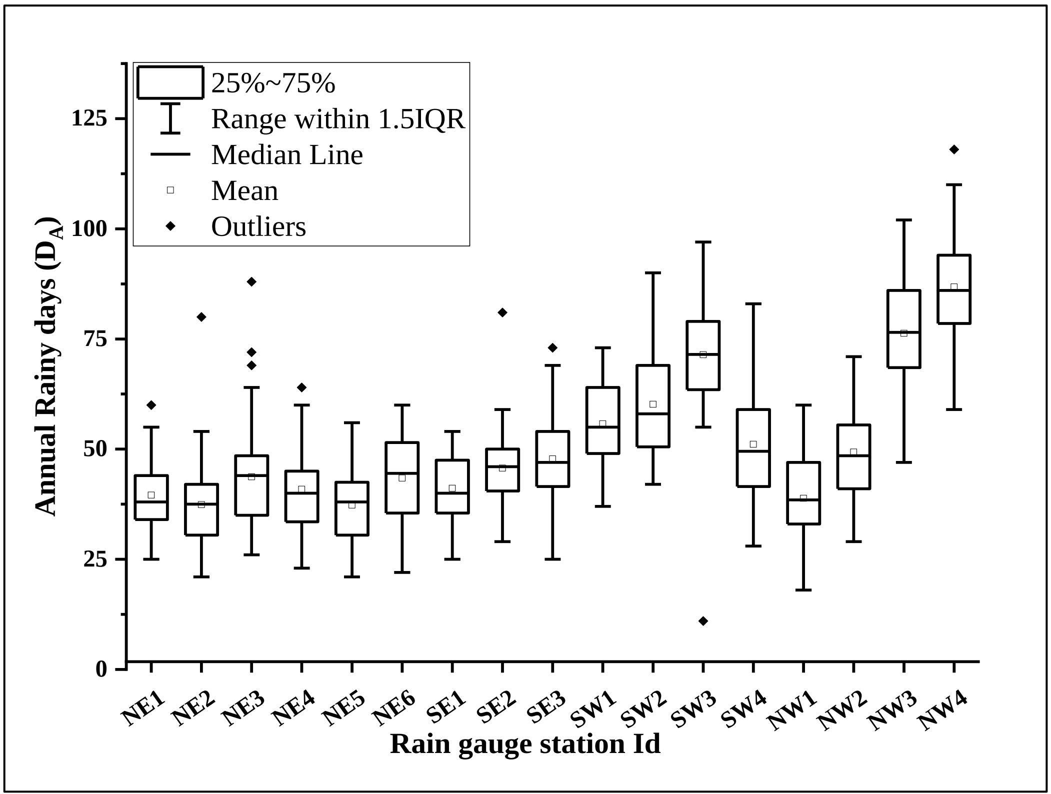


Figure 4.5: Station-wise box-whisker plots for annual rainy days during 1960-2015 in the Malaprabha river basin

Box-whisker plots for annual rainy days (D_A) recorded at each station during the period 1960-2015 are shown in Figure 4.5. It is apparent that the magnitude of dispersion as deduced from the heights of the boxes in much higher for D_A in comparison to R_A (Figure 4.4). In other words, the inter-annual variabilities in D_A are much larger than in R_A. Despite this, it is interesting to note that the pattern of variabilities for stations located in a given geographical divisions/agro-climatic zone is strikingly similar to the patterns exhibited for R_A (Figure 4.4). Therefore, it appears that box-whisker plots not only provide a concise description of important statistical properties of datasets but can also prove to be useful in classifying stations based on similarity in statistical properties.

4.4 STREAMFLOW

Historical stream-flow records are the most essential in the planning and design of water resources projects. However, streamflow is affected by a host of factors related to natural climate variability and anthropogenic activities resulting in significant temporal and spatial variabilities. The present work considers 3 gauging stations (Table 4.2 and Figure 3.2) for the analysis, namely the station at Khanapur which is located in the hilly region and upstream side of the dam and represents streamflow from a forested catchment. Cholachgudda gauging station is located across the main river on the downstream side of the dam and therefore represents stream flows out of the Malaprabha irrigable command area. The Huvanuru gauging station is located further downstream and represents the outlet of entire the Malaprabha river basin.

Table 4.2 Locational details stream gauge stations considered in the Malaprabha river basin

Sl. No.	Name	Latitude (N)	Longitude (E)	Duration	Source
1	Huvanuru	$16^0$10'45.98"	$76^0$2'17.99"	1968-1981	CWC
2	Cholachigudda	$15^0$52'12"	$75^0$43'30"	1983-2006	CWC
3	Khanapur	$15^0$38'9.64"	$74^0$30'51.55"	1980-2015	WRDO

The variation in downstream stream-flows due to reservoir functioning and irrigation development in the river basin after the commissioning of the Malaprabha project is clearly depicted through rainfall-runoff relationships which are shown in Figures 4.6, 4.7, and 4.8. At Huvanuru station, the rainfall-runoff relationship is plotted for two time periods i.e., pre-dam (Figure 4.6) and post-dam (Figure 4.7) condition, and the coefficient of determination (R^2) between mean monthly rainfall and stream-flow is 0.83 and 0.65 for these two periods respectively. It is evident that the nature of the rainfall-runoff relationship is different between the two periods partly on account of a difference in the rainfall pattern and partly due to the dam/reservoir operation, both of which appear to reduce the correlation between the two variables. Further, from Figures 4.6 and 4.7 it can be observed that during the post-dam period there is an increase in low-flows during post-monsoon and summer months (November to April) and a decrease in high-flows during monsoon months (May to October). However, during September stream flows are higher for the post-dam condition. These changes in seasonal streamflow in the basin are on account of reservoir releases during summer months and increased return flows from the irrigable command area to the river result in higher low-flows. Further, storage of water in the reservoir during monsoon months decreases high flows at the gauging station.

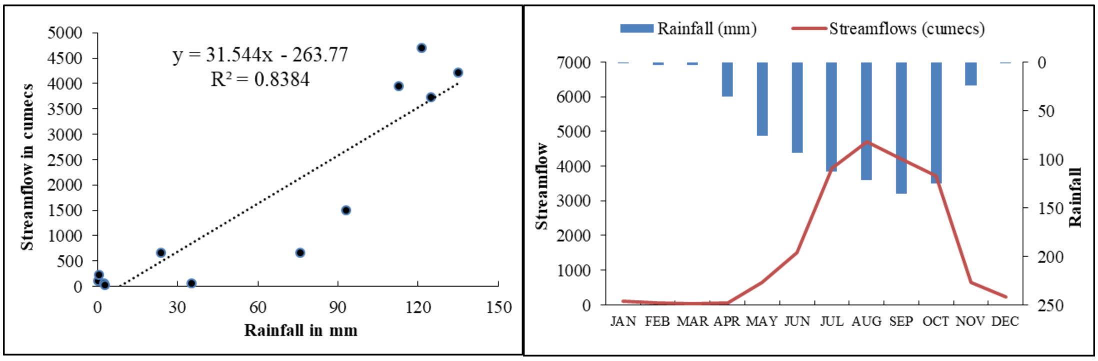


Figure 4.6 Mean monthly rainfall-runoff relationship at Huvanuru for Pre-dam condition for the period 1968-1971

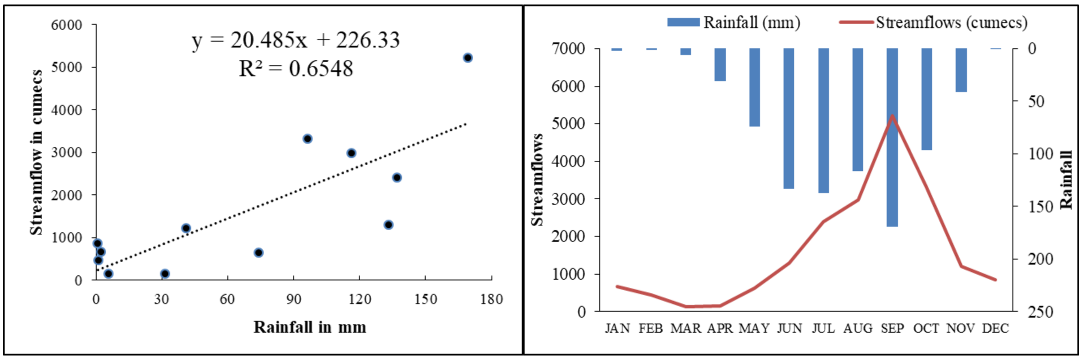


Figure 4.7 Mean monthly rainfall-runoff relationship at Huvanuru for Post-dam condition for the period 1972-1981

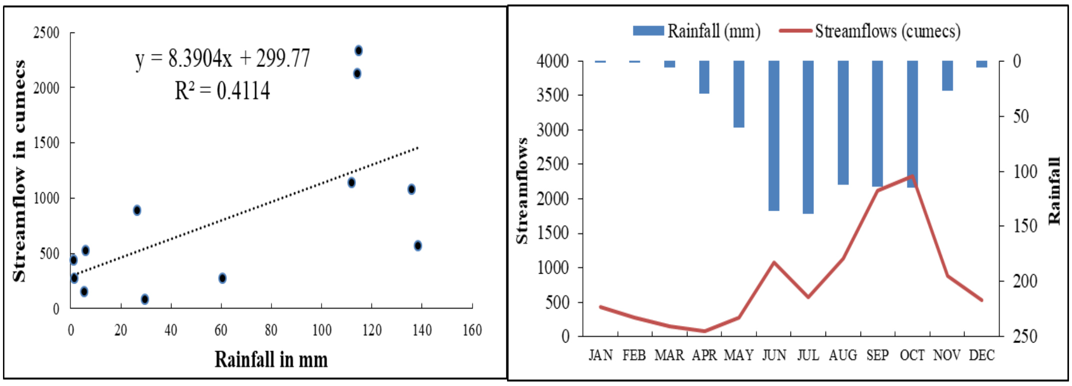


Figure 4.8: Mean monthly rainfall-runoff relationship at Cholachgudda for the period 1983-2006

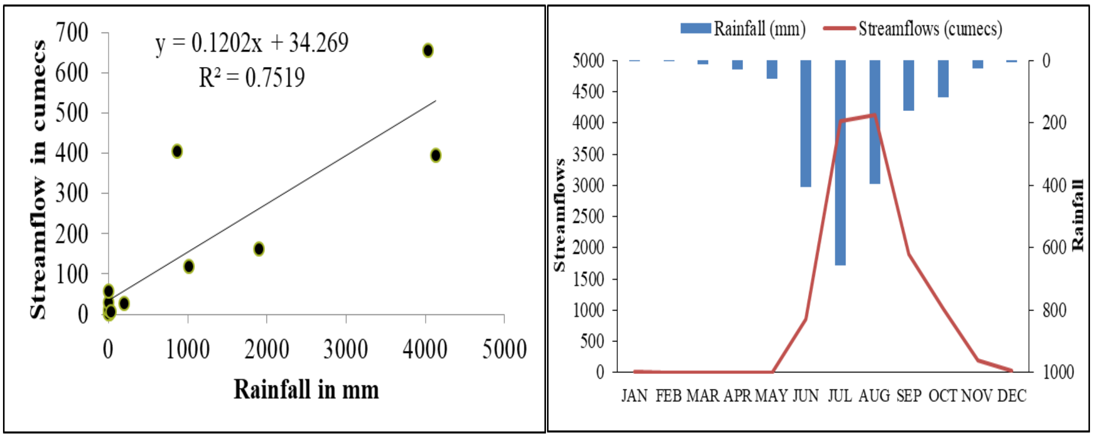


Figure 4.9: Mean monthly rainfall-runoff relationship at Khanapur for the period 1980-2015

The R^2 for the Cholachgudda station (Figure 4.8) is found to be 0.4, which is less than that of Huvanuru station for post-dam condition (R^2 =0.65), indicating a poorer relationship between stream flows and rainfall.

The characteristics of the stream-flow hydrograph are similar to Huvanuru station post-dam condition, with higher summer flows and lower monsoon flows with two peaks in a year i.e., during June and October. It can be observed from Figures 4.8 and 4.7 that, the effect of the reservoir on stream-flows at Cholachgudda is higher than at Huvanuru station for post-dam conditions. This is maybe due to the relatively closer proximity of Cholachgudda station to the reservoir than Huvanuru station (Figure 3.1) which is the outlet of the irrigable command area.

The impact on stream-flow regime due to changes in catchment hydrology can be conveniently depicted using Flow Duration Curves (FDC). A FDC is a plot of discharge against the percent of the time the flow is equaled or exceeded. The FDC for a catchment provides a concise description of stream-flow variability at a given location, with the shape being determined by rainfall pattern, catchment size, and physiographic characteristics of the catchment. The construction of FDC using daily stream-flow observations is performed through a class interval approach. The flow quantiles were derived from FDC and the two flow indices; the High flow index (HFI) and Low flow index (LFI) were calculated.

$$HFI = Q_{10}/Q_{50} \quad (4.1)$$

$$LFI = Q_{90}/Q_{50} \quad (4.2)$$

While the HFI is used to characterize the relative magnitudes of peak flow (Q_{10}) concerning the median flow (Q_{50}), the LFI characterizes relative magnitudes of low flow (Q_{90}) and the median flow.

The records at stations Cholachigudda and Huvanuru represent regulated flows, whereas Khanapur station represents natural flows. The FDC analysis was performed at each gauging station and the obtained magnitudes of flow quantiles along with flow indices are presented in Table 4.3. The Huvanuru station consists of flow records before (1968-1971) and after the dam construction (1972-1981) and hence the FDC analysis was carried out for the respective periods separately. From Table 4.3 it can be observed that at Huvanuru station the magnitude of low-flows (Q_{50} to Q_{99}) increased after the construction of the dam and the magnitude of high-flows (Q_{10} to Q_{40}) decreased. This can also be seen from the significant decrease of HFI to 37.4% and increase in LFI 128.5% during post-dam compared to pre-dam condition. Thus, FDC analysis indicates the alteration in stream flows before and after dam construction. The highest HFI (125.83) was observed for Khanapur gauging station which represents natural streamflow from a forested catchment. Streamflow at Cholachgudda represents regulated flows downstream to the dam with HFI and LFI values 5.76 and 0.08 respectively.

Table 4.3 Flow quantiles of daily streamflow at different gauging stations in the Malaprabha river basin

Flow Quantiles	Huvanuru			Cholachigudda	Khanapur
	Dependable flows in cumecs				
	Pre-DAM (1968-71)	Post-DAM (1972-81)	Total (1968-1981)	1983-2006	1980-2015
Q_{10}	146.54	138.33	140.92	60.66	124.73
Q_{20}	88.40	78.83	82.15	28.67	60.30
Q_{30}	55.63	42.96	46.21	20.36	22.07
Q_{40}	27.38	26.66	26.82	15.37	5.14
Q_{50}	12.19	18.39	17.56	10.53	0.99
Q_{60}	5.50	14.26	12.36	7.09	0.79
Q_{65}	4.29	12.20	9.82	5.45	0.69
Q_{70}	3.38	10.13	7.79	3.76	0.59
Q_{75}	2.47	8.28	5.75	2.06	0.50
Q_{80}	1.81	6.44	4.16	1.61	0.40
Q_{85}	1.35	4.62	2.80	1.21	0.30
Q_{90}	0.90	2.87	1.67	0.81	0.20
Q_{95}	0.45	1.34	0.83	0.40	0.10
Q_{99}	0.08	0.26	0.16	0.08	0.02
HFI	**12.02**	**7.52**	**8.02**	**5.76**	**125.83**
LFI	**0.07**	**0.16**	**0.10**	**0.08**	**0.20**

4.4.1 Box-whisker plots of annual stream flows

Figure 4.10 represents the variability in annual stream flows at gauging stations considered for the study. Huvanuru pre-dam and Khanapur stations represent natural stream flows downstream and upstream to the Malaprabha dam respectively. Since the Khanapur station represents flows out of forested catchment, the annual stream flows are skewed towards high flows as the mean value is above the median line. Huvanuru_Post-dam and Cholachgudda stations represent regulated flows. The interannual variability of the Huvanuru station for the post-dam condition is greater than the pre-dam condition. Although stations Huvanuru_Post-dam and

Cholachgudda located downstream of the reservoir represent regulated flows, Cholachgudda station represents low interannual variability among the stations and possesses a central tendency in the data distribution. This probably is on account that, Huvanuru_Post-dam condition represents the duration soon after the commissioning of the Malaprabha project in 1972-81, where the irrigation development in the command area was still in the developing stage and hence, the amount of water released from the reservoir every year varies significantly. On the other hand, the Cholachgudda station represents a post-dam condition for the period 1983-2006, where the irrigation development in the command area was almost complete and the nature of water release from reservoir every year varies insignificantly.

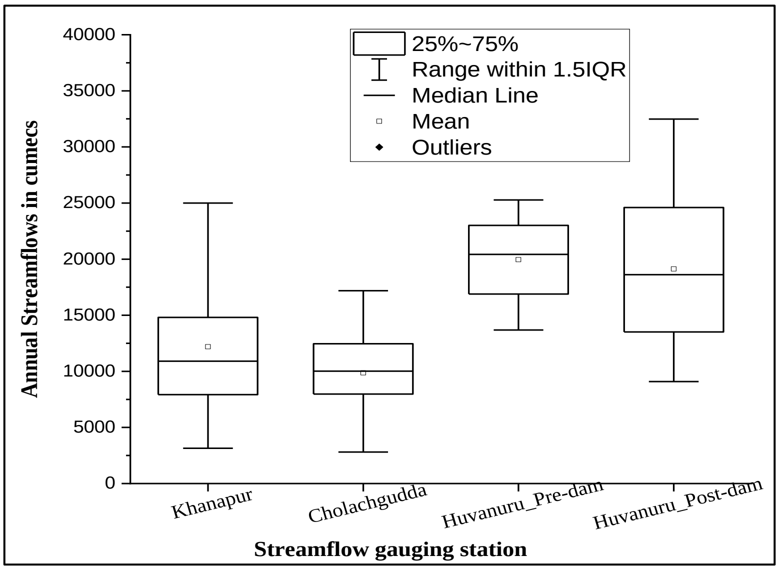


Figure 4.10 Gauging station-wise box-whisker plots for annual streamflow in the Malaprabha river basin

4.5 AIR TEMPERATURE:

The surface temperature over a region varies annually and seasonally depending upon latitude, altitude, and location concerning geographical features like water bodies, mountains, etc., (Jain and Kumar 2012). Many studies in the past decades pointed out that there is a significant increase in the global mean air temperature during the past century. In the present study daily maximum and minimum temperature data for 23 grids of 0.25^0 resolution, for the period 1960 - 2015 (56 years) was procured from recently developed NASA Earth Exchange Global Daily Downscaled Projections (NEXGDDP) data sets (Thrasher et. al. 2013, Thilakarathne and Sridhar 2017).

Average annual temperature values for the 23 grids (Figure 4.11) were computed for the 56 years 1960-2015. Table 4.4 shows the locational details of temperature grids along with average annual maximum ($T_{\max}$), minimum ($T_{\min}$), and average temperatures ($\bar{T}_A$). The grid ids are assigned based on four divisions and it can be seen that the number of stations in the NE, SE, SW, and NW divisions is 6, 6, 6, and 5 respectively. The spatial distribution of $\bar{T}_A$ over the Malaprabha river basin is represented in Figure 4.11.

Substantial spatial variability in $\bar{T}_A$ is noticed ranging from 26.6^{0}C in the northeastern part of the basin which belongs to the ND climatic zone, to 24.3^{0}C in the Western Ghats mountains to the west belongs to the HY zone. A large part of the basin experiences $\bar{T}_A$ between the ranges 25 to 27^{0}C. The seasonal analysis of basin $\bar{T}_A$ revealed that, the pre-monsoon season of the Malaprabha river basin records the highest temperature ranging 27-30^{0}C, followed by monsoon (24-26^{0}C), post-monsoon (22-25^{0}C), and winter (23-25^{0}C) respectively. The basin average monthly maximum temperature (T_{max}^{B}) (Figure 4.12) varies from 28^{0}C to 36^{0}C and monthly minimum temperature (T_{min}^{B}) varies from 16^{0}C to 22^{0}C. A greater variation of maximum temperature is observed between non-monsoon and monsoon months. However, not much variability is observed for minimum temperature.

4.5.1 Grid-wise box-whisker plots of $\bar{T}_A$

Figure 4.13 shows grid-wise box-whisker plots for average annual temperature ($\bar{T}_A$) over the recorded period (1960-2015). It can be seen from the figure that, there occurs an almost uniform inter-annual dispersion of the datasets as the length of the box is more or less similar for all grids, although the overall range in their magnitudes is different. The mean value of $\bar{T}_A$ of grids belong to ND agro-climatic zone is 26.3^{0}C, and that of NT and HY zone are 24.8^{0}C and 24.4^{0}C respectively.

Table 4.4 Coordinates, maximum (T_{max}), minimum (T_{min}) and average annual temperature ($\bar{T}_A$) for the selected grid points

Station Id	Agro-Climatic zone	Grid Id	Longitude (E)	Latitude (N)	T_{max} (^{0}C)	T_{min} (^{0}C)	$\bar{T}_A$ (^{0}C)
NE1	ND	17	75° 22' 30"	15° 52' 30"	31.72	20.27	26.00
NE2	ND	18	75° 37' 30"	15° 52' 30"	32.07	20.49	26.28
NE3	ND	19	75° 52' 30"	15° 52' 30"	32.08	20.41	26.24
NE4	ND	21	75° 22' 30"	16° 7' 30"	32.17	20.56	26.36
NE5	ND	22	75° 37' 30"	16° 7' 30"	32.52	20.79	26.65
NE6	ND	23	75° 52' 30"	16° 7' 30"	32.13	20.48	26.30
SE1	NT	2	75° 22' 30"	15° 7' 30"	30.66	19.97	25.32
SE2	ND	4	75° 22' 30"	15° 22' 30"	31.11	20.15	25.63
SE3	ND	5	75° 37' 30"	15° 22' 30"	31.02	19.88	25.45
SE4	ND	10	75° 22' 30"	15° 37' 30"	31.48	20.25	25.86
SE5	ND	11	75° 37' 30"	15° 37' 30"	31.73	20.35	26.04
SE6	ND	12	75° 52' 30"	15° 37' 30"	31.79	20.29	26.04
SW1	NT	1	75° 7' 30"	15° 7' 30"	30.42	19.99	25.20
SW2	NT	3	75° 7' 30"	15° 22' 30"	30.62	19.87	25.24
SW3	HY	6	74° 22' 30"	15° 37' 30"	29.23	19.38	24.31
SW4	HY	7	74° 37' 30"	15° 37' 30"	30.02	19.49	24.75
SW5	NT	8	74° 52' 30"	15° 37' 30"	30.40	19.45	24.92
SW6	ND	9	75° 7' 30"	15° 37' 30"	30.94	19.85	25.40
NW1	NT	13	74° 22' 30"	15° 52' 30"	29.33	19.05	24.19
NW2	NT	14	74° 37' 30"	15° 52' 30"	29.85	18.98	24.42
NW3	ND	15	74° 52' 30"	15° 52' 30"	30.65	19.43	25.04
NW4	ND	16	75° 7' 30"	15° 52' 30"	31.20	19.86	25.53
NW5	ND	20	75° 7' 30"	16° 7' 30"	31.77	20.29	26.03

The grids belonging to NE and SE divisions (from NE1-SE6) have almost equal lengths of both whiskers and the mean values are slightly higher than the median. On the other hand, the grids of SW and NW (from SW1-NW5) depict moderately skewed towards higher temperature values as the upper whisker is lengthier than the lower one. Grids SW3; SW4 which are located in the HY zone and NW1; NW2 located in the NT and close to HY zone records the lowest mean/median average temperature amongst all the grids considered in this study. From Figure 4.13 it is evident that the grids of ND zone exhibit a greater range of $\overline{T}_A$ values fallowed by NT and HY zones.

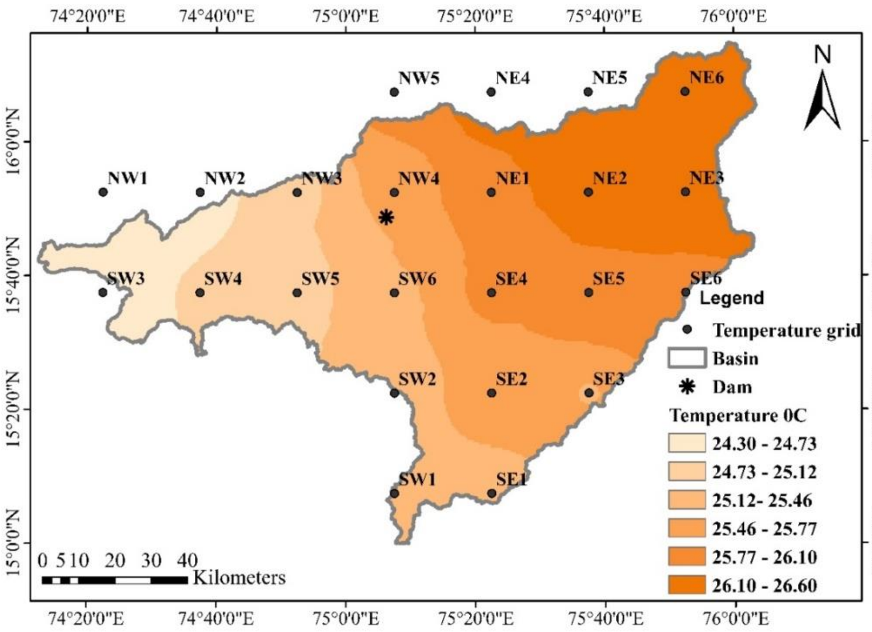


Figure 4.11: Spatial distribution of annual average temperature ($\overline{T}_A$) over the Malaprabha river basin

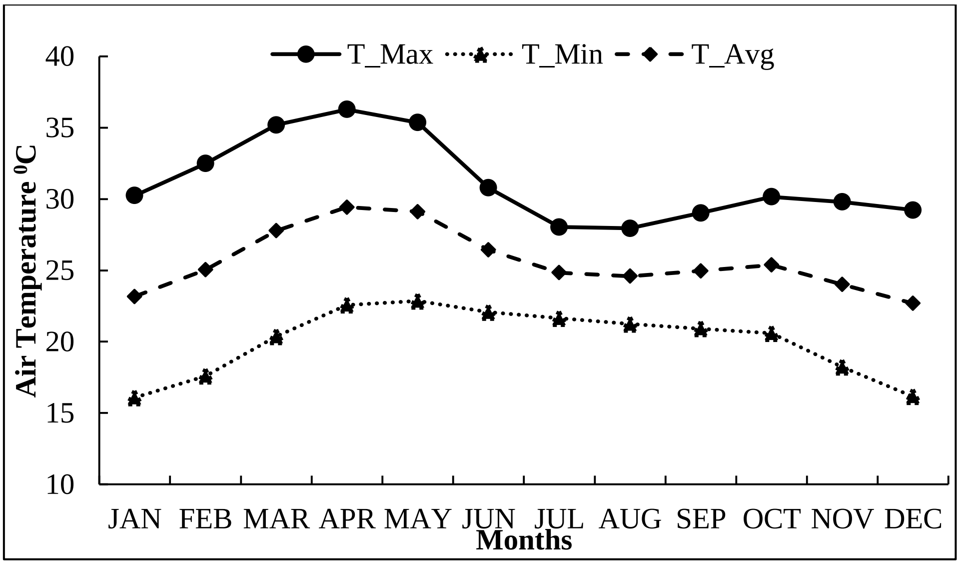


Figure 4.12: Monthly variation of maximum, minimum, and average air temperature over Malaprabha river basin

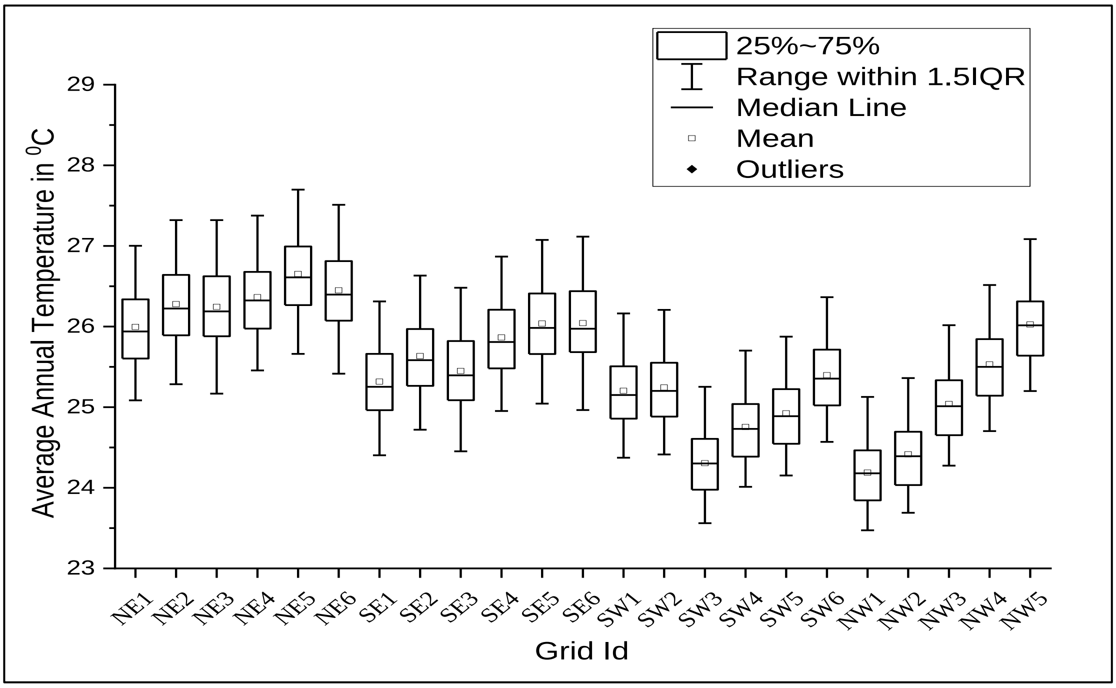


Figure 4.13: Grid-wise box-whisker plots for average annual temperature during 1960-2015 in the Malaprabha river basin.

4.6 GROUNDWATER LEVEL

Characterization of groundwater (GW) resources in the Malaprabha river basin is necessary since its contribution as a source of irrigation water is significant for the past two decades. In the present study, the seasonal groundwater level (GWL) data of 45 observatory dug-wells (Table 4.5) located in the study area was procured for the period 1996 to 2015 from Central Ground Water Board (CGWB). GWLs are measured in observation wells by CGWB four times a year during January, May, August, and November representing Post-monsoon Rabi (POMRB), Pre-monsoon (PREM), Monsoon (M), and Post-monsoon Kharif (POMKH) seasons respectively.

The overall extent of GWL fluctuation observed in the study area ranges from 0 to 35 mbgl (meters below ground level) in dug-wells and 0 to 65 mbgl in bore wells. Reshmidevi and Nagesh Kumar (2014) in their study of the status of GW resources in the study area. They reported that bore wells are drilled to depths >100 mbgl in the study area. The present study considers only dug-wells for the analysis, as the numbers of bore-wells monitored by CGWB were less in number and data was not continuously available for the period of analysis.

Figure 4.14 depicts the spatial distribution of average annual and seasonal GWL fluctuations in the Malaprabha river basin over the period 1996-2015. The overall extent of GWL fluctuation in the study area ranges from 0.7 mbgl at hilly regions to 24 mbgl in the downstream command area and southern regions. The major portion of the study area comes under the GWL fluctuation range of 6 to 10 mbgl during all the seasons. Although the Malaprabha irrigation project was envisaged to be protective in nature, it is interesting to note that, the greater extent (10 to 20mbgl) of GWL fluctuations was observed in the downstream command area and >20 mbgl in the southern regions in the study area during all seasons. The wells numbering 18, 19, 20, and 37 located immediately downstream to the dam show fluctuation of 10 to 15 mbgl during all seasons. This is evidence of excessive groundwater utilization for growing paddy and sugarcane crops near the reservoir. The extraction of GW for irrigation of water-intensive crops is the root cause for this condition in the command area which is explained in detail in Chapter 6.

Table 4.5 Locational details of CGWB observation wells selected for the study

Well No.	District	Site Name	WELLCODE	Longitude (E)	Latitude (N)
1	Belgaum	Londa1	W06119	74^0 30' 0"	15^0 27' 0"
2	Belgaum	Gunji	W05511	74^0 29' 25"	15^0 32' 9.99"
3	Belgaum	Bidi	W05263	74^0 40' 0.01"	15^0 31' 59.98"
4	Belgaum	Khanapur1	W05759	74^0 30' 0"	15^0 40' 0.01"
5	Belgaum	Prabhunagar	W06123	74^0 30' 29.98"	15^0 41' 9.99"
6	Belgaum	Peerwadi	W06110	74^0 28' 59.98"	15^0 46' 30"
7	Belgaum	Uchagaon	W06435	74^0 28' 5.016"	15^0 47' 30.01"
8	Belgaum	Halaga	W05742	74^0 33' 29.98"	15^0 46' 8"
9	Belgaum	Belgaum1	W05256	74^0 30' 0"	15^0 52' 0.01"
10	Belgaum	Kudachi-2	W05745	74^0 34' 0.01"	15^0 52' 0.02"
11	Belgaum	Kittur1	W05771	74^0 46' 59.98"	15^0 33' 0"
12	Belgaum	Hire bagewadi	W05769	74^0 38' 44.98"	15^0 50' 15"
13	Belgaum	Sutagatti1	W06458	74^0 42' 29.98"	15^0 52' 30"
14	Belgaum	Nesaragi1	W06132	74^0 46' 30"	15^0 54' 29.98"
15	Belgaum	Halaki	W05760	74^0 55' 0.01"	15^0 54' 50"
16	Belgaum	Bailhongal	W05265	74^0 55' 5.01"	15^0 50' 15"

17	Belgaum	Soppadla	W06448	75^0 3' 0"	15^0 59' 30.01"
18	Belgaum	Achamatti	W05264	75^0 16' 59.98"	15^0 46' 0.01"
19	Belgaum	Saundatti	W06447	75^0 15' 59.98"	15^0 45' 5"
20	Belgaum	Ramdurg1	W06451	75^0 21' 0"	15^0 52' 59.98"
21	Dharwad	Mugad	W06215	74^0 54' 0"	15^0 26' 30.01"
22	Dharwad	Amminabhavi	W05356	75^0 3' 15.01"	15^0 32' 30.01"
23	Dharwad	Morab	W06218	75^0 9' 0"	15^0 35' 30.01"
24	Dharwad	Shanawad	W06560	75^0 18' 45"	15^0 33' 34.99"
25	Dharwad	Basapur	W05364	75^0 22' 59.98"	15^0 28' 0.01"
26	Dharwad	Hebsur1	W05879	75^0 18' 0"	15^0 25' 59.98"
27	Dharwad	Kundgol	W05882	75^0 15' 0"	15^0 15' 15.01"
28	Dharwad	Gudgeri	W05579	75^0 22' 0.01"	15^0 7' 0.01"
29	Haveri	Wadarahalli	W06609	75^0 17' 30.01"	15^0 4' 59.99"
30	Haveri	Tumminakatti	W06608	75^0 13' 59.98"	15^0 1' 0.01"
31	Haveri	Kuppelur	W05943	75^0 8' 30.01"	14^0 57' 45"
32	Gadag	Ramgeri	W06562	75^0 26' 3.01"	15^0 8' 21.98"
33	Gadag	Magdi	W06230	75^0 31' 0.01"	15^0 12' 29.98"
34	Gadag	Shirhatti1	W06564	75^0 34' 30"	15^0 13' 45.01"
35	Gadag	Hulkoti	W05883	75^0 33' 0"	15^0 25' 45.01"
36	Gadag	Nagasamudra	W06222	75^0 40' 0.01"	15^0 28' 0.01"
37	Gadag	Nargund1	W06226	75^0 22' 59.98"	15^0 43' 45.01"
38	Gadag	Belavaniki-1	W05366	75^0 34' 0.012"	15^0 40' 0.01"
39	Gadag	Hunagundi	W05887	75^0 45' 0"	15^0 48' 0"
40	Bagalkot	Kulageri1	W05695	75^0 30' 20.01"	15^0 54' 0"
41	Bagalkot	Pattadakal	W06087	75^0 48' 0"	15^0 57' 0"
42	Bagalkot	Guledagudda	W05482	75^0 47' 15"	16^0 3' 0"
43	Bagalkot	Amingad	W05230	75^0 56' 30.01"	16^0 3' 15.01"
44	Bagalkot	Vadageri	W06399	75^0 57' 0"	15^0 58' 30"
45	Bagalkot	Nagur	W06088	75^0 0' 29.98"	16^0 0' 29.98"

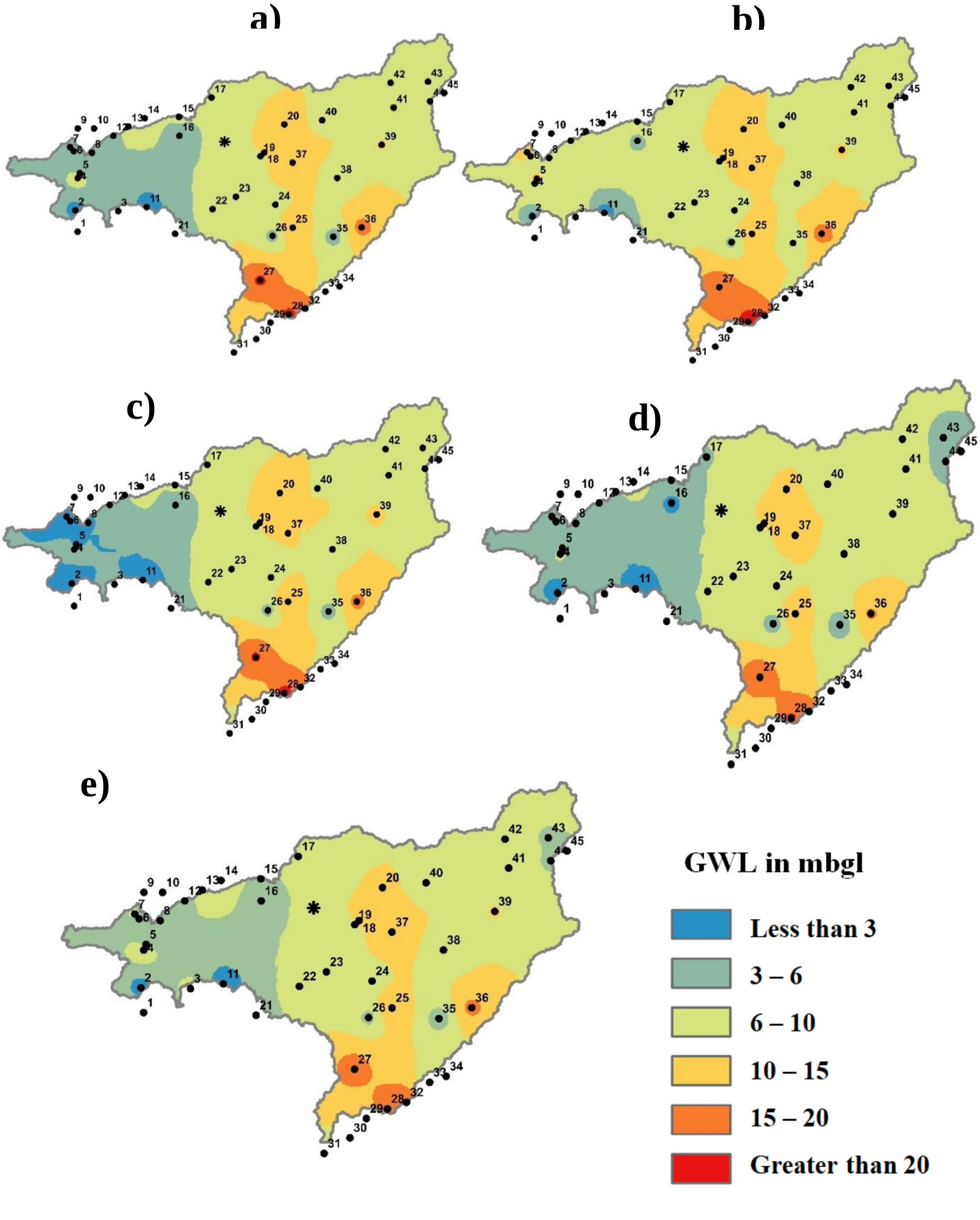


Figure 4.14: Box-whisker plots for average annual groundwater levels of CGWB observation wells during 1996-2015 in the Malaprabha river basin.

4.6.1 Box-whisker plots of annual average GWL

Figure 4.15 represents the average annual GWL fluctuations in the study area for the 20 years (1996-2015). Wells in the upper hilly regions (well number 1 to 11) of the basin show very little inter-annual variability as the width of the box is relatively less. Most of these wells are located in the close vicinity to the forest area and are mostly unaffected by human intervention. Wells 12 to 17 located on the upstream side of the Malaprabha dam show slightly higher inter-annual variability, the withdrawal of GW for irrigation (Reshmi et.al. 2008; Reshmidevi and Nagesh Kumar, 2014) may have caused this variability.

The wells located downstream to Malaprabha dam, in and around the irrigable command area (well number 18 to 40) show higher inter-annual variability. Also, no similarity in the pattern of variability is observed as the amount of water withdrawal depends on the type of crops cultivated each year in close proximity to the wells. The highest variability is observed for well number 37 located immediately downstream to the dam. The cultivation of water-intensive crops like sugarcane, paddy, tobacco, etc., immediately downstream of the reservoir may be the cause for this fluctuation. Excessive annual GW withdrawal was detected at the southern region of the basin where there is a lack of reservoir supply for irrigation as indicated by wells numbered 27, 28 29, 32, and 36. The easternmost region of the basin shows a lower amount of annual GW extraction and also inter-annual variability as indicated by wells 41 to 45 which are located beyond the irrigable command area of the Malaprabha project.

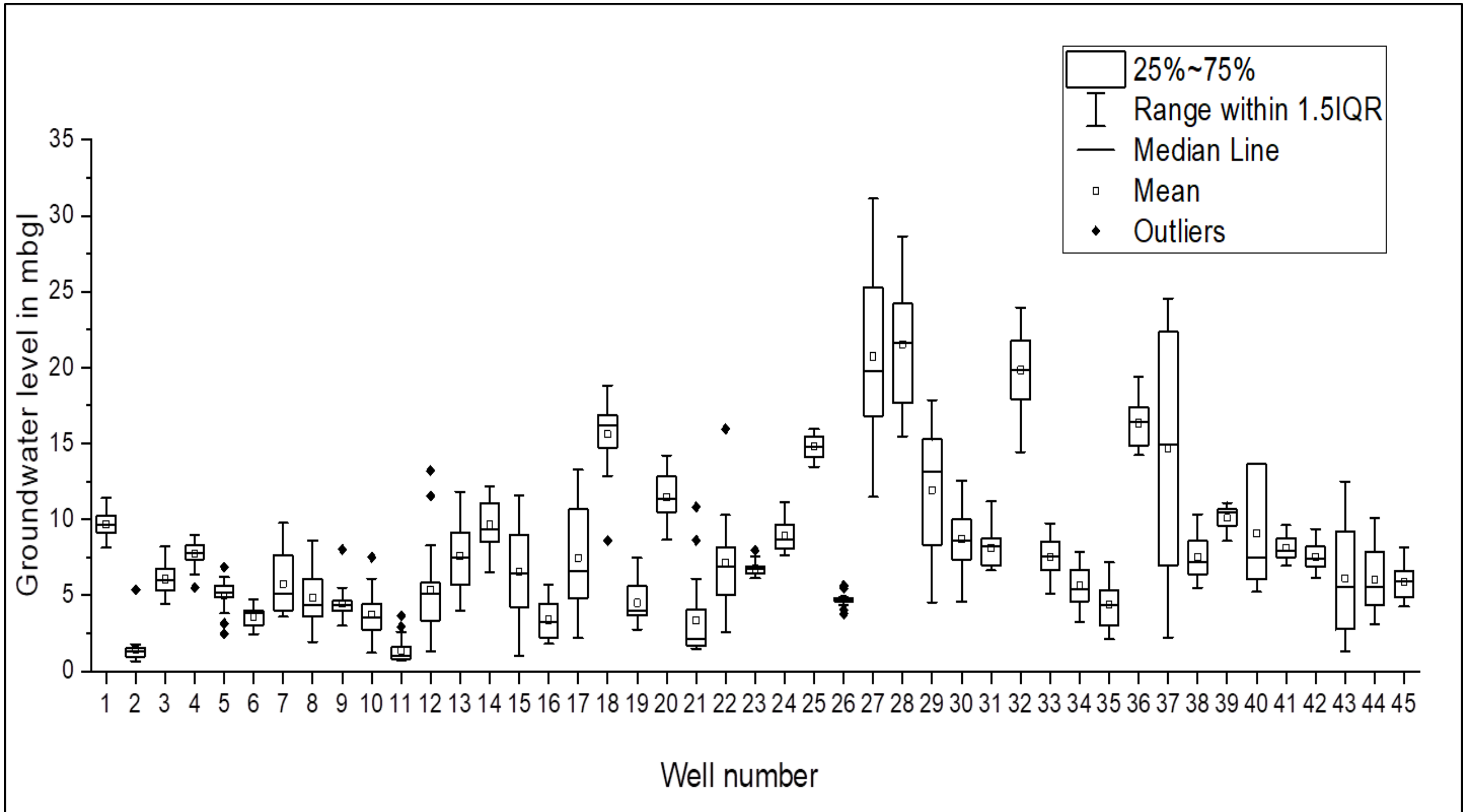


Figure 4.15: Box-whisker plots for average annual groundwater levels of CGWB observation wells during 1996-2015 in the Malaprabha river basin

4.7 CLOSURE

With the obtained historical hydro-meteorological data, a preliminary analysis was carried out using box-whisker plots and Spatio-temporal maps over the Malaprabha river basin. The box-whisker plots not only provide a concise description of important statistical properties of datasets but can also prove to be useful in classifying stations based on similarity in statistical properties.

The annual average rainfall and rainy days over the basin range between 1900-500mm and 87-37 respectively for the period 1960-2015. A large part of the basin experiences annual average rainfall between 544 mm to 700 mm, which is a typical range for a semi-arid climate. The basin is found to be subjected to effective pre-monsoon, monsoon, and post-monsoon rainfall and rainy days. The streamflow regime at downstream gauging stations was significantly affected by the Malaprabha irrigation project in the study area causing increased low flows (LFI up to 111%) during summer months and decreasing amount of peak flows (HFI up to 37.4%) during monsoon. A large part of the basin experiences average annual temperature between the ranges 25 to 27^0C. The pre-monsoon season records highest temperature ranging $27\text{-}30^0$C, followed by monsoon ($24\text{-}26^0$C), post-monsoon ($22\text{-}25^0$C) and winter ($23\text{-}25^0$C). A larger variation of maximum temperature was observed between non-monsoon and monsoon months. However, not much variability was observed for minimum temperature.

The major portion of the study area comes under the GWL fluctuation range of 6 to 10 mbgl during all the seasons. It is interesting to note that, higher GWL fluctuations (10 to 20 mbgl) were observed in the downstream command area and fluctuations >20 mbgl in the southern regions in the study area during all seasons. The wells located immediately downstream to the dam showed fluctuation of 10 to 15mbgl during all seasons. Excessive groundwater extraction for growing water-intensive crops like paddy and sugarcane crops in the immediate vicinity of the reservoir may be the reason for this behavior.

CHAPTER 5

VARIABILITY AND TREND ANALYSIS OF HYDROMETEOROLOGICAL DATA

5.1 GENERAL

Characterization of trends in historical time series of hydro-climatological data is essential to understand the long-term variability of past events which in turn will provide an insight into the nature of future events. Information on trends in hydro-climatological variables is also useful in the planning and design of water resources projects and the design of hydraulic structures (Ghil et. al. 2002, Sang et. al. 2014). Trend analysis of a time series must yield information on four aspects: 1) the magnitude of trend 2) the direction of trend (increase or decrease) 3) whether the identified trend is statistically significant 4) variation or shape of the trend over the period analyzed (Sang et. al. 2014). A variety of parametric and non-parametric methods have been proposed to extract information on some if not all four of these aspects. Parametric methods require data to be independent and normally distributed, while non-parametric methods work with the assumption that data is independent (Krishnan et. al. 2017). Although the non-parametric tests are considered to perform better than parametric tests while analyzing trends in hydrological variables (De Luís et. al. 2000), choosing an appropriate test can be a challenging task since previous studies have shown significant differences in the performances of different methods (Adam and Lettenmaier 2008, Kahya and Kalayci 2004). Among the non-parametric methods, the Sen's slope analysis (Sen 1968) provides information on the magnitude and direction of the trend while the Mann-Kendall (Mann 1945, Kendall 1975) and the Sphearman's Rho (Lehmann 1975, Sneyers 1990) methods test whether a trend exists and if so whether it is significant at a given probability level. That these non-parametric methods are extremely popular is revealed by the large number of previous studies which have successfully implemented them on a variety of hydro-meteorological variables (e.g., Jain et. al. 2013, Han et. al. 2014, Kiros et. al. 2017, Krishnan et. al. 2017, Kumar et. al. 2010, Kumar Raju and Nandagiri 2017, Subash et. al. 2011, Zhang et. al. 2007). However, these methods work on an implicit assumption of stationarity of the time series considered which may not be valid for hydro-meteorological variables since they are known to exhibit non-stationarity and also nonlinear trends (Kahya and Kalayci 2004, Unnikrishnan and Jothiprakash 2015). Assumption of stationarity in the time series can lead to increased risks in hydraulic structures due to severe underestimation of critical design variables such as peak flows (e.g., Li et. al. 2015). Also, none of the conventional methods provide information on the variation or shape of the trend throughout the analysis.

Therefore, spectral analysis-based methods such as Singular Spectrum Analysis (SSA), Morphological Despiking, and Empirical Mode Decomposition (EMD) have been proposed as more attractive alternatives, with the SSA attracting the most research attention. SSA is a nonparametric method in which Principal Component Analysis (PCA) is applied to a time series (Alexandrov et. al. 2012) to decompose it into a small number of interpretable components representing trend, periodicity, cyclicity, and noise (Golyandina and Zhigli͡avskiĭ 2013). The corresponding smooth and slowly varying components are then reconstructed to obtain the shape of the trend in the observed time series. During the last decade a few studies have successfully demonstrated the applicability of SSA to extract trends from a variety of time series (e.g., Bojar 2011, Kandlikar 2007, Sang et. al. 2014, Solow and Patwardhan 1996, Tzagkarakis et. al. 2009, Unnikrishnan and Jothiprakash 2015, Valdés-Pineda et. al. 2018).

Gill and Vautard (1991) used SSA to analyze the time series of global surface air temperatures for about 135 years. They were able to separate trend components from the noise and successfully extracted inter-annual and inter-decadal oscillations in the time series. Tzagkarakis et. al. (2009) utilized SSA to forecast the trend of traffic load in a wireless Local Area Network (LAN). They found that the first few Eigenvalues form the major part of trend information and the same was used to identify components for trend extraction. They reported that the SSA increased the understanding of complex traffic load patterns and enhanced the forecasting performance of the trend. Bojar (2011) projected a combination of SSA and Morphological Filtering methods to extract trends from noisy time series. The principal component corresponding to the foremost Eigenvalue was used to recreate the trend in the series. The study concluded that the proposed method could be used for trend extraction of several types of signals by fine-tuning the parameters.

Recently, Unnikrishnan and Jothiprakash (2015) used SSA to analyze trends in the England and Wales Precipitation (EWP) data and also in historical rainfall data of the Koyna watershed, Maharashtra, India. They considered the periodogram analysis method proposed by Alexandrov (2009) for selecting Eigenvalues and extraction of trend components. The SSA results were compared with the MK test, and they reported that the SSA method was successful in extracting nonlinearity in trends of rainfall series and suggested that the technique can be applied to other hydro-climatological variables. Valdés-Pineda et al. (2018) successfully analyzed the low-frequency patterns of precipitation at multi-decadal scales over Chile using SSA.

Along with trend extraction, the SSA method has also proven to be one of the effective pre-processing algorithms that can remove noise from time-series data and it has found wide application in various fields including image processing, economics, marketing, and engineering (Alexandrov 2009). SSA can extract nonlinear trends in the time series data along with their shape and give more information to the hydrologist about the time-varying location parameter. However, the original SSA method does not provide any information on the statistical significance of the identified trend. Allen and Smith (1994, 1996) proposed a Monte Carlo-based implementation of the SSA method which permits quantification of the statistical significance of the trend. Kandlikar (2007) applied the Monte-Carlo SSA approach to extract trends and periodic oscillations in daily air pollution concentration in New Delhi, India over a 6-year historical period and identified 95% statistically significant Eigenvalues.

The objective of the present work is to 1) determine whether hydro-meteorological variables over the Malaprabha river basin exhibit trends and variation over a long period of record using conventional and spectral-based time series analysis techniques 2) determine whether the large-scale irrigation implemented in the river basin has its impact on these variables. The present work also 3) explores the advantages offered by the MC-SSA approach over the conventional Sen's slope and MK methods in providing information on the trajectories of non-linear trends in time series.

The study objectives were addressed by using historical time-series of rainfall, air temperature, groundwater levels and stream flows in the Malaprabha river basin.

5.2 THEORY

The trend and variability analyses of observed time series of hydro-climatic variables were carried out using nonparametric Singular Spectrum Analysis (Broomhead and King 1986) and Sen's slope Estimator (SE) (Sen 1968). The statistical significance of non-linear and linear trends was identified using Monte-Carlo SSA (Allen and Smith 1994, 1996) and Mann-Kendall (Mann 1945, Kendall 1975) methods respectively. The temporal variability of the data was analyzed using the Coefficient of Variation (CV) statistic. A detailed description of these methods follows.

5.2.1 Singular Spectrum Analysis:

The basic SSA methodology as applied to a given time series to extract the trend component consists of two important stages 1) decomposition and 2) reconstruction. Each stage in turn comprises two steps – embedding and singular value decomposition (SVD) in the decomposition stage and eigen-triple grouping and diagonal averaging in the reconstruction stage. In the present study, the univariate SSA method was adopted and a detailed discussion of the stages/steps is provided herein.

In the embedding step, the observed time series is mapped into a trajectory matrix thereby transforming a univariate time record into a multivariate form (Elsner and Tsonis 1996). The trajectory matrix is a Hankel matrix in which the anti-diagonal elements will be the same.

Consider $x(t) = x_1 , x_2 , x_3 , ... x_N$ as the observed non-zero time series record of length N, with $N > 2$. An essential first step in embedding is to choose a window length L, which is an integer such that $2 \le L \le N - 1$. Considering the lag parameter K

$= N - L + 1$, the trajectory matrix $Y_{ij} = x_{i+j-1}$ with $i = 1,2,3 \dots K$, $j = 1,2,3 \dots L$ can be obtained as,

$$Y = \begin{bmatrix} x_1 & x_2 & x_3 & \cdots & x_L \\ x_2 & x_3 & x_4 & \cdots & x_{L+1} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ x_K & x_{K+1} & x_{K+2} & \cdots & x_N \end{bmatrix} \quad (5.1)$$

Y is an $L \times K$ Hankel matrix.

Although there are no set rules in the choice of window length (L), the range should be in $2 \le L \le N/2$ (Wang H. et. al. 2015, and Wang R. et. al. 2015). However, if there is any periodic component observed in the given time series record (typically evident in daily time scale), then it is desirable to take window length equal to the duration of the periodic component (Unnikrishnan and Jothiprakash 2015).

In the next step of decomposition, a lagged covariance matrix defined as $Z = Y^T Y$ is decomposed into Eigen-triplets (equal to window length) by using Singular Value Decomposition (SVD). SVD produces Y in the form of $Y = UDV^T$ where $U (L \times L)$ and $V (K \times L)$ are the left and right eigenvectors and D is a diagonal matrix of square roots of eigenvalues of the matrix Z. Therefore, SVD yields the trajectory matrix Y into the sum of d matrices as,

$$Y = \sum_{i=1}^{d} Y_i \quad (5.2)$$

$$Y_i = U_i \sqrt{\lambda_i} V_i^T \quad (5.3)$$

Where, λ_i = Eigenvalues of Z with $i = 1, 2, 3 \dots d$, where d = maximum value of i when $\sqrt{\lambda_i} > 0$. The set of values of ($\sqrt{\lambda_i}$, U_i, V^T_i) is known as the i^{th} Eigen-triple.

The second stage of SSA is reconstruction in which the trajectory matrix Y is re-transformed to time series of length N. The first step in this stage involves choosing suitable eigenvalues and corresponding eigenvectors for trend extraction from SVD and subsequent Hankelization (averaging along with components of matrices) of ($K \times L$) matrix from selected components of the SVD. In this eigen-triple grouping step, the method of leading eigenfunction is adopted to select only those components which explain the long-term trends in the original time series and thereby eliminate noise from the data (Elsner and Tsonis 1996).

The selected leading eigenfunctions can be used to determine the principal components (PCs) (a_k) by projecting corresponding eigenvalues into the original time record *x(t)* as,

$$a_{ik} = \sum_{j=1}^{k} x_{i+j-1} e_{jk} \qquad (5.4)$$

Where e_{jk} is the j^{th} component of the k^{th} Eigenvector. The PCs are then ranked according to the amount of variance or Eigen-Fraction (calculated as the ratio of the corresponding eigenvalue to the sum of total eigenvalues) in the data along the axis of variation defined by $a_{k.}$

In the final step, reconstruction of a time series of length N from the Hankel matrix is achieved by averaging the diagonal elements of selected matrices in the grouping stage. The PCs and corresponding Eigenvectors are then considered to reconstruct the time series trend by the method of diagonal averaging. The reconstructed trend components (R) of the original time series can be obtained as,

$$R_{i+j-1} = \sum_{k=1}^{L} a_{ik} e_{jk} \qquad (5.5)$$

Monte Carlo SSA

In the present work, the statistical significance of the nonlinear trends obtained by SSA was tested using Monte-Carlo SSA (MCSSA) method proposed by Allen and

Smith (1994, 1996). The algorithm tests the null hypothesis of "original time series generated by a first-order auto-regressive AR (1) process with unknown mean". The AR (1) process of the original time series x_i is given by,

$$x_{i+1} = \bar{x} + r_1(x_i - \bar{x}) + \varepsilon_i \tag{5.6}$$

Where $\bar{x}$ is the mean of original time series, r_1 is autocorrelation function at lag1 and ε_i is the residual error which is identically and independently distributed as a normal distribution with a mean zero and variance σ^2. i.e., $\varepsilon \approx i.i.d.\ N(0, \sigma^2)$. It can be shown that,

$$\varepsilon_i = t_i s\sqrt{1 - r_1^2} \tag{5.7}$$

Where t_i is a random number generated from a normal distribution, s is the standard deviation value of the original time series. The AR (1) parameters were estimated from x_i used to generate Monte-Carlo surrogate realizations, by randomizing the original data series using equation 5.6. Each surrogate data set represents a particular instance of the randomized time series;

i.e., $x_s^j(t)$, with $t = 1, 2, \dots N$ and $j = 1000$, number of surrogate time series. Later, covariance matrices (C_s) are computed for each surrogate realization and they are projected into Eigenvectors of original time series E_X such as,

$$\Lambda_S = E_X{}^T C_S E_X \tag{5.8}$$

The eigenmatrix Λ_S of surrogate series is generally not diagonal, since Λ_S is not the result of SVD of the surrogate data set, but is a measure of the similarity of the given surrogate data set with the original time series. The degree of similarity can be quantified by computing the statistics of the diagonal elements of Λ_S via Monte-Carlo simulation. The null hypothesis is accepted if eigenvalues of the original time series are within the confidence limits by (Barkhuizen 2003, and Barkhuizen and Aldrich 2003) generated by the eigenvalues of the surrogate data sets.

The confidence limits *(φ)* for each eigenvalue λ_i of original time series is obtained,

$$\varphi(\lambda_i) = \bar{\lambda}_i \pm \sigma_\lambda t_{\alpha/2} \qquad (5.9)$$

Where, *i* = average of all the surrogate eigenvalues *λ* at the same position *i* in the eigenspectra, σ_λ = is the standard deviation of the eigenvalues and *α*= confidence level.

5.2.2 Sen's slope estimator (SE):

Sen (1968) developed a non-parametric procedure for estimating the magnitude of the slope of a trend in the sample of N pairs of data,

$$Q_i = \frac{x_j - x_k}{j - k} \qquad \text{for } i = 1, 2\ldots\ldots \text{ N}, \qquad (5.10)$$

Where x_j and x_k are the data values at times *j* and *k* (*j*>*k*), respectively. The N values of Q_i are ranked from smallest to largest and the median of slope or Sen's slope estimator is computed as,

$$Q_{med} = \begin{cases} Q\left[\frac{N+1}{2}\right], & if\ N\ is\ odd \\ \frac{Q\left[\frac{N}{2}\right]+Q\left[\frac{N+1}{2}\right]}{2}, & if\ N\ is\ even \end{cases} \qquad (5.11)$$

While the sign (+/-) of Q_{med} reflects the direction (increase/decrease) of the trend, its magnitude indicates the steepness of the trend.

5.2.3 Mann-Kendall (MK) test:

The widely used MK test is a nonparametric method, which statistically evaluates the presence of a monotonic increasing or decreasing trend in a variable over the given period (Mann 1945, Kendall 1975). However, the method does not specify whether the detected trend is linear or nonlinear (Sang et al. 2014).

For a given time series x_i with length n, the MK test statistic (S) can be defined as,

$$S = \sum_{i=0}^{n-1} \sum_{j=i+1}^{n} \text{sgn}[x_j - x_i] \tag{5.12}$$

Where

$$\text{sgn}\,(x) = \begin{cases} 1 & x > 0 \\ 0 & x = 0 \\ -1 & x < 0 \end{cases} \tag{5.13}$$

The statistic S is approximately normally distributed if the length of the data $n > 8$, with a mean [E(S)] and variance of S [*Var (S)*] as,

$$E(S) = 0 \tag{5.14}$$

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p-1}^{g} t_p(t_p - 1)(2t_p + 5) \right] \tag{5.15}$$

Where g = number of tied groups; and t_p = number of observations in the p^{th} group. The standardized test statistic (Z) is given by,

$$Z = \begin{cases} S - \frac{1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ S + \frac{1}{\sqrt{Var(S)}} & S < 0 \end{cases} \tag{5.16}$$

If the absolute value of Z is greater than the theoretical value of $Z_{1-\alpha/2}$, the null hypothesis of no trend is rejected and an alternate hypothesis with the presence of a monotonic trend is accepted. Here α is the statistical significance level specified. The sign (+/-) of Z denotes the direction (increase/decrease) of the trend.

Since the magnitude of Z does not directly provide a measure of the magnitude of the trend but only serves as a statistic for hypothesis testing, it is advisable to calculate the direction and magnitude of trend ($\pm Q_{med}$) in a given time series using the SE method (Eq. 5.11) and subsequently determine whether the trend is statistically significant at a given probability level using the MK test (Equations. 5.12-5.16).

5.2.4 Coefficient of Variation (CV):

The coefficient of variation explains the variation within sample values and it is widely used for variability studies. It is a statistical measure of the dispersion of data points in a data series around the mean. CV for a time series is calculated as

$$CV = \frac{\sigma}{\mu} \tag{5.17}$$

Where μ is the mean of the dataset and σ is the standard deviation. IMD proposed numerical criteria to define the dry and wet years. i.e., negative deviation equal to or greater than 25% of mean annual will be termed as a dry year and positive deviation of the same value range will be indicated as a wet year.

5.3 METHODOLOGY

The hydro-climatic variables considered for analysis include, rainfall totals and number of rainy days (1960-2015) of 17 RG stations, average air temperature (1960-2015) of 23 grid points, groundwater levels (1996-2015) of 45 wells, and stream flows at 3 gauging sites in the Malaprabha river basin. Locational details of the stations are presented in Chapter 4. The analysis was performed at annual and seasonal time scales separately for individual hydro-climatic stations and the areal average calculated over the entire basin. Thiessen polygon technique was used to determine areal average climatic variables over the basin.

5.4 RESULTS AND DISCUSSIONS

Statistical trend analysis of the hydro-climatic variables was carried out in three phases. In the first phase statistical parameter, the Coefficient of variation (CV) is calculated. The second phase involved the extraction of trends using the MK test and SSA methods. The third phase consists of finding the magnitude of linear trends using Sen’s slope estimator.

5.4.1 Co-efficient of variation

Values of coefficient of variation (CV) were computed using Equation 5.17 for annual and seasonal values of hydro-climatic variables of the Malaprabha river basin. CV is normally used as a relative measure of dispersion between datasets and accordingly, maps depicting the spatial variability of CV values for hydro-climatic variables for annual and seasonal periods were prepared and analyzed as described below.

5.4.1.1 Rainfall and Rainy days

Rainfall and rainy days considering data for the historical period 1960-2015 were analyzed at annual and seasonal periods except for the winter season as its contribution to total annual rainfall and number of rainy days is < 1%. The maps depicting the spatial variability of CV values of rainfall and rainy days were presented in figures 5.1 and 5.2 respectively.

Figure 5.1(a) indicates a clear pattern of increasing CV values for annual rainfall (R_A) from the western part (0.26 – 0.28) of the basin to the eastern part (0.31 – 0.35). It is interesting to note that the three climate stations, Badami (NE1), Ramdurga (NE5) and Navalgund (SE1) located downstream of the Malaprabha dam record smaller values of CV despite being located in the Northern Dry (ND) agro-climatic zone. As regards the spatial variability of pre-monsoon rainfall (R_{PR}) (Figure 5.1b), not only are the CV values significantly larger (0.43 – 0.72), a pattern in the north-south direction is evident with the CV values being higher in the northern part of the basin. Since the contribution of monsoon season rainfall (R_M) to the annual total is quite large, Figure 5.1(c) indicates that the spatial variability of CV for the monsoon season follows a pattern similar to the one for annual rainfall (Figure 5.1a) but with somewhat higher values of CV (0.28 – 0.46). Again, it can be seen that the Badami station (NE1) has a smaller CV in comparison to other stations in the vicinity. Figure 5.1(d) indicates relatively higher values of CV for all stations for rainfall during the post-monsoon season (R_{PM}). Stations Ramdurga (NE5) and Navalgund (SE1) located immediately downstream of the dam indicate relatively smaller CV values during this season. Overall, it appears that the presence of the Malaprabha dam/reservoir results in relatively lower variability in rainfall recorded at stations located immediately downstream. The potential for higher evaporation from the reservoir and the associated increase in atmospheric moisture levels may be a possible cause for this phenomenon.

Figure 5.2 depicts the spatial variability of the CV of rainy days for annual and seasonal periods. It can be seen from Figure 5.2(a) that relatively high values of CV prevail over most of the basin for the annual number of rainy days (D_A). Interestingly, CV is highest at the Bailhongla station (NW1) which is located very close to the Malaprabha reservoir. Annual rainy days show the lowest variability in the northwest region of the basin. As expected, CV values for rainy days in the pre-monsoon season (D_{PR}) are high and as shown in Figure 5.2(b) variability is higher in the northern part of the basin in comparison to the southern part. During the monsoon season (Figure 5.2c), the range of CV values of rainy days (D_M) is similar to that of the annual period, but the spatial extent of high CV values is the largest for this season. Also, it can be seen from Figure 5.2(c) that the variability of D_M is high both at the location of the reservoir and also downstream of it.

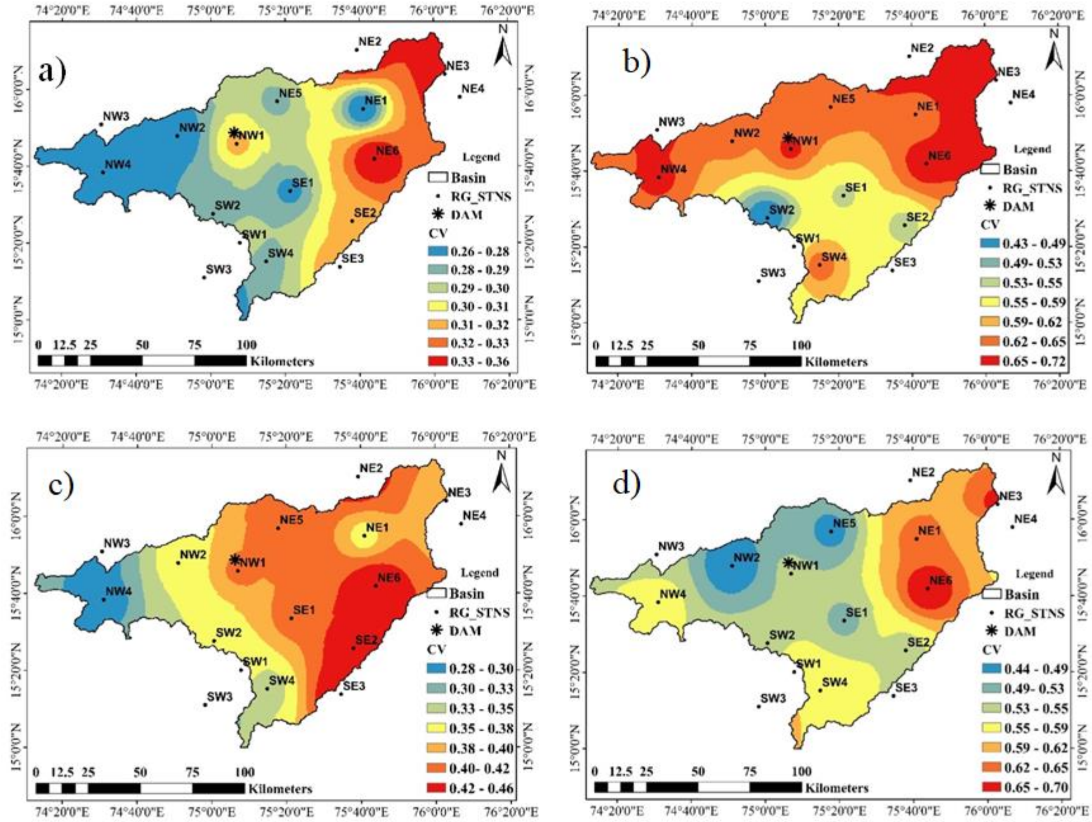


Figure 5.1: Spatial distribution of coefficient of variation (CV) of rainfall over Malaprabha river basin for a) Annual b) Pre-monsoon c) Monsoon and d) Post-monsoon

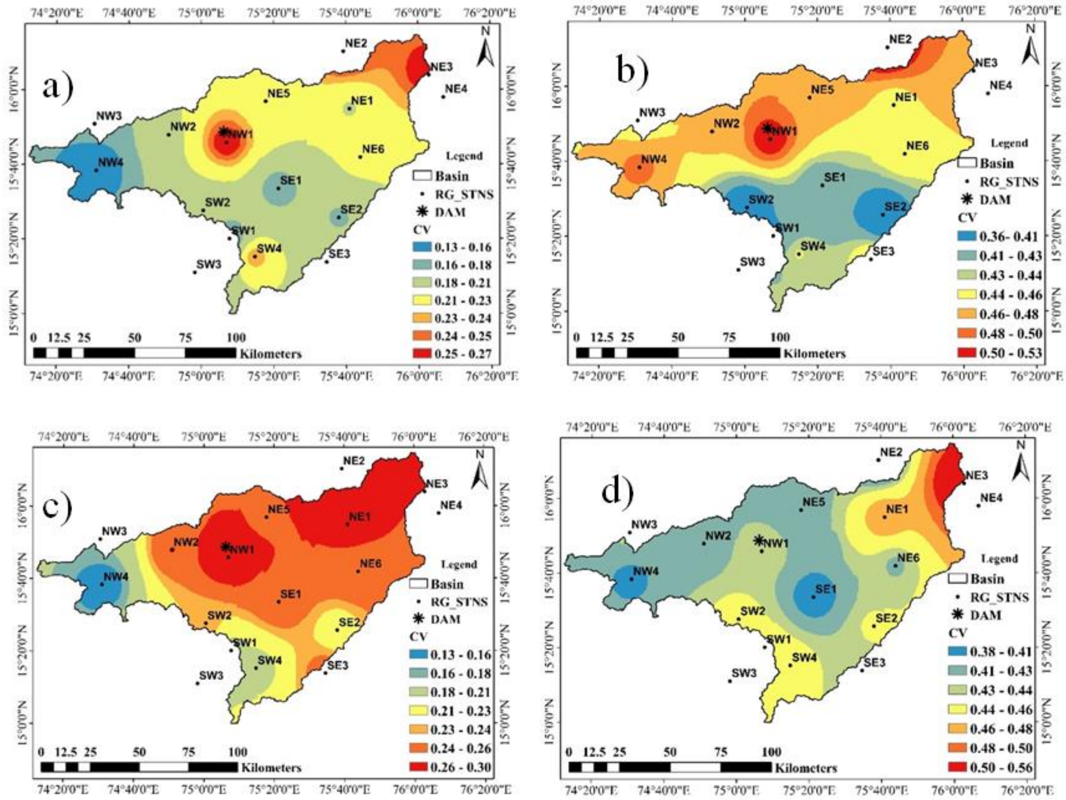


Figure 5.2: Spatial distribution of coefficient of variation (CV) of rainy days over Malaprabha river basin for a) Annual b) Pre-monsoon c) Monsoon and d) Post-monsoon

The range of CV values for post-monsoon rainy days (D_{PM}) is higher than for annual and monsoon periods but except for a small part of the basin towards the north-east, the lowest values of CV are recorded for most of the basin (Figure 5.2d). Based on the spatial variabilities of the CV of rainy days depicted in Figures 5.2(a) and 5.2(c), it may be concluded that in the region close to and downstream of the Malaprabha dam, the number of rainy days for annual and monsoon periods exhibit higher variabilities. This is in contrast to the finding that CV values for annual and monsoon rainfall totals are lower in this part of the basin (Figure 5.1). This implies that it is likely that the presence of the reservoir has resulted in the occurrence of rainfall events with higher intensities in its vicinity.

5.4.1.2 Stream flows

Streamflow records at three gauging stations (Figure 5.3) were considered for statistical analysis in the present work. The locational details and duration of data considered were presented in Table 4.2 (Chapter 4). Since the duration of data availability of stream-flow records is different for the three gauging stations, representing CV values through spatial maps will not be appropriate. Thus, CV values for the three stations were tabulated (Table 5.1) for annual and seasonal time steps.

Among the stations considered, Khanapur represents the natural stream-flows from the forested watershed located upstream to the Malaprabha dam. The annual and seasonal CV values of the station are higher compared to other stations (Table 5.1). Also, the Huvanuru station for pre-dam condition (H.pre_Dam) represents the natural flows located downstream of the dam. The annual and seasonal CV values are comparatively less for this station. However, pre-Monsoon CV values are the highest (3.7 and 0.6 respectively) for the two stations.

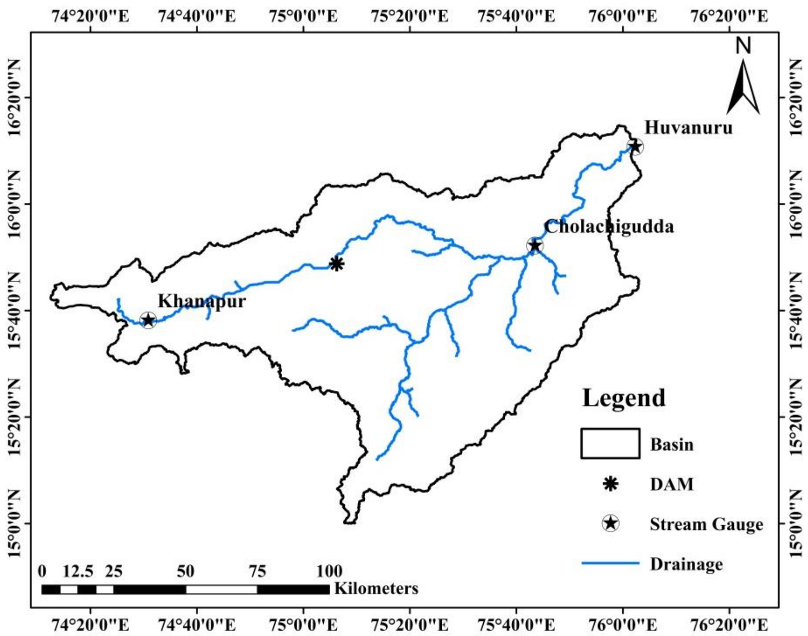


Figure 5.3 Streamflow gauges over the Malaprabha river basin considered for the analysis

Table 5.1 Coefficient of variation for stream-flow records considered for the study.

	CV				
Station Name	**Annual**	**Winter**	**Pre-Monsoon**	**Monsoon**	**Post-Monsoon**
Khanapur	0.482	1.619	3.756	0.451	1.207
Cholachgudda	0.374	0.805	0.629	0.592	0.563
Huvanuru	0.356	1.118	0.657	0.323	0.752
H.pre_Dam	0.239	0.165	0.646	0.233	0.306
H.post_Dam	0.407	0.906	0.696	0.360	0.849

Cholachgudda and Huvanuru station for post dam condition (H.Post_Dam) represents regulated stream-flows located downstream to the Malaprabha dam. CV values for the winter season are higher (0.8 and 0.9 respectively) for these two stations compared to other seasons. From Table 5.1 it is evident that CV values of natural stream-flows from the forested watershed (Khanapur) are higher compared to that of stream-flows from the agricultural watershed (Huvanuru) at annual and seasonal time steps. Also, referring to CV values of H.pre_Dam and H.post_Dam, it is evident that construction of the Malaprabha Dam/Reservoir has increased the variability in stream-flows at annual and seasonal time scales.

5.4.1.3 Average temperature

Figure 5.4 represents spatial variability of CV values of average temperatures over the period 1960-2015 at annual and seasonal time scales.

The magnitude of CV values for average temperatures are lesser (0.01 to 0.03) compared to other hydro-meteorological variables for annual as well as the seasonal time scale. Among all the seasons, monsoon represents very little variability in CV values (0.017 to 0.019), followed by winter, pre-monsoon, and post-monsoon seasons respectively.

As presented in Figures 5.4 a, c, and e, relatively greater CV values are registered for the stations located in the closer vicinity to the dam during annual (NW3, SW5), pre-monsoon (NW3, NW4, NW5), and post-monsoon (NW4) seasons. This indicates the presence of reservoir exhibits its effect on temperature variability, although its significance is very less during the pre-and post-monsoon seasons.

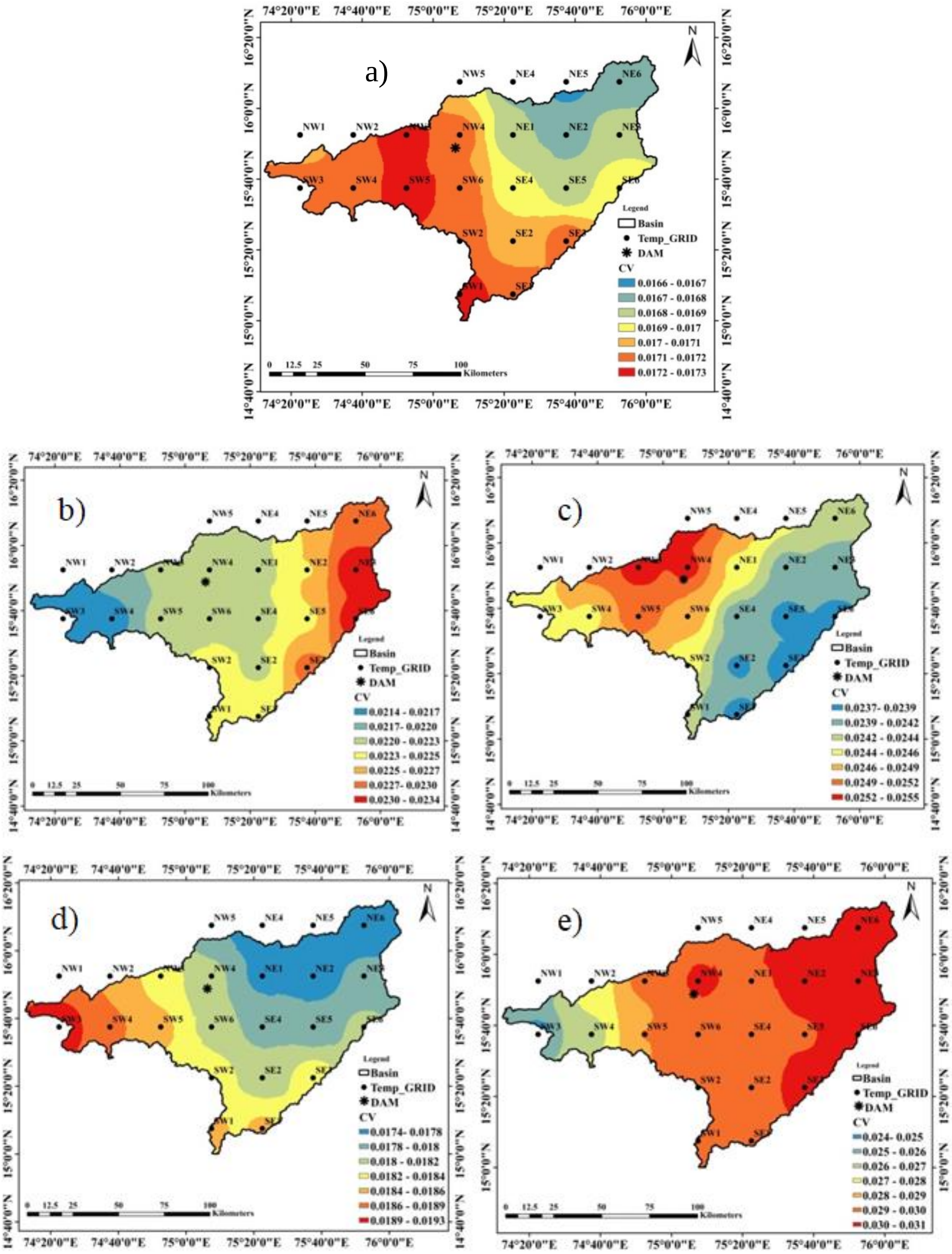


Figure 5.4: Spatial distribution of coefficient of variation (CV) of average temperature over Malaprabha river basin for a) Annual b) Winter c) Pre-monsoon d) Monsoon and e) Post-monsoon

5.4.1.4 Groundwater levels

Figure 5.5 represents a spatial variation of CV values for annual and seasonal groundwater levels over the Malaprabha river basin collected from 45 wells for the period of 1996 to 2015.

The Malprabha river basin is primarily an agricultural-dominated one and a greater extent of groundwater extraction is observed for irrigation purposes at both upstream and downstream of the dam (Reshmidevi and Nageshkumar, 2014; Madar, 1993; Chitraghr 2018). From figure 5.5(a) it is evident that annual groundwater levels (G_A) in the wells upstream of the Malaprabha Dam show higher annual CV values (0.4 to 0.7). Also, well numbers 37, 40, and 35 which are located in the downstream command area of the reservoir show the same extent of variation. However, most of the wells in the Malaprabha downstream command area show lesser CV values in the range of 0.05 to 0.20. These regions are in close vicinity to the Malaprabha left and right bank canal and the majority of the region is irrigated by canal water supply. Spatial variability of CV value of Pre-monsoon (G_{PREM}) (Figure 5.5(b)) and monsoon (G_M) (Figure 5.5(c)) groundwater levels follow a pattern similar that of annual variation (Figure 5.5(a)). It is interesting to note that well numbers 37, 40, and 35 located in the downstream command area show comparatively greater CV values for both seasons. Although, the spatial variability of the CV of post-monsoon Kharif (G_{POMKH}) (Figure 5.5(d)) and post-monsoon Rabi (G_{POMRB}) (Figure 5.5(e)) groundwater levels show a similar pattern. i.e., lesser CV in the downstream command area compared to upstream, the extent of CV is higher (0.09 to 1.12) for G_{POMKH} compared to all other seasons. Also, the intensity of CV is relatively lesser for the wells 37, 40, and 35 among other seasons.

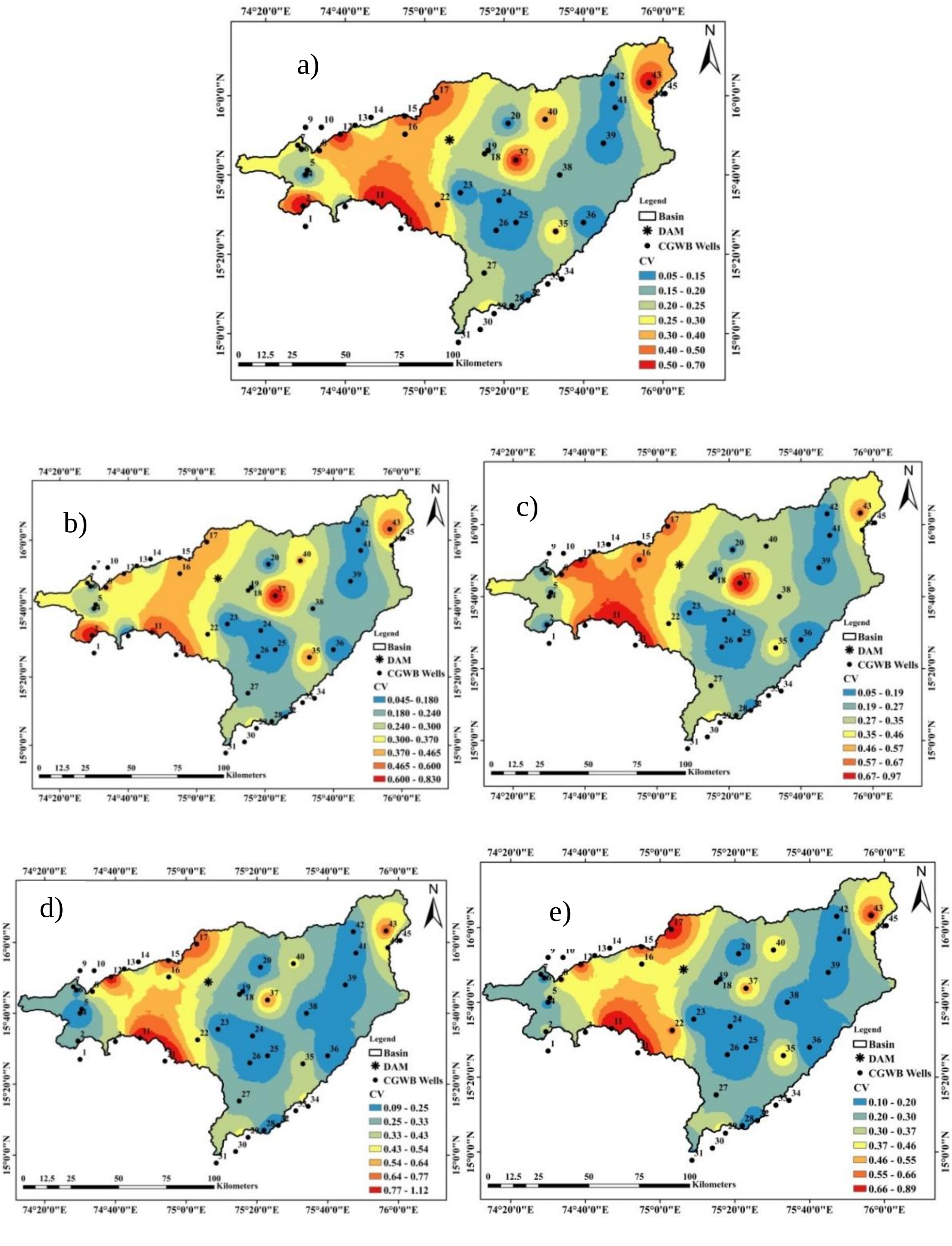


Figure 5.5: Spatial distribution of coefficient of variation (CV) of Groundwater levels over Malaprabha river basin for a) Annual b) Pre-Monsoon c) Monsoon d) Post-Monsson Kharif and e) Post-monsoon Rabi

Overall, it is evident from Figure 5.5 that, the CV values of groundwater levels in the downstream command are of the Malaprabha Dam and especially the regions around the main canal systems shows lesser variation for annual and seasonal time scales.

However, the upstream region and interestingly three wells in the downstream command area show greater CV for all the seasons. This suggests that there is significant variation in the groundwater levels on account of extractions in these regions mainly for irrigation purposes.

5.4.2 Trend analysis of hydro-meteorological variables:

In the present study, conventional Sen's slope Estimator (SE) and spectral-based - Singular spectrum analysis (SSA) tests were applied to identify long-time trends in considered hydro-meteorological variables at every station as well as basin average for annual and seasonal time scales. The SE method was applied using Equations 5.10 and 5.11. Also, the MK test defined by Equations (5.12-5.16) was implemented to these variables considering a confidence interval of 95%.

Also, the SSA method (Eqs. 5.1-5.9) was applied to extract nonlinear trends in the time series data. The window length (L) was set to (*N/2*) (N is the length of the dataset in time series data) since no periodic component was observed in the time series for the recorded period. Accordingly, N Eigen-triplets *(U, D, and V)* were formed after *SVD*. The MC-SSA algorithm was then applied by generating 1000 surrogate realizations for a significance test at a 95% confidence interval.

5.4.2.1 Rainfall and Rainy days

5.4.2.1.1 Results of Sen's slope and MK test

Station-wise results of SE are presented in Table 5.2 separately for the two variables – rainfall magnitude and rainy days, for both annual and seasonal periods. For cases where the trend was statistically significant as per the MK test, values of SE are shown in bold font. The last row of Table 5.2 shows results of SE for basin-average values for annual rainfall (R_A^B) and annual rainy days (D_A^B).

All stations showed a decreasing trend in annual rainfall (R_A) except for Badami and Ramadurga which despite being located in the Northern Dry (ND) agro-climatic zone showed increasing trends. Although not statistically significant, the increase in rainfall at these two stations which are located downstream of the Malaprabha dam may be on account of irrigated agriculture in the vicinity since no other station in the study area recorded an increase in annual rainfall. Bagalkot (NE2) and Kundagol (SW4) (Table 5.2) were the only stations that exhibited statistically significant decreasing trends in R_A at the rates of -4.01 mm/year and -3.59 mm/year respectively. However, the remaining stations irrespective of their geographical location showed insignificant decreasing trends in R_A. Annual rainy days (D_A) exhibited statistically significant decreasing trends at Bagalkot (NE2) and Kundagol (SW4) stations where significant decreasing trends in R_A were also recorded (Table 5.2). In addition, a statistically decreasing trend in D_A was evident at the Shirahatti station (SE3) at which there was a comparatively large decrease in R_A but was not statistically significant. Interestingly, the two stations located downstream of the dam (Badami and Ramadurga) did not show any trend in D_A. A few stations (NE1, NE5, SW3, NW2, and NW3) showed either no trend or small statistically insignificant positive trends (NE6, SW1, SW2, and NW1) in D_A. For the Malaprabha basin as a whole (Table 5.2), insignificant decreasing trends were recorded for both R_A and D_A.

Table 5.2: Sen's estimate of slope (SE) for annual and seasonal rainfall and rainy days over Malaprabha River Basin*

Station Id	Agro-climatic Zone	Station Name	R_A mm/yr	D_A days/yr	R_{PR} mm/yr	D_{PR} days/yr	R_M mm/yr	D_M days/yr	R_{PM} mm/yr	D_{PM} days/yr
NE 1	ND	Badami	0.82	0.00	0.70	0.00	-0.36	0.00	-0.17	0.00
NE 2	ND	Bagalkot	**-4.01**	**-0.17**	-0.06	-0.03	**-3.16**	**-0.13**	-1.23	0.00
NE 3	ND	Hungund	-1.61	-0.14	-0.13	-0.05	-2.47	-0.08	0.12	-0.04
NE 4	ND	Ilkal	-1.47	-0.11	0.07	0.00	-1.38	-0.05	0.09	-0.05
NE 5	ND	Ramdurga	1.02	0.00	-0.34	-0.04	0.85	0.00	0.71	0.00
NE 6	ND	Rona	-1.14	0.05	0.99	0.03	-1.75	0.03	-0.42	0.00
SE 1	ND	Navalgund	-0.71	-0.06	-0.60	0.00	-0.61	-0.07	-0.14	0.00
SE 2	ND	Gadag	-1.07	-0.02	-0.35	0.00	-0.80	0.00	-0.17	-0.02
SE 3	ND	Shirahatti	-3.15	**-0.21**	-0.78	-0.04	-1.48	**-0.16**	-0.41	0.00
SW1	NT	Hubli	-0.45	0.08	0.13	0.02	-1.71	0.11	0.51	0.03
SW2	NT	Dharwad	-1.20	0.10	-0.07	0.03	0.18	0.06	-0.68	-0.03
SW3	NT	Kalghatgi	-0.27	0.00	0.07	0.00	0.15	-0.03	-0.11	0.00
SW 4	NT	Kundagol	**-3.59**	**-0.22**	-0.32	0.00	-2.08	**-0.19**	-0.85	-0.06
NW1	ND	Soundatti	-1.40	-0.03	-0.94	-0.05	-0.85	0.00	0.21	0.00
NW2	NT	Bailhongala	-0.97	0.07	-0.55	-0.03	-0.56	0.07	0.43	0.02
NW3	NT	Belgaum	-2.19	0.00	-1.26	**-0.08**	0.04	0.05	-0.29	-0.05
NW4	HY	Khanapur	-1.73	-0.03	0.60	0.00	-2.86	-0.05	0.79	0.00
		Malaprabha Basin	-1.43	-0.03	-0.20	-0.01	-0.90	-0.01	-0.23	-0.01

*SE values in **bold** only are statistically significant at 95% confidence level as per Mann-Kendall test

None of the stations exhibited statistically significant trends in the pre-monsoon season for rainfall (R_{PR}) or rainy days (D_{PR}) except the Belgaum station (NW2) where a small statistically significant decrease in D_{PR} was seen. The magnitudes of SE for rainfall in the monsoon season (R_M) for most stations were smaller in magnitude than annual totals (Table 5.2) but larger than for the other two seasons. Only Bagalkot (NE2) showed a statistically significant negative trend in monsoon rainfall which was also reflected in annual rainfall for this station. Similarly, Bagalkot (NE2), Shirahatti (SE3), and Kundagol (SW4) which recorded a statistically significant trend at the annual time step also showed negative trends during the monsoon season for rainy days (D_M). This is because of the major contribution from the monsoon season to annual rainfall and annual rainy days. During the post-monsoon season, none of the stations showed statistically significant trends in both rainfall (R_{PM}) and rainy days (D_{PM}). Also, from the results shown in Table 5.2, it can be seen that trends in rainy days at several stations irrespective of their location, were either very small in magnitude or even zero for all the periods considered. Combined with the fact that most of these stations recorded negative trends in rainfall totals this is indicative of reducing rainfall intensities.

5.4.2.1.2 Results of Singular Spectrum Analysis

The SSA method was applied to extract nonlinear trends in the time series data. The window length (L) was set to 28 (*N/2*) since no periodic component was observed in the annual time series for the period 1960-2015. Accordingly, 28 Eigen-triplets *(U, D, and V)* were formed after *SVD*. The MC-SSA algorithm was then applied for a significance test at a 95% confidence interval.

Figures 5.6 and 5.7 show the Eigen-spectrum for the time series of basin average values of annual rainfall (R_A^B) and annual rainy days (D_A^B) respectively. Also shown are the upper and lower limits of the chosen significance level. Since no initial eigenvalues were found to be significant, the eigenvalues explaining the highest variance (Eigen-fraction) were chosen to be leading as well as slowly varying compared to others and the corresponding Eigen-vectors were selected for extraction of long-term trend components. The second and third Eigen-values of R_A^B were found to be above the confidence level indicating significant oscillations during the considered period.

The shape of the long-term trend in basin average values of R_A^B and D_A^B extracted using SSA along with the observed data are shown in Figures 5.8 and 5.9 respectively.

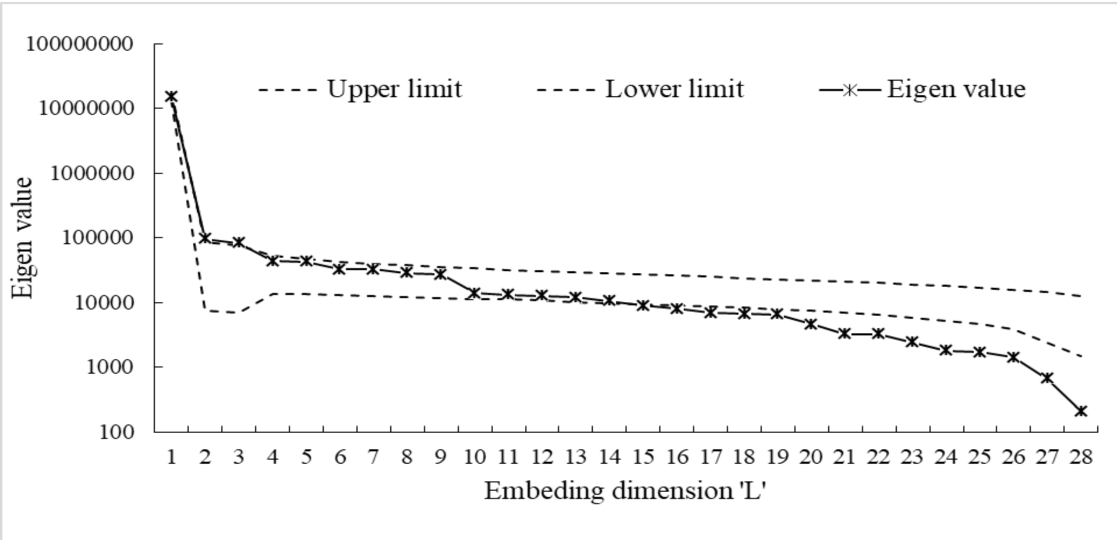


Figure 5.6: Eigen spectrum for basin average annual rainfall along with upper and lower limits of 5% significance level

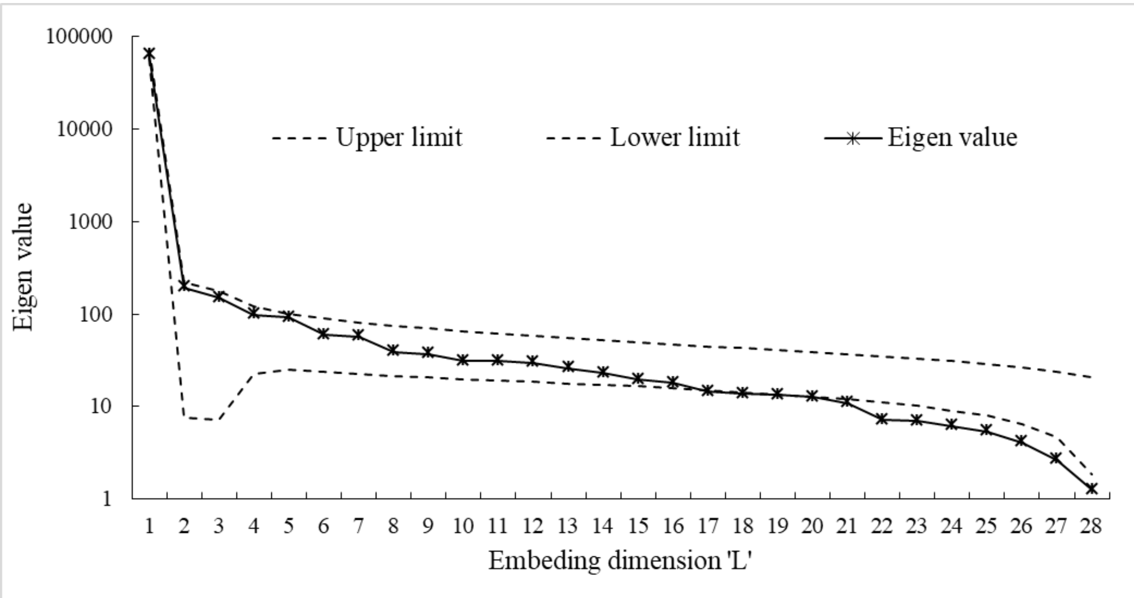


Figure 5.7: Eigen spectrum for basin average annual rainy-days along with upper and lower limits of 5% significance level

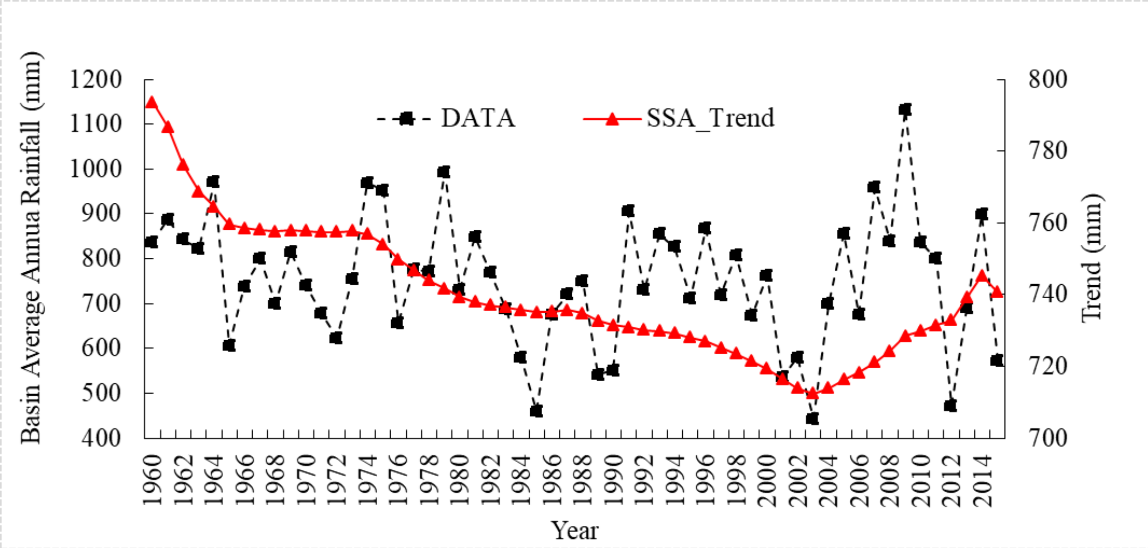


Figure 5.8: Time series of observed basin average annual rainfall (R_A^B) and non-linear trendline obtained from SSA

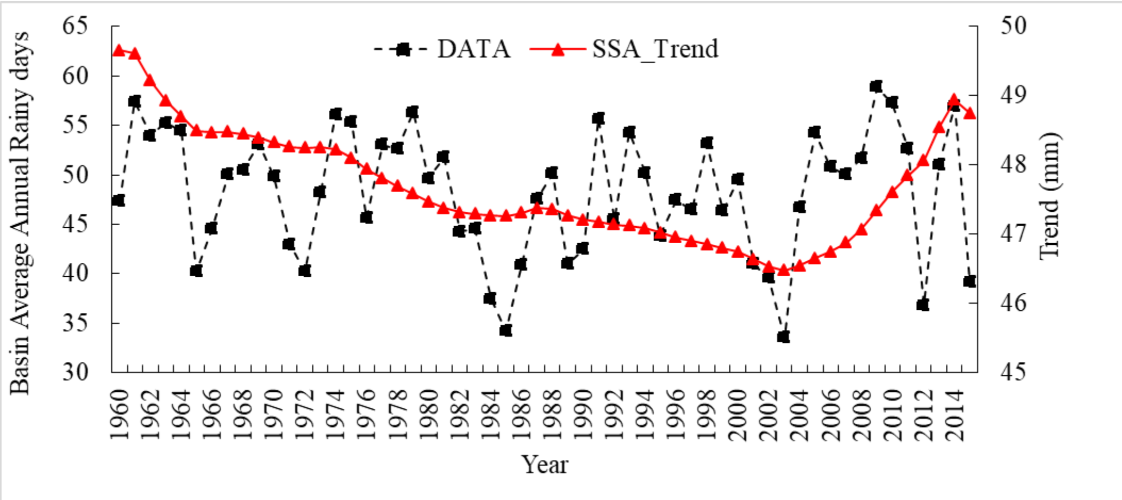


Figure 5.9: Time series of observed basin average annual rainy days (D_A^B) and non-linear trendline obtained from SSA

Although these plots mask the spatial variabilities, they indicate the random nature of intra-annual fluctuations in R_A^B and D_A^B over the historical period 1960-2015. However, from Figure 5.8 it can be seen that during some decades basin average annual rainfall appeared lower in comparison to the other decades. Examination of data revealed that the number of years when the basin-average rainfall was ≥ 800 mm was 6, 4, 1, 4, and 5 for the periods 1960-1971, 1972-1981, 1982-1991, 1992-2001, and 2002-2011 respectively.

Figure 5.9 also indicates a similar pattern with the number of years when basin-average annual rainy days was ≥ 50 days was 7, 6, 2, 3, and 7 for 1960-1971, 1972-1981, 1982-1991, 1992-2001, and 2002-2011 respectively. Evidently, the decade 1972-1981 and to a slightly lesser extent, 1992-2001 experienced relatively drier conditions. The decade 2002-2011 on the other hand, appeared to be relatively wetter with the year 2009 experiencing the highest annual rainfall on record (Figure 5.8). This decadal variability in rainfall and rainy days is captured quite accurately by the trends extracted using SSA. Eigen-Fraction (EF) values which explain the % of the variance in the trend obtained were 96.78% and 98.43% for R_A^B and D_A^B respectively. Examination of Figure 5.8 indicates that during the 5 years starting from 1960, R_A^B showed a declining trend and then remained constant for the next 10 years. Following that, a continuous declining trend in R_A^B was recorded for the next 30 years. Interestingly, the start of this long declining trend coincides with the commissioning of the Malaprabha project in 1972. From the year 2002, results of SSA indicate an increasing trend in R_A^B up to 2014. Figure 5.9 indicates a more or less similar pattern in the trend in D_A^B albeit with a milder decrease during the post-project period and a steeper increase in trend towards the end of the study period. It is interesting to compare these results from SSA with the results obtained using Sen's Slope estimator for basin average annual rainfall and rainy days (Table 5.2). SE values of -1.43 mm/yr for R_A^B and -0.03 days/yr for D_A^B were obtained for the entire period of record indicating very small and statistically insignificant trends. On the other hand, the results are shown in Figures 5.8 and 5.9 highlight the ability of SSA to capture the complete pattern of non-linear variations in trends throughout the analysis. Evidently, there are periods during the record when the trends yielded by SSA are far in excess and even opposite in direction to the linear monotonic trends identified by the SE approach considering the entire record.

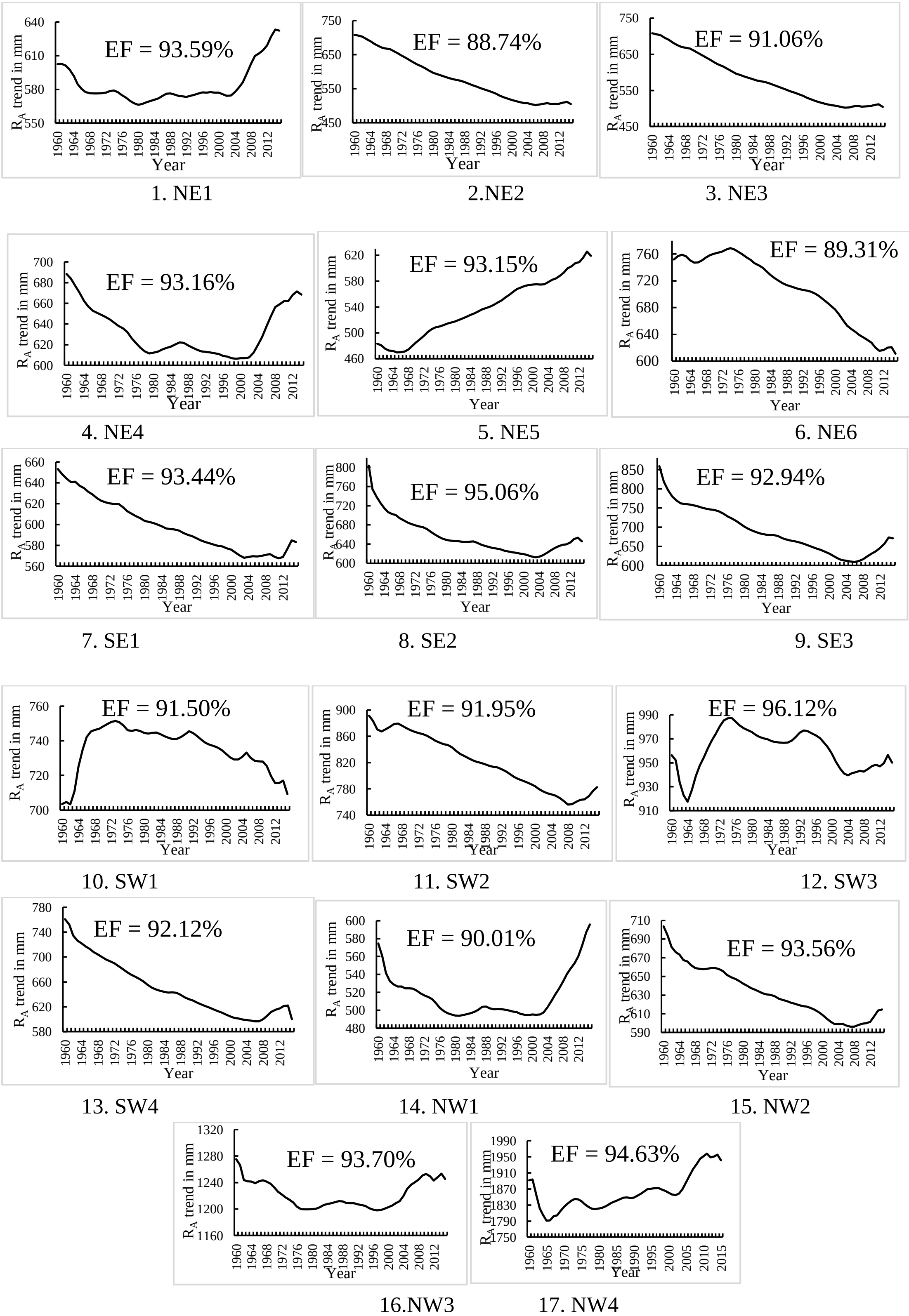


Figure 5.10: Non-linear trendline obtained from SSA for time series of observed annual rainfall (R_A) at rain gauge stations

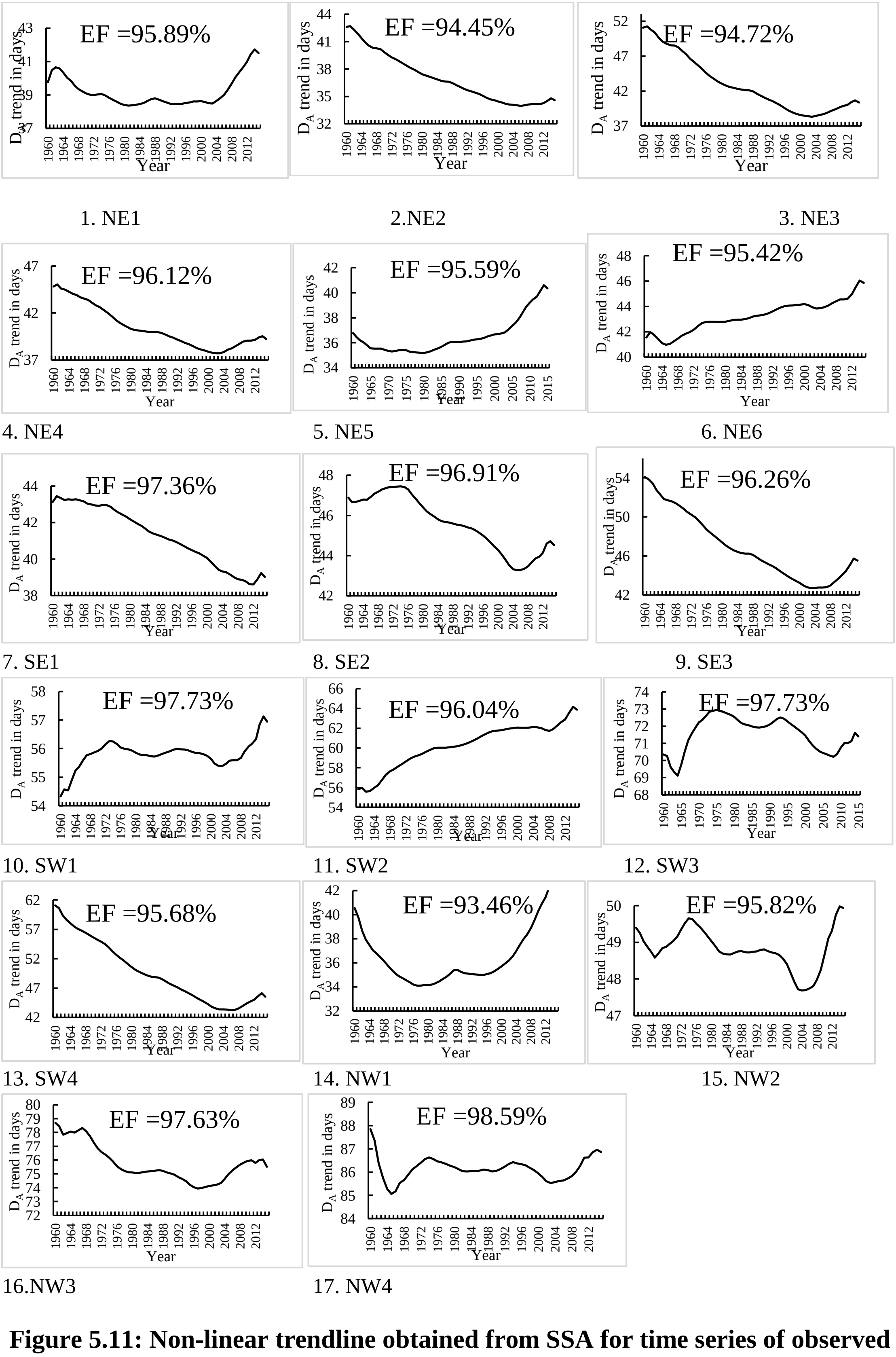


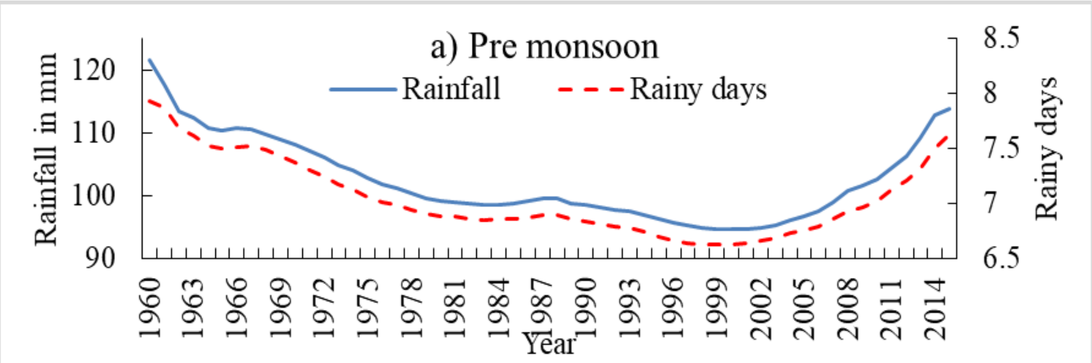
Figure 5.11: Non-linear trendline obtained from SSA for time series of observed annual rainy days (D_A) at rain gauge stations

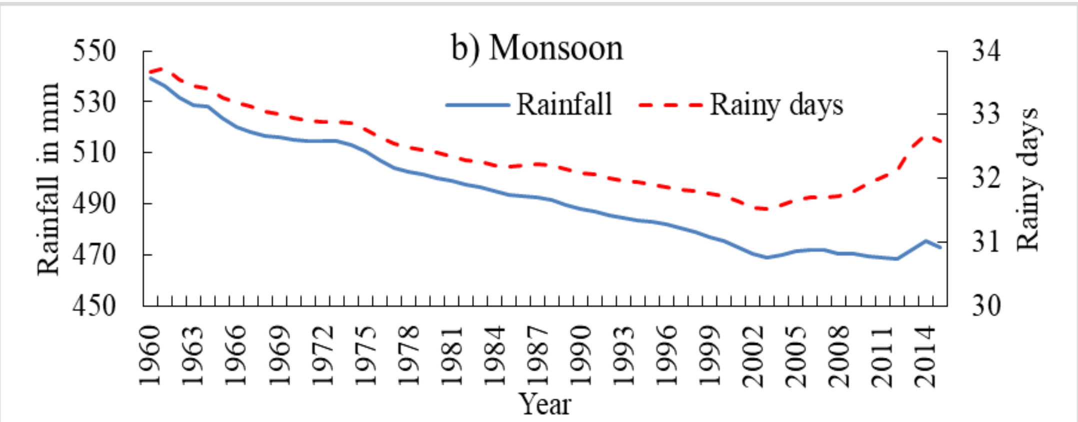
A similar pattern of nonlinearity in trends for annual rainfall (R_A) obtained by SSA can be seen for individual stations (Figure 5.10). Also shown in the figure are values of Eigen-fraction which is in the reasonably high range of 88.74% to 96.12% for the stations considered. At most of the stations, a monotonically decreasing trend starting from the beginning till the end of the record is evident. At a few stations, however, following a decreasing trend for most of the period, a small increase in trend can be seen towards the end of the record, a pattern which is consistent with the trend of the basin average rainfall (Figure 5.9). On the other hand, the Hubli (SW1) and Kalgahati (SW3) stations located in the south-western part exhibit a somewhat different pattern with an increase in trend during the beginning of the record and a decreasing trend thereafter. Interestingly, the Ramadurga station (NE5) which is located directly downstream of the Malaprabha dam is the only station to record a monotonically increasing trend in R_A from 1972 (Figure 5.10), which corresponds to the year when the project was commissioned.

Figure 5.11 depicts the trends in annual rainy days (D_A) at individual stations extracted using SSA along with the Eigen-fractions which vary over the range of 94.45% to 98.59%. Comparing results shown in Figure 5.11 with those shown in Figure 5.10, a striking similarity in the pattern trends can be seen at most stations for R_A and D_A except at Bailahongala (NW1), Hubli (SW1), and Gadag (SE2) stations where a slight dissimilarity exists. However, at the Dharawad (SW4) and Rona (NE6) stations which recorded a decreasing trend in R_A (Figure 5.10), an increasing trend in D_A was noted (Figure 5.11) indicating the possible increase in smaller rainfall events.

Considering basin average values of rainfall totals for pre-monsoon (R_{PR}^{B}), monsoon (R_{M}^{B}) and post-monsoon (R_{PM}^{B}) seasons, trends over the period 1960-2015 were extracted using SSA. Similarly, basin average values of rainy days for pre-monsoon (D_{PR}^{B}), monsoon (D_{M}^{B}) and post-monsoon (D_{PM}^{B}) seasons, SSA was used to extract trends throughout the record. Results are shown in Figure 5.12. [redacted]Considering the pre-monsoon season (Fig. 5.12a), the non-linear pattern in trend is very similar for both R_{PR}^{B} andD_{PR}^{B}. A steep decrease in trend from the beginning of the period up to the year 2003 followed by a steep increase in trend thereafter is evident for both variables.

During the monsoon season (Figure 5.12b) the trend lines for R_M^B and D_M^B show divergence with a steeper decrease in R_M^B in comparison to D_M^B from the beginning up to the year 2003. Subsequently, D_M^B shows a steep increase in trend whereas R_M^B records a relatively flat trend. Figure 5.12c shows that during the post-monsoon season, both R_{PM}^B and D_{PM}^B show a decreasing trend for the first 5 years and then record an increasing trend. However, while the pattern remains similar, R_{PM}^B possesses a steeper increasing trend in comparison to D_{PM}^B. Comparing results shown in Figure 5.12 with those shown in Figures 5.8 and 5.9, it appears that the increasing trend in basin average annual rainfall (R_A^B) during the post-2003 period (Figure 5.8) is mostly on account of higher contributions from the pre-monsoon and post-monsoon rainfall. On the other hand, an increase in rainy days in all three seasons (Figure 5.12) seems to have contributed to the increase in basin average annual rainy days (D_A^B) during the same period (Figure 5.9).





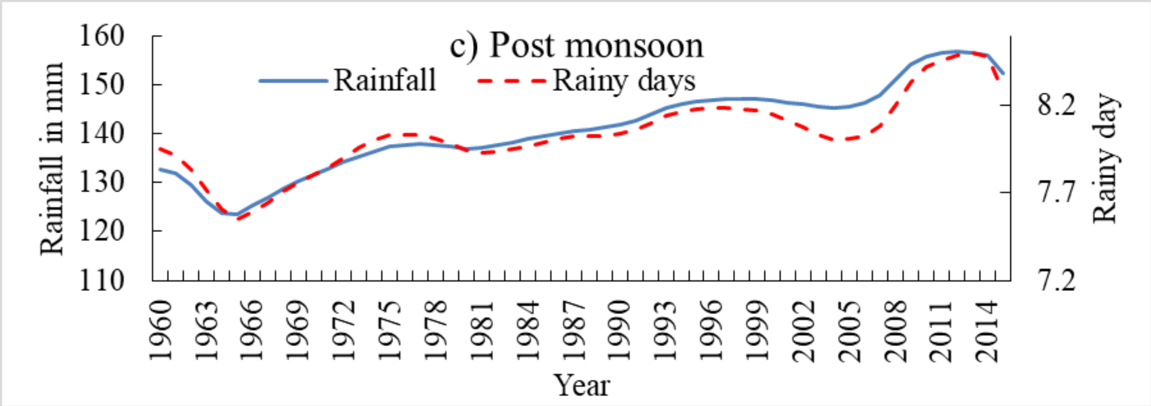


Figure 5.12: Trends in basin average totals of rainfall and rainy days extracted using SSA for a) pre-monsoon b) monsoon and c) post-monsoon seasons

Overall, as was mentioned earlier, the time series analysis was conducted to assess whether trends in rainfall characteristics were influenced by the introduction of large-scale irrigation in 1972. Interestingly, the analysis indicated that a few stations located in the vicinity and downstream of the dam did register rainfall patterns that were somewhat different from the other stations. The CV values (Figures 5.1) for annual and monsoon season rainfall indicated smaller variabilities throughout the record for a station close to the dam. On the other hand, this station indicated somewhat higher temporal variability in the annual number of rainy days (Figure 5.2). Also, for two stations located immediately downstream of the dam, the SE-MK tests showed increasing trends in annual rainfall whereas most of the other stations showed a decreasing trend (Table 5.2). Results of SSA provided more explicit evidence of a decreasing trend in basin-average values of annual rainfall and annual rainy days from the year 1972 which coincides with the commissioning of the Malaprabha dam (Figures 5.8 and 5.9). Also, while SSA showed a declining trend in rainfall and rainy days at most of the stations, a station located immediately downstream of the dam showed a monotonically increasing trend in these variables since the commissioning of the dam (Figures 5.10 and 15.11).

5.4.2.2 Stream flows

5.4.2.2.1 Results of Sen's slope and MK test

Table 5.3 represents the results of the SE test for annual (Q_A) and seasonal (Q_W, Q_{PR}, Q_M, Q_{PM}) stream-flow values at each gauging station considered for the study. For cases where the trend was statistically significant as per the MK test, values of SE are shown in bold font.

From Table 5.3 it is observed that the station Khanapur (1980-2015) shows increasing annual trends and is the only station with a statistically significant trend with a relatively high magnitude (217.46 m^3/yr). The station represents natural flows from a forested catchment (Hilly climatic zone) overhead to Malaprabha dam (Figure 5.3) and the annual rainfall trend was also observed to be increasing (Station 17.NW4 in Figure 5.10) for the same period for the station. Interestingly the station shows no trend during winter (Q_A) and pre-monsoon (Q_{PR}) seasons. However, statistically increasing trends were observed for the monsoon (Q_M) and post-monsoon (Q_{PM}) seasons, and their contribution is reflected in annual trends.

Table 5.3: Sen's estimate of slope (SE) for annual and seasonal stream flows over Malaprabha River Basin*

Station Id	Station Name	Q_A m_3/yr	Q_W m_3/yr	Q_{PR} m_3/yr	Q_M m_3/yr	Q_{PM} m_3/yr
1	Huvanuru	39.62	58.07	12.54	86.57	-77.94
2	Cholachigudda	-57.62	2.05	-8.47	-40.08	35.40
3	Khanapur	**217.46**	0.00	0.00	**152.66**	**40.04**

*SE values in **bold** only are statistically significant at 95% confidence level as per Mann-Kendall test

The stations Cholachigudda (1983-2006) and Huvanuru (1968-1981) are located downstream of the Malaprabha Dam (Figure 5.3) (Northern dry climatic zone) and represent completely regulated flows. Though the initial 4years of the station Huvanuru represents natural stream-flows as Malaprabha Dam was commissioned in the year 1972, no statistically significant trends were observed for any season at the two stations (Table 5.3). This indicates greater variability involved in the data which can be better analyzed using the SSA method.

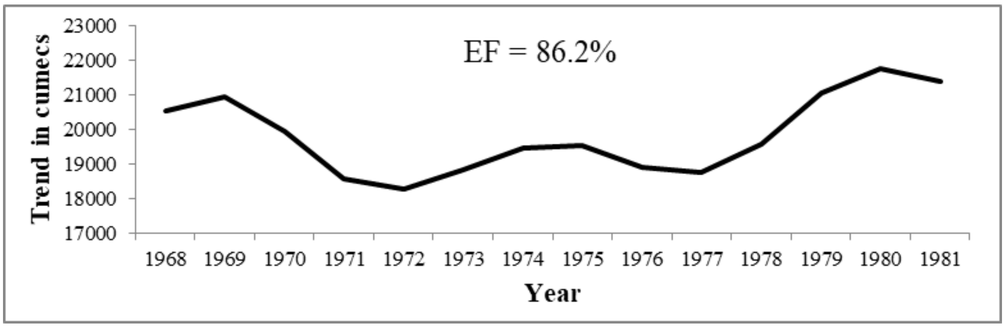
Considering the duration of observations at the two stations, Huvanuru represents the initial conditions of irrigation development in the Malaprabha command area (1972-1981). The increase in trends at the station for all the seasons (except post-monsoon (Q_{PM})) (Table 5.3), maybe the result of increased reservoir releases to the downstream river and due to less consumption of water for irrigation. On the other hand, Cholachigudda (1983-2006) represents the developed conditions of irrigation in the command area (detailed explanation regarding the growth of irrigation in the Malaprabha command area is presented in Chapter 6). The overall decreasing trends for Q_A, $Q_{PR,}$ and Q_M, are indicative of reduced reservoir releases to the downstream river as the result of increased use of reservoir water for irrigation. Although relatively less magnitude, the increasing trends for the non-monsoon seasons (winter (Q_W) and post-monsoon (Q_{PM})), indicate release of surplus water from the reservoir and increased return flows from irrigated fields.

5.4.2.2.2 Results of Singular Spectrum Analysis

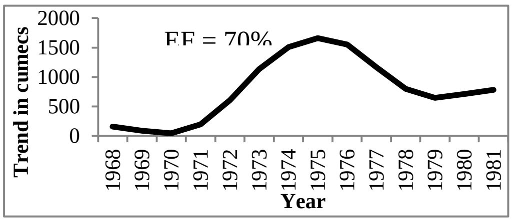
The annual and seasonal nonlinear trends extracted for the stream-flows at three gauging stations using SSA are presented in Figures 5.13, 5.14, and 5.15. A window length of L=N/2 was selected for each station and varies as per the duration of the dataset considered.

The annual trend of streamflow at the Huvanuru station (1968 to 1981) (Figure 5.13 (a)) shows decreasing trend during the initial years (1968 to 1972) which also represents a pre-dam condition. Interestingly the later years (1972 to 1981), which represents initial phases of irrigation development in the Malaprabha command area show a small amount of variation in the trend (1973 to 1977), and from the year 1978 onwards an increasing trend was observed till 1980. This indicates that increased reservoir outflows to the river as irrigation may not have fully developed in the command area. The winter (Figure 5.13 (b)) and pre-monsoon seasons (Figure 5.13 (c)) show a similar trend for the initial years wherein decreased trend of stream-flows was observed for pre-dam duration and increased thereafter. However, for the winter season decreased stream-flow trend was observed from 1975 onwards till 1979 when it started increasing. The monsoon flows (Figure 5.13(d)) follow the annual trend

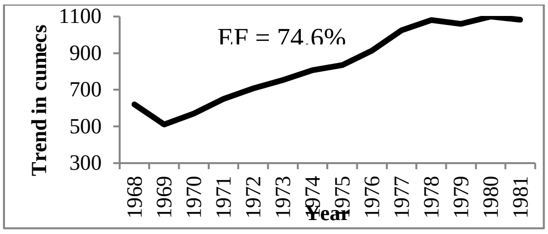
(Figure 5.13 (a)) with the observed decreased trend for the pre-dam condition. For the years 1972 to 1977, a small amount of fluctuation in the trend line is visible. This probably accounts for reservoir storage during the season. On the other hand, a greater extent of cyclic variability in trend exists for the post-monsoon season (Figure 5.13(e)).



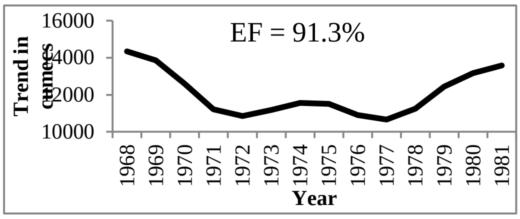
a) Annual



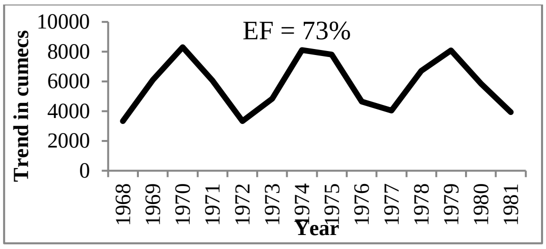
b) Winter



c) Pre-Monsoon



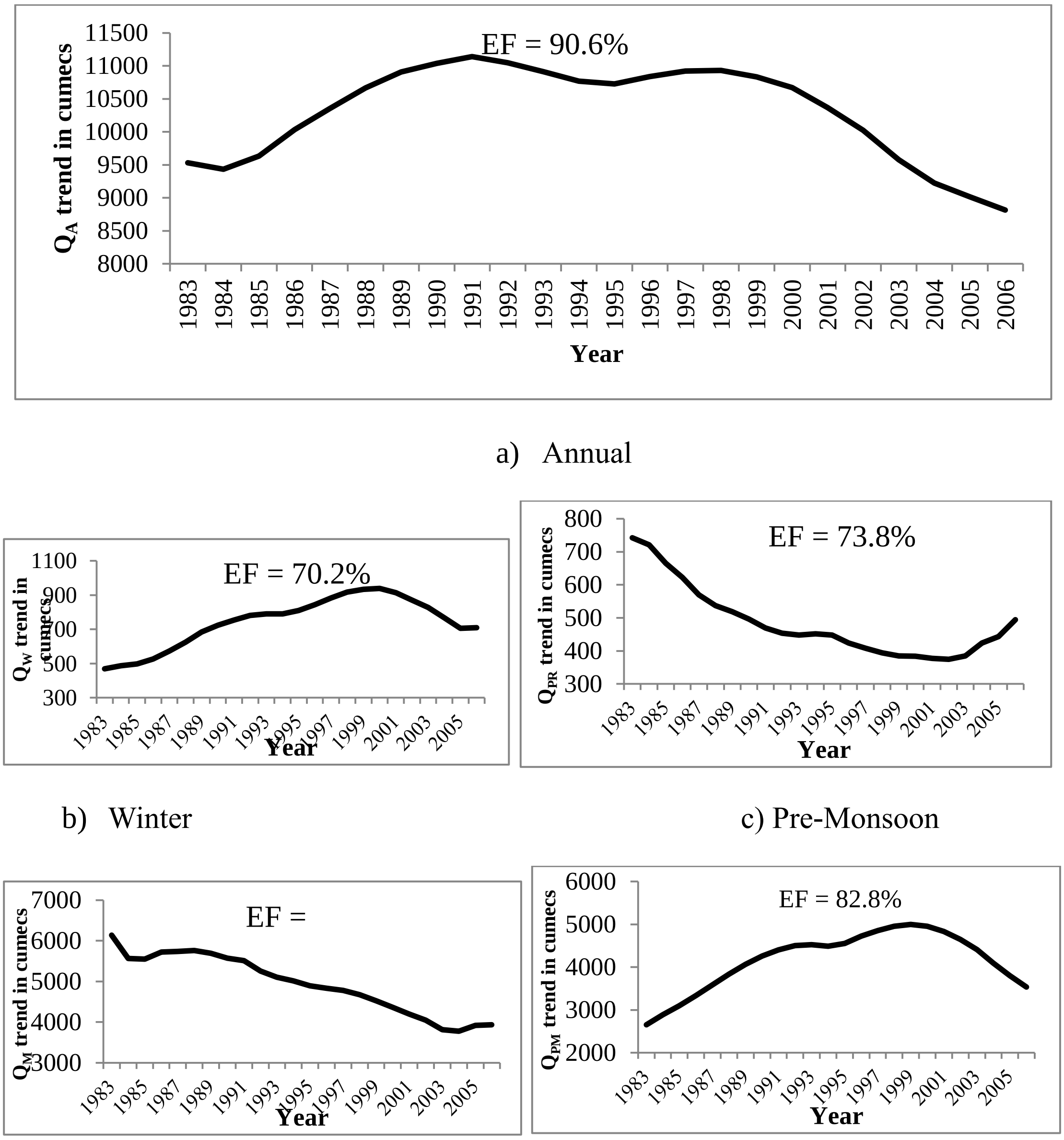
d) Monsoon



e) Post-Monsoon

Figure 5.13: Non-linear trendline obtained from SSA for time series of observed annual and seasonal Stream flows at Huvanuru stream gauge station

The stream-flows at Cholachigudda gauging station (1983 to 2006) represent the fully regulated flows with the developed condition of irrigation in the command area. An increasing annual trend line (Figure 5.14 (a)) was observed for the period 1984 to 1991 and was almost constant up to the year 2000 and steeply decreased thereafter till 2006. This is indicative that, as there was progression in the irrigated agriculture in the command area after the commissioning of the Malaprabha dam in 1972, the amount of stream-flows reaching the downstream river has decreased significantly.



d) Monsoon **e) Post-Monsoon**

Figure 5.14: Non-linear trendline obtained from SSA for time series of observed annual and seasonal Stream flows at Cholachigudda stream gauge station

The winter (Figure 5.14 (b)) and post-monsoon (Figure 5.14 (c)) season trends follow a similar pattern. Increasing trends were observed up to the year 2000 for both seasons indicative of increased outflows from the reservoir for the duration. However, for the later years i.e., 2000 to 2006 the seasonal flows show decreasing trends. The reason for decreased flows is due to the increased demand for irrigation water in the command area during the decade 2000 -2010 (explained in Chapter 6) as water-intensive crops were grown in the area. As expected, there is a decrease in trends of stream-flows of pre-monsoon (Figure 5.14 (c)) and monsoon (Figure 5.14 (d)) seasons. This is due to increased reservoir storage for irrigation purposes during the season.

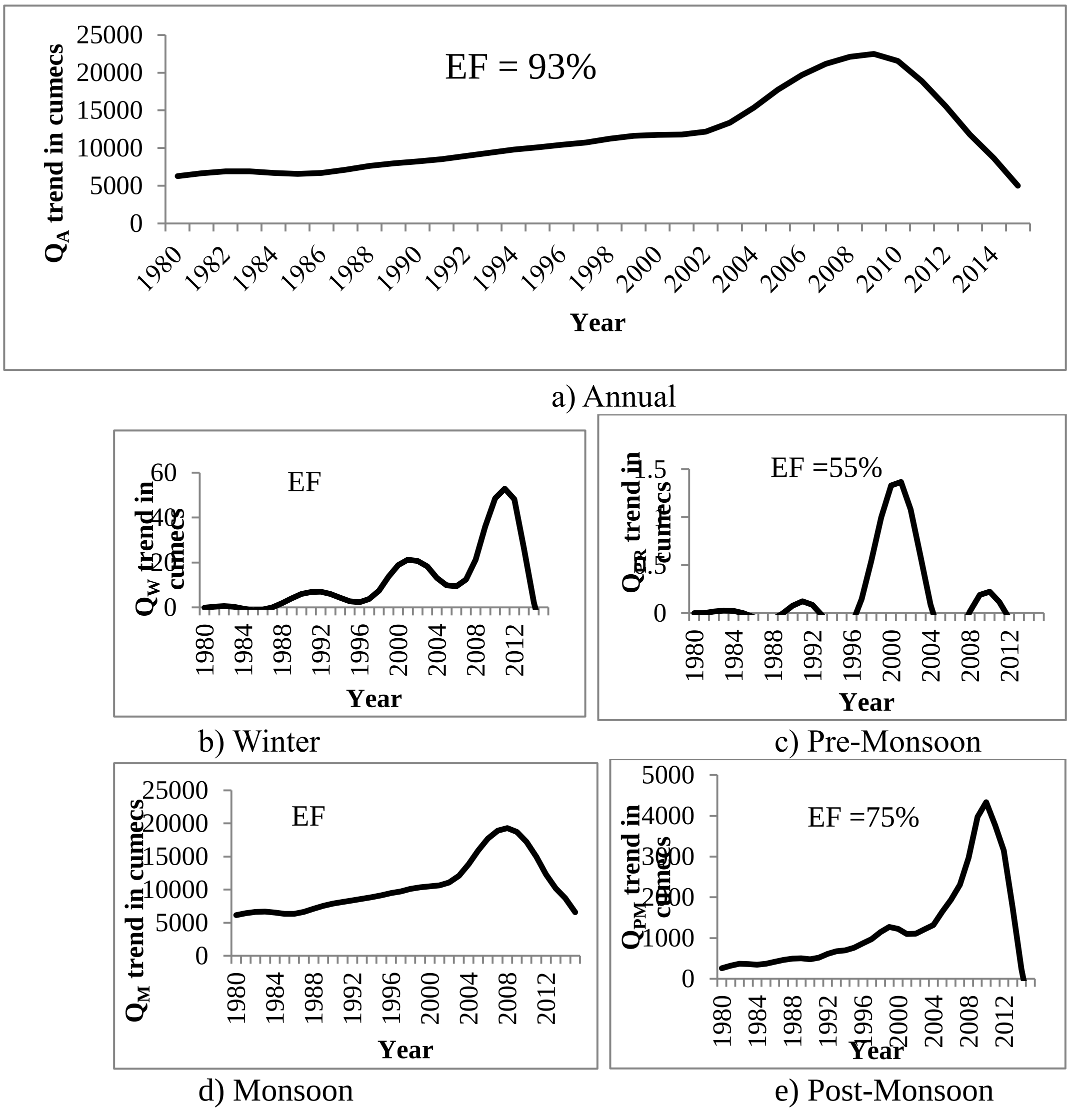


Figure 5.15: Non-linear trendline obtained from SSA for time series of observed annual and seasonal Stream flows at Khanapur stream gauge station

The Khanapur station (1980 to 2015) is located upstream of the Malaprabha dam and represents the natural outflows from the forested catchment. The increasing annual trend (Figure 5.15 (a)) of stream-flows was observed till the year 2010 for the station and a steep decrease thereafter. A similar pattern of trend variability is observed for Monsoon (Figure 5.15 (d)) and Post-monsoon seasons (Figure 5.15 (e)) for the station. The winter (Figure 5.15 (b)) and pre-monsoon (Figure 5.15 (c)) season's trends display a greater extent of variability. Overall, it is found that the reservoir operations and irrigation demand have altered the downstream river flows to a great extent. The temporal variability in trend is well captured by the SSA method.

5.4.2.3 Average Air temperature

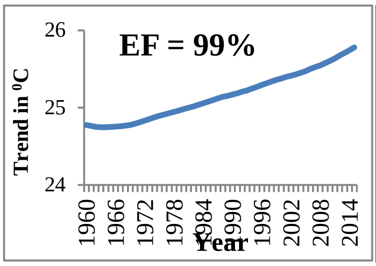
Table 5.4 represents the SE test results for the average temperature at 23 grids for the annual and seasonal time scale for the duration 1960 to 2015. All grids exhibit statistically significant increasing trends for annual and seasonal time scales at a 5% significance level. The basin average magnitude of increasing annual trend (T_A) is 0.2 ^{0}C/decade. The magnitude of increase in average temperature trend is found to be high at all grids during pre-monsoon (T_{PR}) season (0.23^{0}C/decade), followed by post-monsoon (T_{PM}) (0.19^{0}C/decade), winter (T_W) (0.18^{0}C/decade) and monsoon (T_M) (0.17^{0}C/decade) seasons. Figures 5.15 displays the grid-wise nonlinear trends extracted using SSA for average annual temperature for the period 1960 to 2015. Figure 5.16 represents the seasonal variation of basin average temperature for the same duration. The monotonic increase in trend line is noticeable at all grids explaining the variability with an account of 99% Eigen fraction.

Overall, significant increasing trends were observed for average temperature for annual and seasonal scales over the Malaprabha river basin. The previous studies (Schickendanz, 1976, Barnston and Schickedanz 1984, de Ridder and Galle´e 1998, Adegoke et al. 2003) have identified cooling effects in daily mean and maximum temperature over the irrigated land cover at a regional scale. However, in the present study, no significant variation in trends was observed for grids around the Malaprabha reservoir and over irrigated areas for the considered temporal duration.

Table 5.4: Sen's estimate of slope (SE) for annual and seasonal average temperature over Malaprabha River Basin*

Station Id	Agro-Climatic zone	Grid Id	T_A $^0C/yr$	T_W $^0C/yr$	T_{PR} $^0C/yr$	T_M $^0C/yr$	T_{PM} $^0C/yr$
NE1	ND	17	**0.0208**	**0.0191**	**0.0243**	**0.0174**	**0.0203**
NE2	ND	18	**0.0205**	**0.0183**	**0.0254**	**0.0176**	**0.0192**
NE3	ND	19	**0.0205**	**0.0186**	**0.0256**	**0.0174**	**0.0192**
NE4	ND	21	**0.0212**	**0.0185**	**0.0257**	**0.0169**	**0.0201**
NE5	ND	22	**0.0211**	**0.0181**	**0.0264**	**0.0169**	**0.0196**
NE6	ND	23	**0.0203**	**0.0181**	**0.0258**	**0.0172**	**0.0190**
SE1	NT	2	**0.0207**	**0.0175**	**0.0221**	**0.0181**	**0.0198**
SE2	ND	4	**0.0208**	**0.0182**	**0.0226**	**0.0180**	**0.0197**
SE3	ND	5	**0.0203**	**0.0177**	**0.0224**	**0.0184**	**0.0200**
SE4	ND	10	**0.0208**	**0.0184**	**0.0237**	**0.0177**	**0.0198**
SE5	ND	11	**0.0207**	**0.0184**	**0.0238**	**0.0178**	**0.0196**
SE6	ND	12	**0.0202**	**0.0181**	**0.0247**	**0.0183**	**0.0188**
SW1	NT	1	**0.0209**	**0.0180**	**0.0219**	**0.0168**	**0.0197**
SW2	NT	3	**0.0210**	**0.0190**	**0.0226**	**0.0170**	**0.0199**
SW3	HY	6	**0.0205**	**0.0184**	**0.0214**	**0.0185**	**0.0172**
SW4	HY	7	**0.0206**	**0.0184**	**0.0222**	**0.0184**	**0.0183**
SW5	NT	8	**0.0209**	**0.0187**	**0.0226**	**0.0172**	**0.0194**
SW6	ND	9	**0.0210**	**0.0190**	**0.0231**	**0.0175**	**0.0200**
NW1	NT	13	**0.0199**	**0.0177**	**0.0215**	**0.0172**	**0.0175**
NW2	NT	14	**0.0203**	**0.0183**	**0.0224**	**0.0173**	**0.0189**
NW3	ND	15	**0.0207**	**0.0188**	**0.0226**	**0.0171**	**0.0193**
NW4	ND	16	**0.0210**	**0.0190**	**0.0239**	**0.0172**	**0.0202**
NW5	ND	20	**0.0207**	**0.0190**	**0.0249**	**0.0168**	**0.0209**
		BASIN	**0.0206**	**0.0189**	**0.0235**	**0.0176**	**0.0198**

*SE values in **bold** only are statistically significant at 95% confidence level as per Mann-Kendall test



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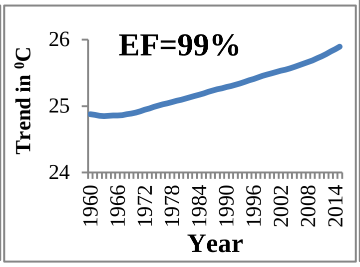

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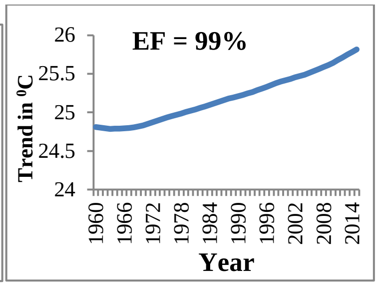

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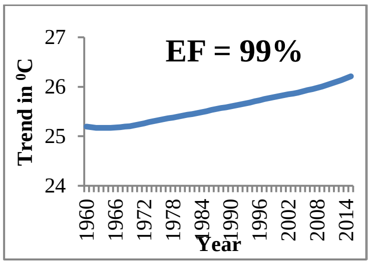

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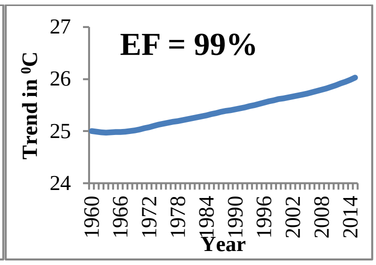

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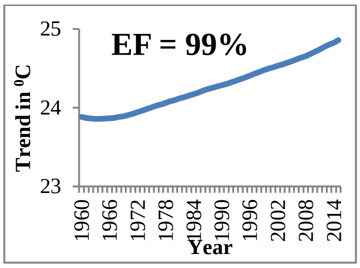

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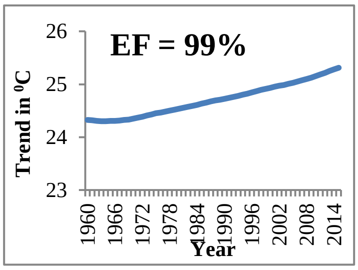

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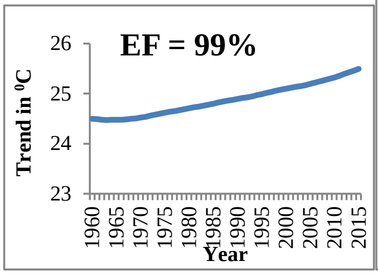

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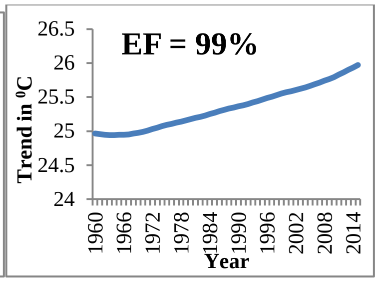
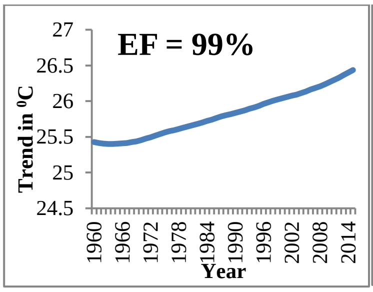


9.



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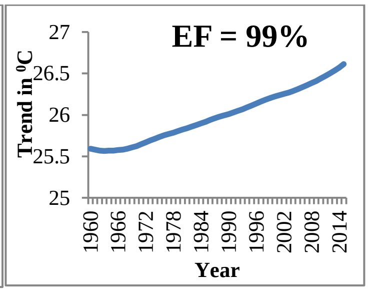

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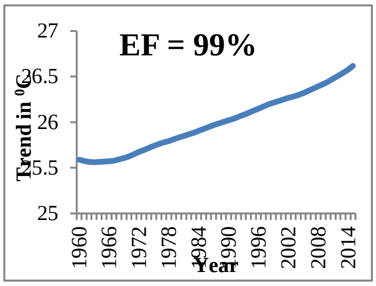

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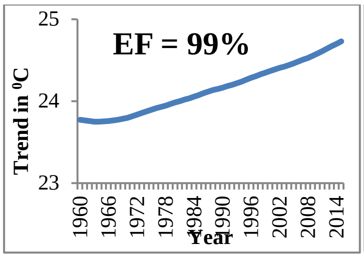

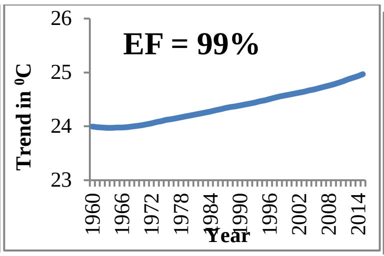

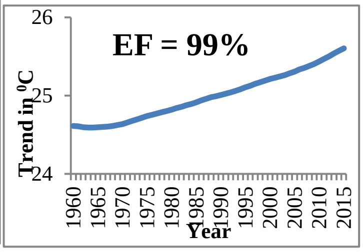

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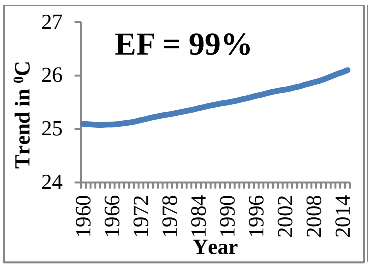

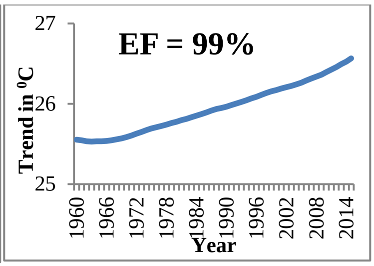

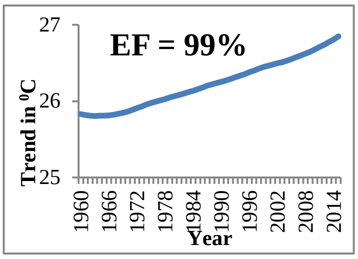

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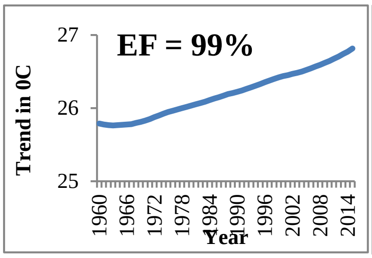

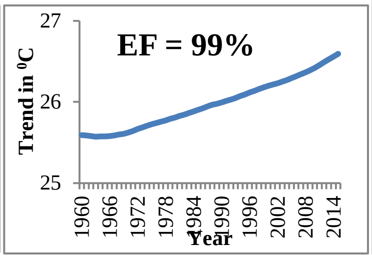

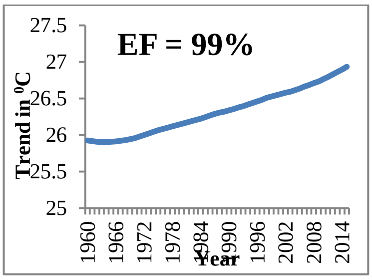

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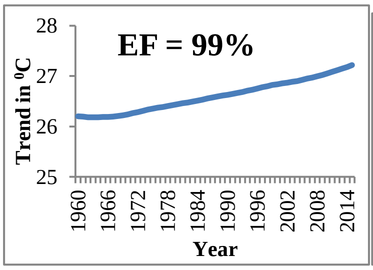
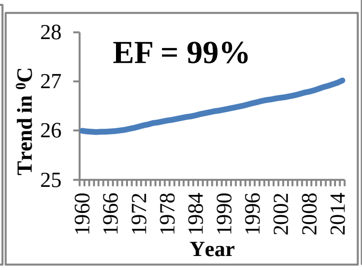
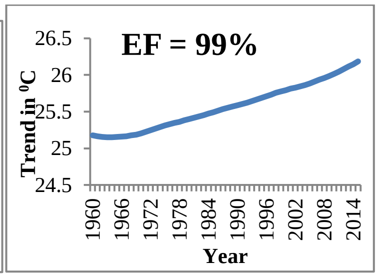






22. 23. BASIN

Figure 5.16: Non-linear trendline obtained from SSA for time series of annual average temperature at climatic grids

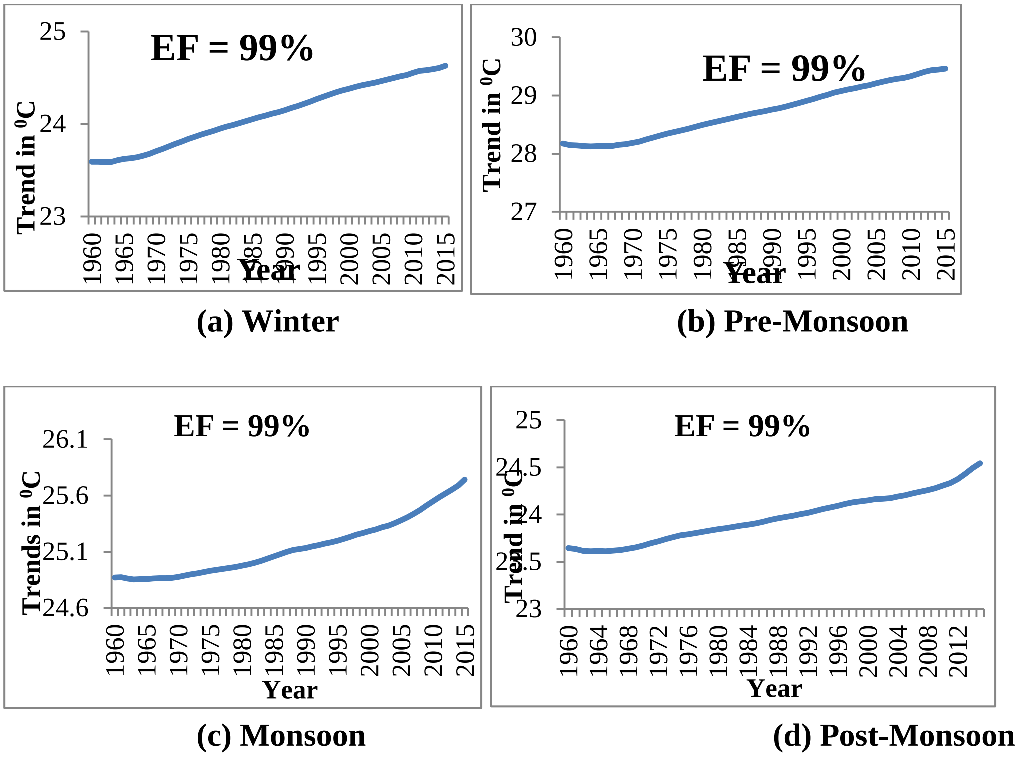


Figure 5.17: Non-linear trendline obtained from SSA for time series of seasonal average temperature over the Malaprabha basin

5.4.2.4 Groundwater levels

5.4.2.4a Results of Sen's slope and MK test

Table 5.5 represents the annual and seasonal results of SE and MK tests applied for GWLs of 45 observatories' dug wells (Figure 5.5). The seasonal GWL data for the wells was procured for the period 1996 to 2015 from CGWB.

Table 5.5: Sen's estimate of slope (SE) for annual and seasonal Groundwater levels over Malaprabha River Basin

WELL_ID	SITE_NAME	Annual SE m/yr	Monsoon SE m/yr	POMRB SE m/yr	POMKH SE m/yr	PREMON SE m/yr
1	Londa1	**0.077**	0.075	0.031	0.040	0.030
2	Gunji	**0.036**	0.008	**0.044**	0.018	0.071
3	Bidi	-0.047	0.022	-0.049	-0.009	0.000
4	Khanapur1	0.018	0.050	0.011	-0.017	0.035
5	Prabhunagar	0.050	0.023	**0.050**	0.022	0.012
6	Peerwadi	**-0.073**	-0.005	0.022	-0.003	0.000
7	Uchagaon	**-0.174**	0.008	0.009	0.004	0.128

8	Halaga	0.091	0.085	**0.096**	0.068	0.201
9	Belgaum1	0.046	0.033	**0.079**	0.033	0.070
10	Kudachi-2	**0.123**	**0.035**	**0.108**	0.037	**0.311**
11	Kittur1	**0.031**	0.005	0.002	-0.010	**0.132**
12	Hire bagewadi	0.049	0.063	0.088	0.048	0.008
13	Sutagatti1	0.089	0.061	0.127	0.070	0.051
14	Nesaragi1	0.005	0.054	0.056	-0.044	-0.091
15	Halaki	-0.035	0.061	0.003	-0.043	-0.020
16	Bailhongal	0.067	0.102	0.115	0.080	0.028
17	Soppadla	0.131	0.246	0.114	-0.075	0.304
18	Achamatti	**0.164**	0.148	**0.179**	0.173	**0.190**
19	Saundatti	0.026	0.013	0.027	-0.031	0.014
20	Ramdurg1	**-0.194**	**-0.207**	**-0.122**	**-0.181**	**-0.156**
21	Mugad	**0.102**	0.027	**0.116**	0.025	**0.198**
22	Amminabhavi	0.120	0.090	0.068	0.158	0.017
23	Morab	0.026	0.010	0.031	0.018	0.041
24	Shanawad	-0.064	-0.006	-0.064	-0.114	-0.051
25	Basapur	-0.069	**-0.093**	-0.068	-0.081	-0.062
26	Hebsur1	0.003	0.012	0.041	-0.009	0.039
27	Kundgol	-0.180	-1.738	-0.322	-0.105	-0.234
28	Gudgeri	-0.060	0.052	-0.043	-0.146	0.065
29	Wadarahalli	**0.394**	**0.651**	0.485	0.429	-0.122
30	Tumminakatti	**0.221**	**0.228**	**0.218**	**0.296**	0.162
31	Kuppelur	**0.127**	0.102	**0.126**	0.048	**0.251**
32	Ramgeri	**0.250**	**0.209**	0.189	**0.273**	0.129
33	Magdi	0.102	**0.246**	0.090	-0.025	**0.189**
34	Shirhatti1	**0.133**	0.088	**0.110**	0.050	**0.145**
35	Hulkoti	**0.137**	0.195	**0.156**	0.090	0.091
36	Nagasamudra	**-0.300**	**-0.162**	**-0.310**	**-0.276**	**-0.303**
37	Nargund1	**1.210**	**1.700**	**0.993**	**1.237**	**1.338**
38	Belavaniki-1	**0.178**	**0.245**	**0.168**	0.085	**0.201**
39	Hunagund	-0.004	0.028	0.077	-0.058	**-0.113**
40	Kulageri1	**-0.277**	**-0.211**	**-0.242**	**-0.420**	-0.206
41	Pattadakal	0.039	0.042	0.038	0.015	0.050
42	Guledagudda	0.014	0.002	0.012	0.001	-0.010
43	Amingad	0.209	0.317	0.194	0.129	0.270
44	Vadageri	-0.078	-0.056	-0.071	-0.108	-0.162
45	Nagur	-0.062	-0.070	-0.025	-0.072	-0.053

***SE values in **bold** only are statistically significant at 95% confidence level as per Mann-Kendall test

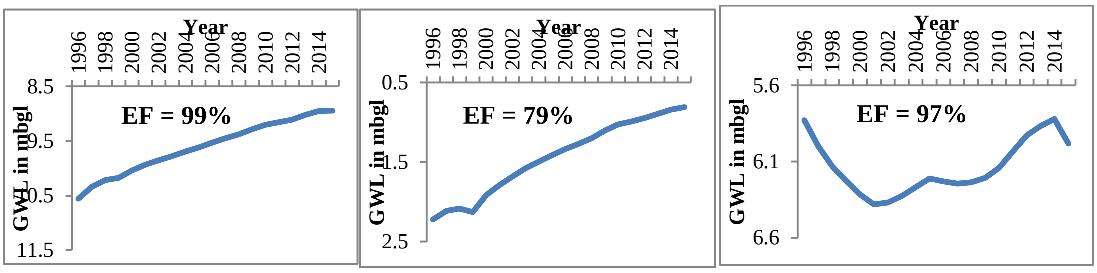
From Table 5.5 it can be observed that for the monsoon season (August) as expected, the majority of the wells showed increasing trends. Among those, wells 10, 29, 30, 32, 33, 37 and 38 showed significantly increasing trends with a magnitude of 0.035, 0.65, 0.23, 0.21, 0.25, 1.7 and 0.25 m/yr (Table 5.5) respectively. Wells 37 and 38 are located in close vicinity to the Malparabha dam towards the downstream side. It is interesting to note that, the four wells (well Id 20, 25, 36, and 40) located in the downstream command area (Figure 5.5) of the Malaprabha dam show significantly decreasing trends for the monsoon season. The excessive withdrawal of GW to grow water-intensive crops in the command area during the season could be the cause for this nature of the trend. During Post-monsoon Kharif (POMKH) season (November), around 45% of the wells showed decreasing trends (Table 5.5) indicating increased GW withdrawals mainly for irrigation purposes during the season. Further, well 37 showed a significantly increasing trend with a magnitude of 1.24m/yr which is located closer vicinity to the Malaprabha dam. Conversely, the three wells 20, 36, and 40, located in the command area (Figure 5.5) showed significantly decreasing trends at the rate of 0.18, 0.28, and 0.42m/yr respectively during the season. Most of the wells located in the upstream forested catchment of the basin showed increasing trends during all the seasons.

The majority of the wells showed increasing trends during Post-monsoon Rabi (POMRB) season (January) (Table 5.5). Thirteen wells (6 upstream of the dam, 4 in the downstream command area, and 3 in the southern region (Figure 5.5)) showed significantly increasing trends during this season. Meanwhile, only wells 20, 36, and 40 located in the irrigated command area showed significant decreasing trends with a magnitude of 0.122, 0.31, and 0.242 m/yr respectively for the season. During Pre-monsoon (PREMON) season (May), around 29% of the wells showed decreasing trends, and about 85% of them being located in the downstream command area of the Malaprabha basin (Figure 5.5). This signifies the increased extent of GW usage in the region. The wells located in the irrigated command area of the Malaprabha dam showed a combination of significantly increasing (well id 18, 37 and 38) and decreasing (well id 20, 36, and 40) trends. Most of the wells in the western region (Figure 5.5) showed increasing annual trends (Table 5.5) except well id 14 and 15 which showed decreasing trends. On the other hand, the wells in the downstream command area indicate the combination of significantly increasing and decreasing trends.

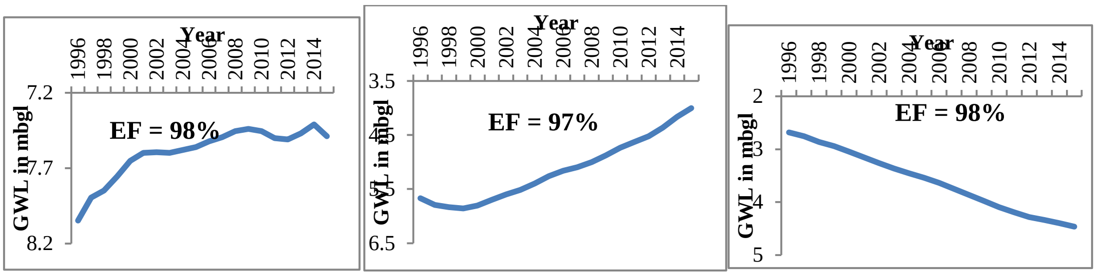
5.4.2.4b Results of Singular Spectrum Analysis

Figures 5.18 to 5.22 represent the nonlinear trends extracted using SSA for GWLs for annual, monsoon, POMRB, POMKH, and PREMON seasons. The SSA method was applied to extract nonlinear trends in the time series data. The window length (L) was set to 20 (*N/2*) since no periodic component was observed in the annual time series for the period 1960-2015. Accordingly, 20 Eigen-triplets *(U, D, and V)* were formed after *SVD*. The MC-SSA algorithm was then applied for a significance test at a 95% confidence interval.

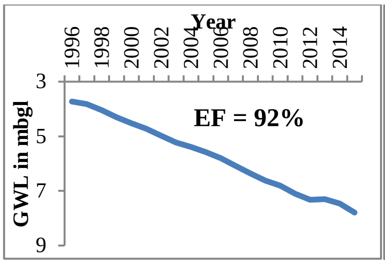
Large variability in GWL trend lines (during all seasons) were observed in majority of wells, probably on account of irrigation water withdrawals both on upstream and downstream side of the reservoir.



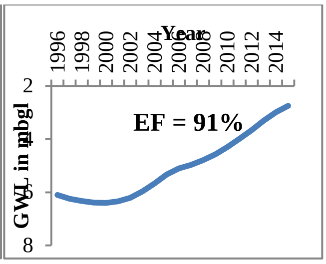
1. Londa1 2. Gunji 3. Bidi



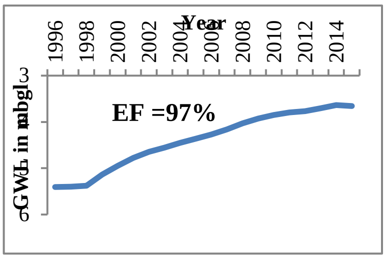
4. Khanapur1 5. Prabhunagar 6. Peerwadi



7. Uchagaon



8. Halaga



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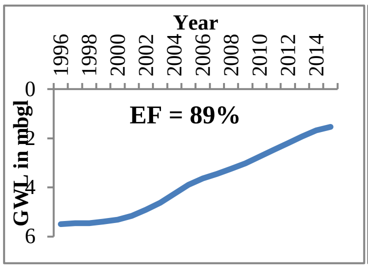
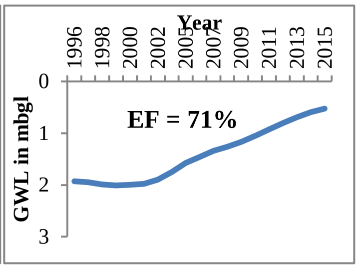
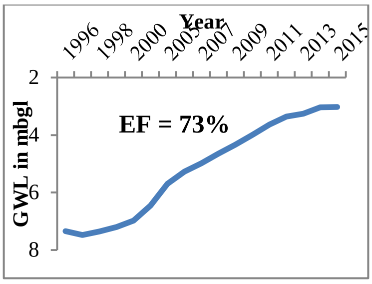


10. Kudachi-2



11. Kittur1



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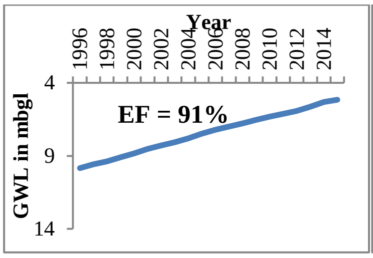

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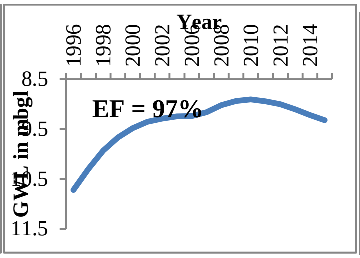
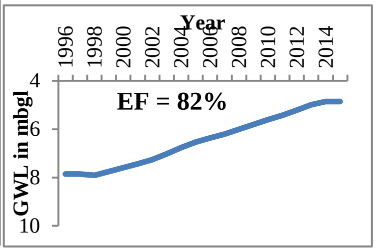
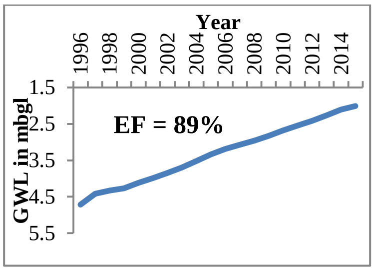


14. Nesaragi1



15. Halaki



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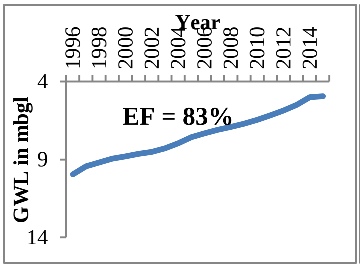
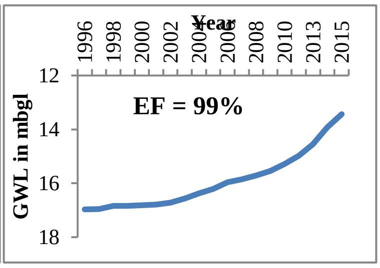
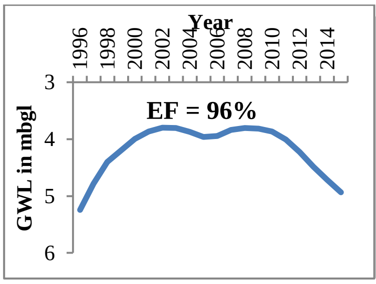


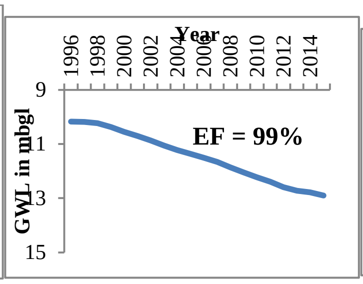
17. Soppadla



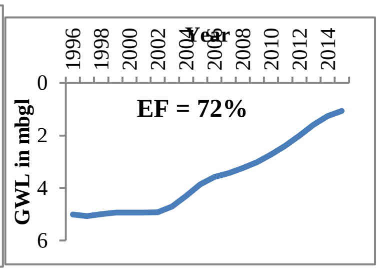
18. Achamatti



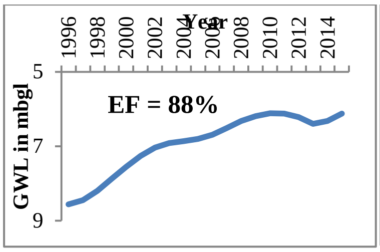
19. Saundatti



20. Ramdurg1



21. Mugad



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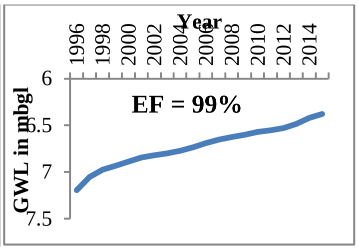
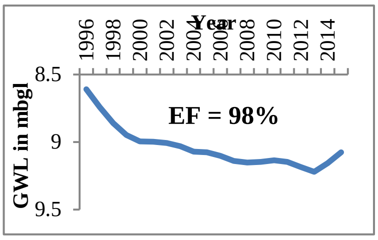
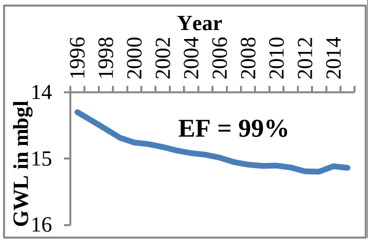


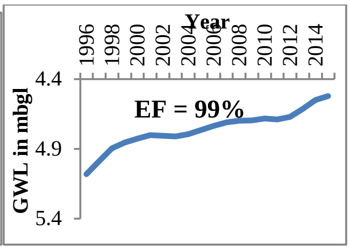
23. Morab



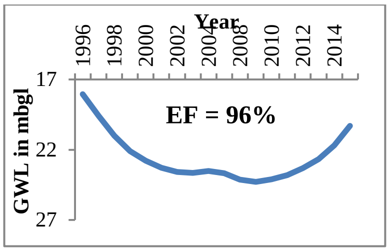
24. Shanawad



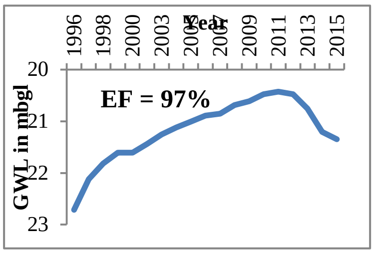
25. Basapur



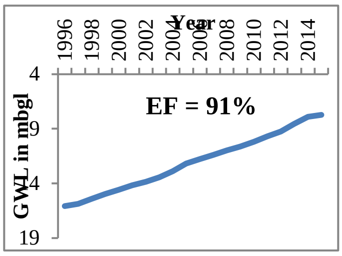
26. Hebsur1



27. Kundgol



28. Gudgeri



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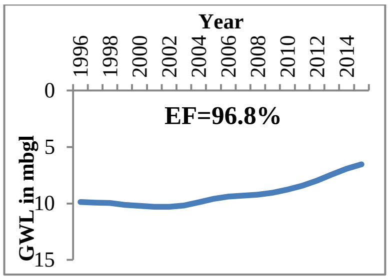

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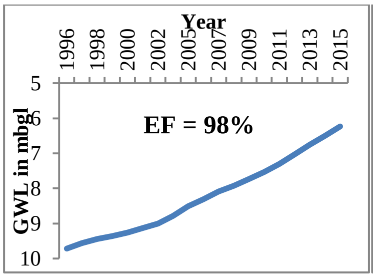
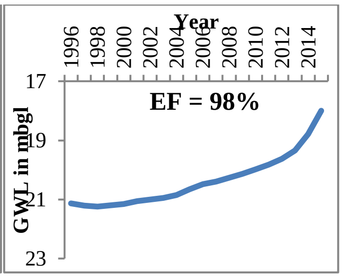
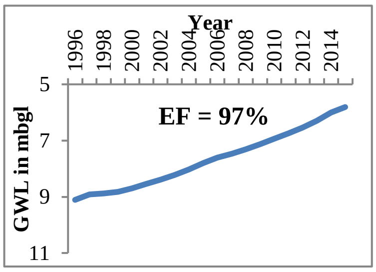


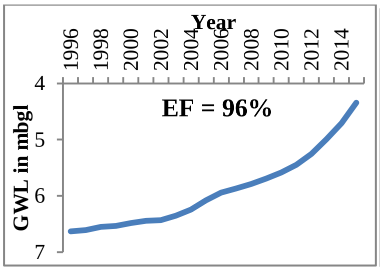
31. Kuppelur



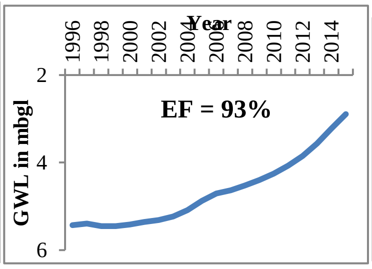
32. Ramgeri



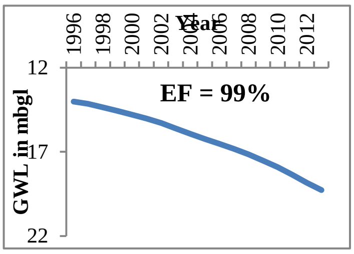
33. Magdi



34. Shirhatti1



35. Hulkoti



36. Nagasamudra

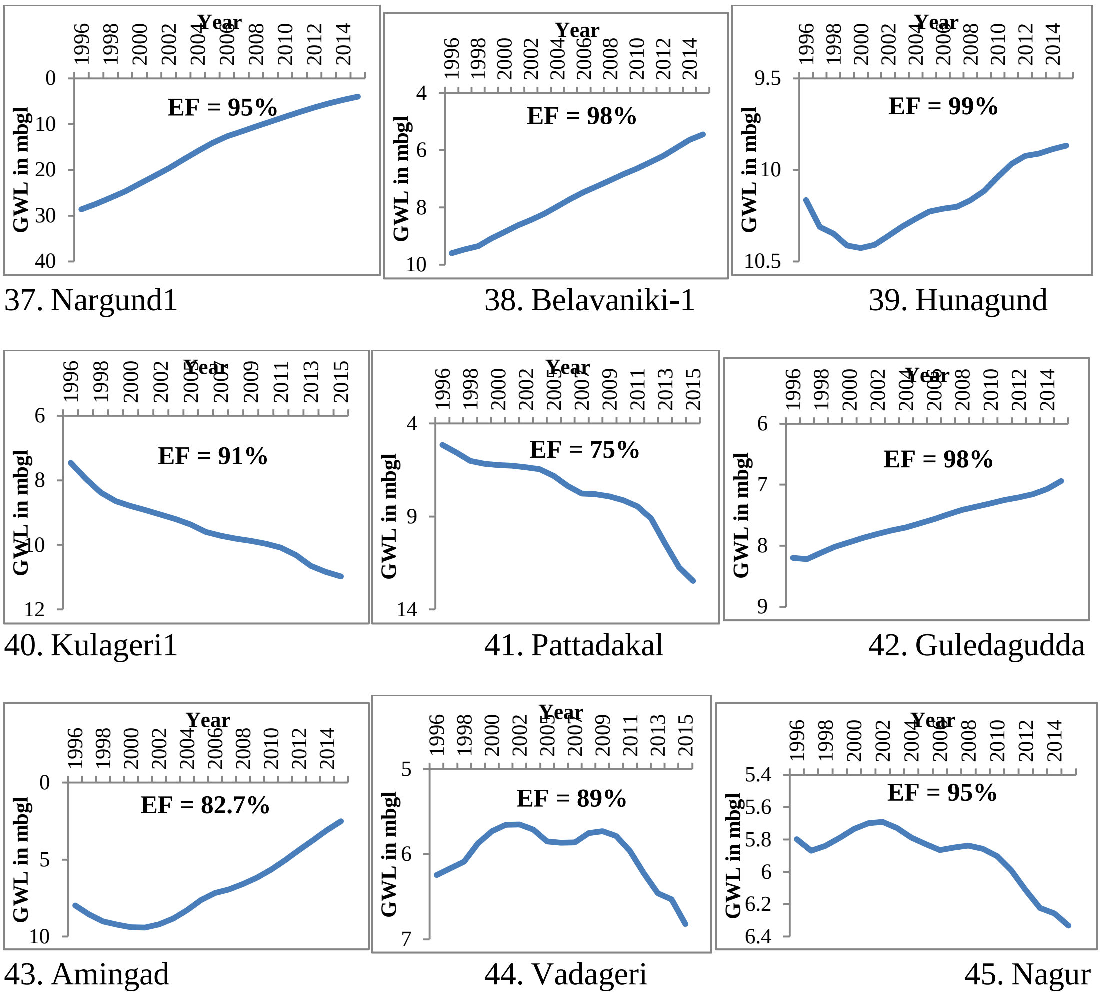
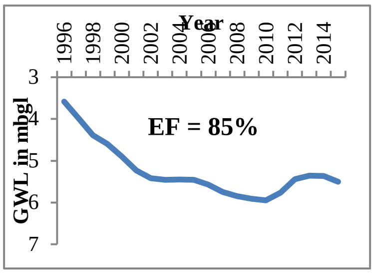
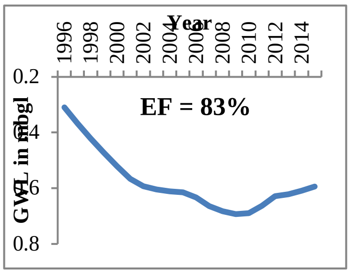
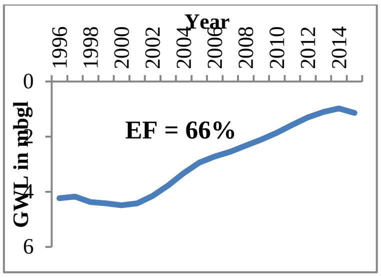


Figure 5.18: Nonlinear trends extracted for annual average GWLs using SSA method

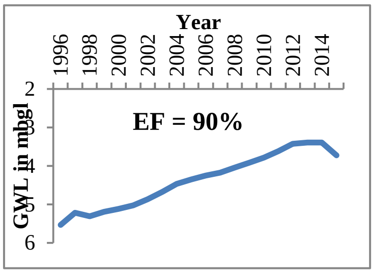
The shape of non-linear trends for the annual GWLs is clearly depicted in Figure 5.18. Although, the majority of SSA trends for GWLs depict the similar trend patterns as that of SE and MK test (Table 5.5), few wells show contrasting trend direction to that of SE and MK test. For example, well id. 15 (Halaki), shows positive non-linear trend by SSA whereas a negative trend was obtained in SE test. Similar is the case with well ids, 28(Gudageri), 39 (Hunagund) and 41 (Pattadakal).

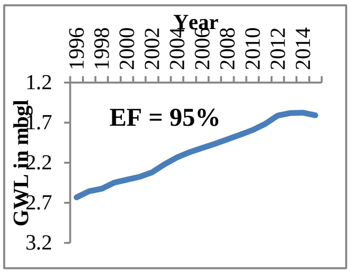


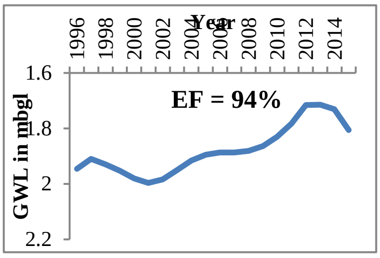




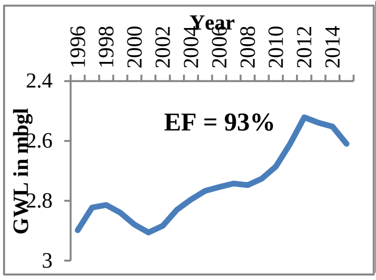
1. Londa1 2. Gunji 3. Bidi

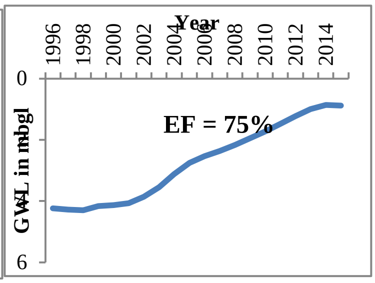


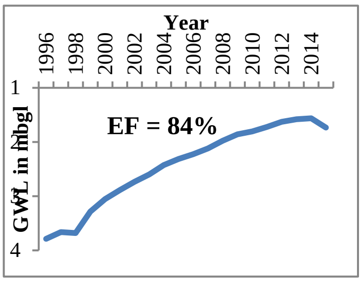




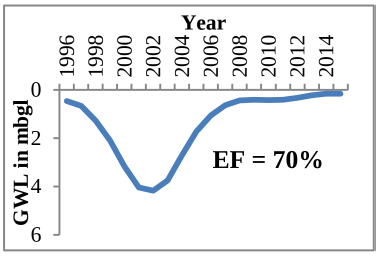
4. Khanapur1 5. Prabhunagar 6. Peerwadi

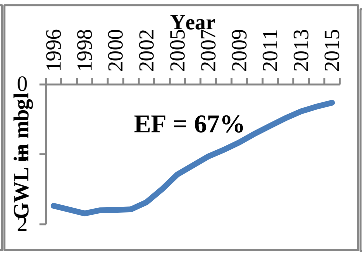


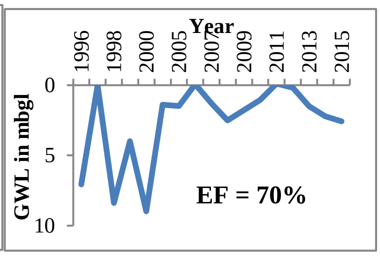




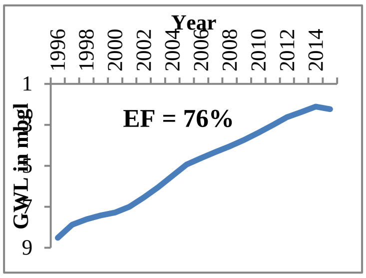
7. Uchagaon 8. Halaga 9. Belgaum1

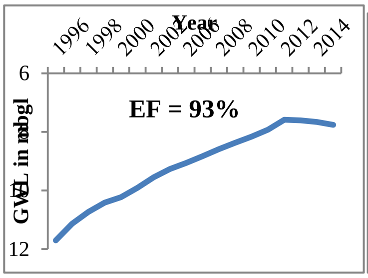


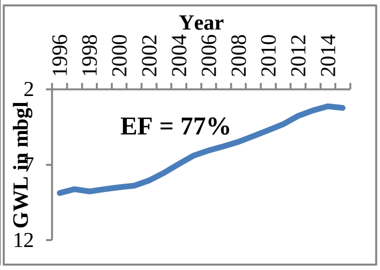




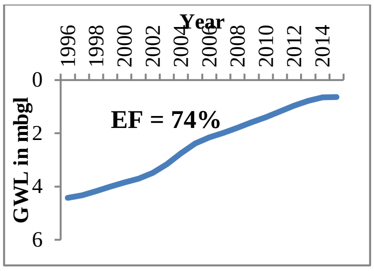
10. Kudachi-2 11. Kittur1 12. Hire bagewadi







13. Sutagatti1 14. Nesaragi1 15. Halaki



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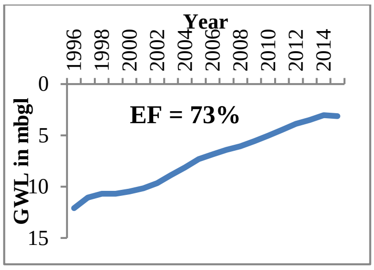

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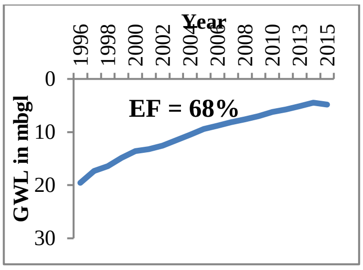
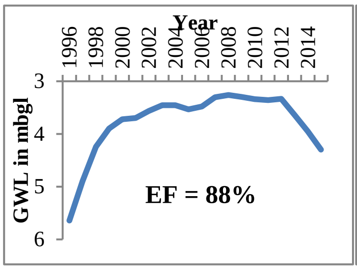
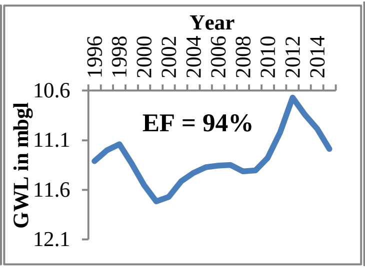


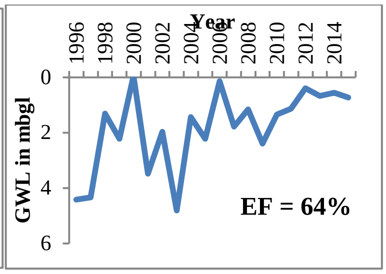
18. Achamatti



19. Saundatti



20. Ramdurg1



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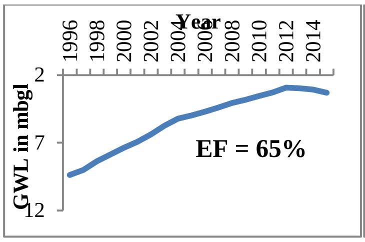

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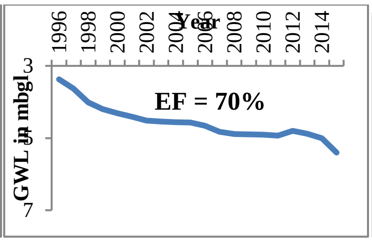

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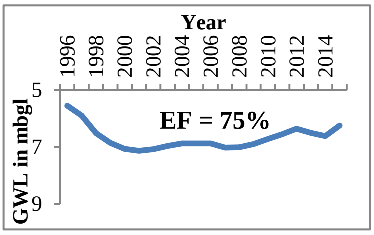

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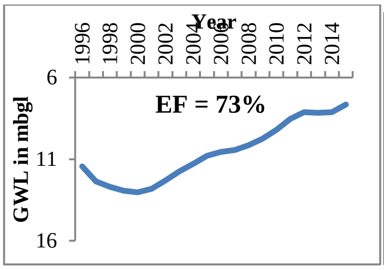

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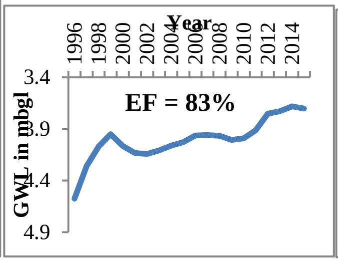

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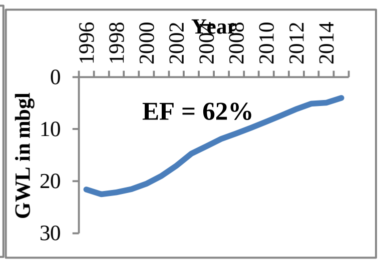

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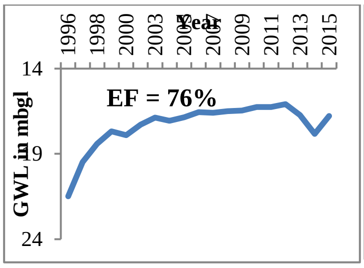

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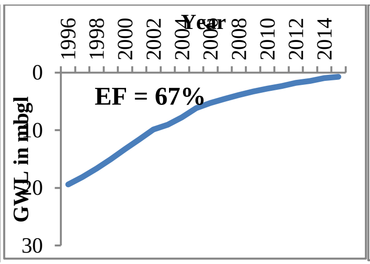

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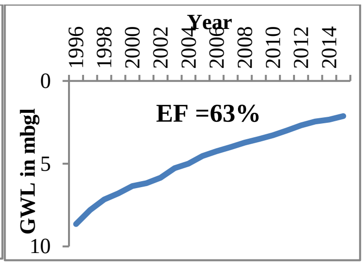

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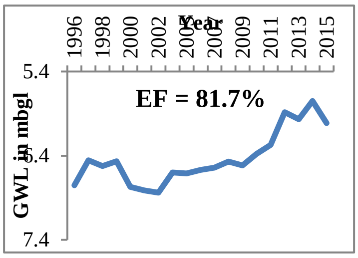
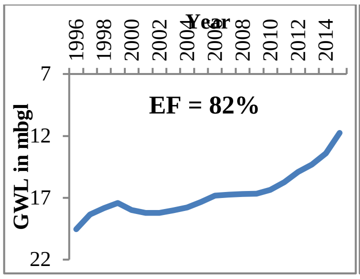
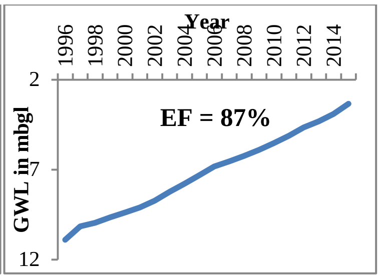


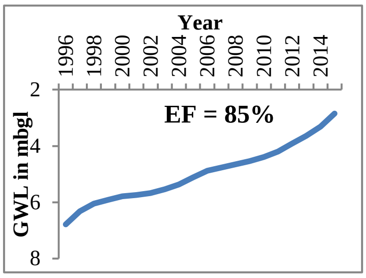
31. Kuppelur



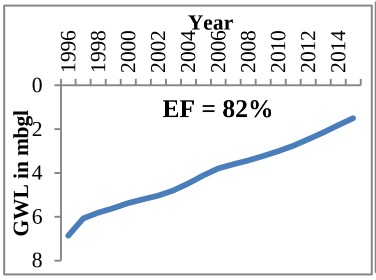
32. Ramgeri



33. Magdi



34. Shirhatti1



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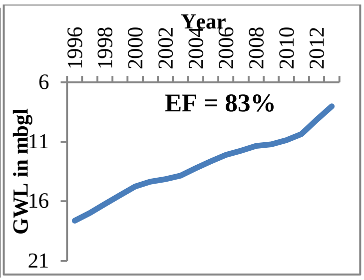
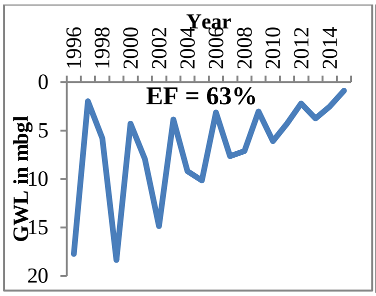
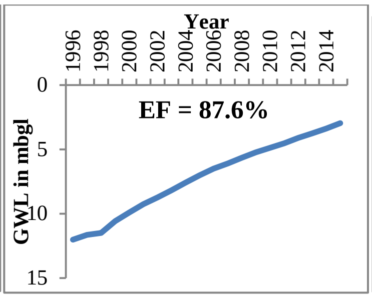


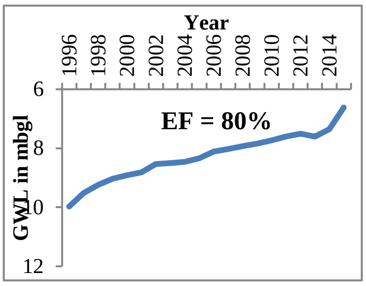
36. Nagasamudra



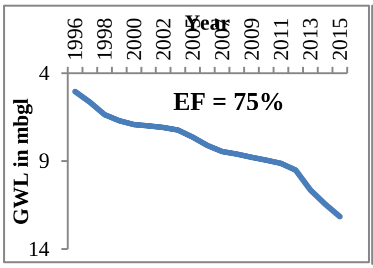
37. Nargund1



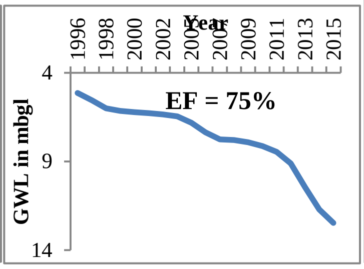
38. Belavaniki-1



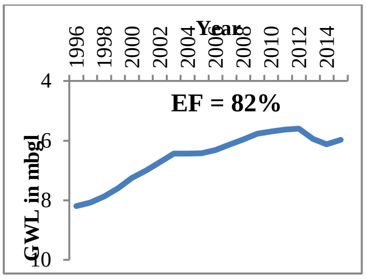
39. Hunagund



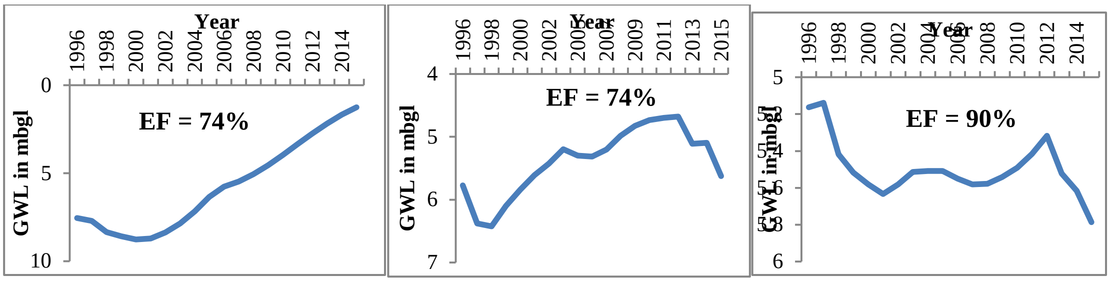
40. Kulageri1



41. Pattadakal



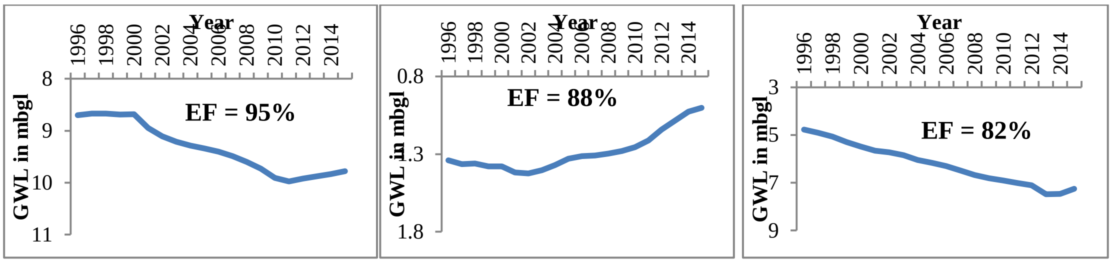
42. Guledagudda



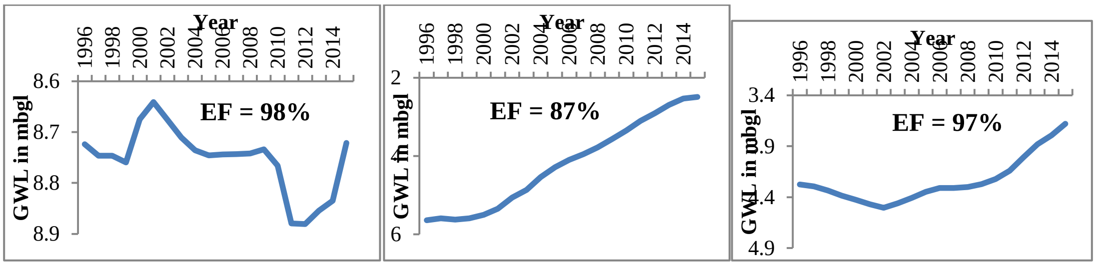
43. Amingad 44. Vadageri 45. Nagur

Figure 5.19: Nonlinear trends extracted for annual monsoon season GWLs using SSA method

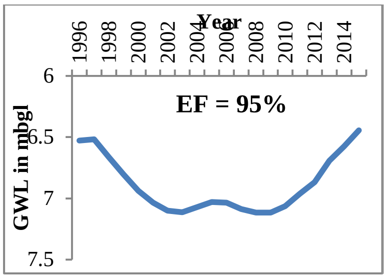
Shape of non-linear trends for monsoon season GWLs are presented in Figure 5.19. Maximum number of wells showed increasing GWLs trends in the monsoon season, except wells 12 (Hire bagewadi), 21 (Mugad), 37 (Naragund 1) which show random fluctuations in trends. Wells 1 (Londa1) and 2 (Gunji) which are located in the forested part of the catchment, showed increasing trends after year 2010. Wells located in the northern dry region (40, 41, 44 and 45) show decreasing trends.

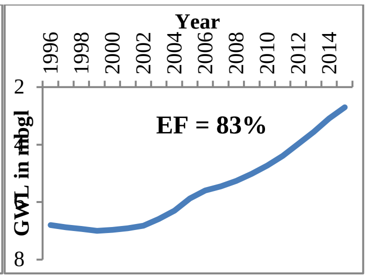


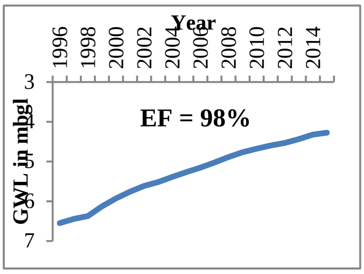
1. Londa1 2. Gunji 3. Bidi



4. Khanapur1 5. Prabhunagar 6. Peerwadi



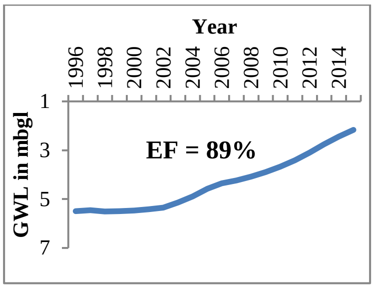


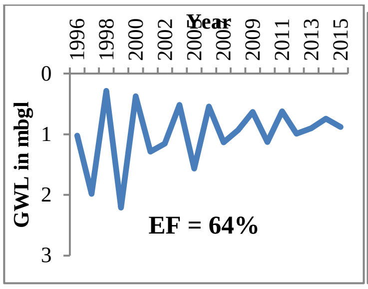


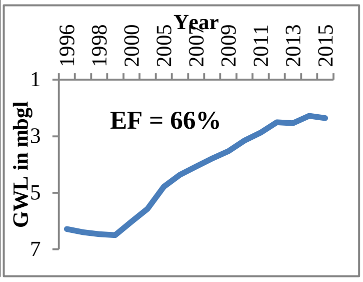
7. Uchagaon

8. Halaga

9. Belgaum1



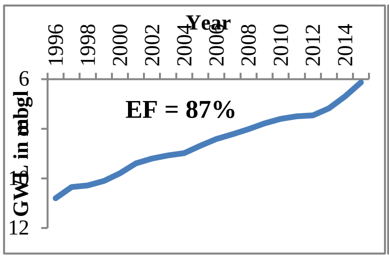


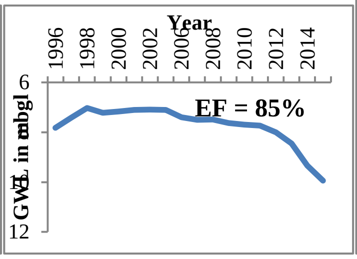


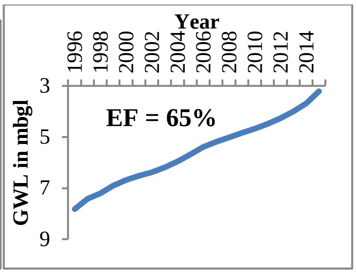
10. Kudachi-2

11. Kittur1

12. Hire bagewadi



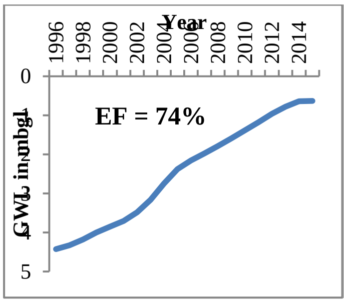


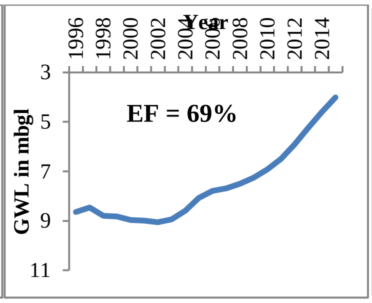


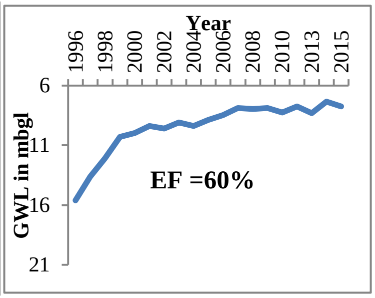
13. Sutagatti1

14. Nesaragi1

15. Halaki



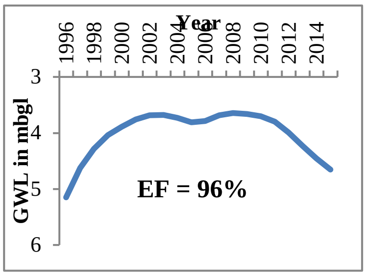




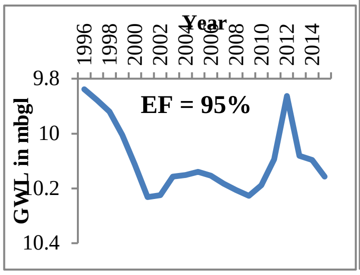
16. Bailhongal

17. Soppadla

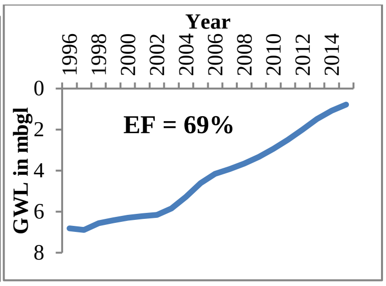
18. Achamatti



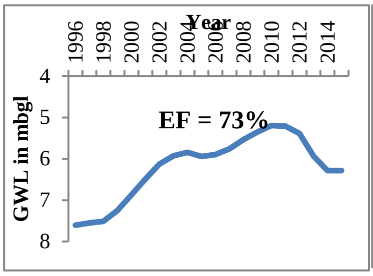
19. Saundatti



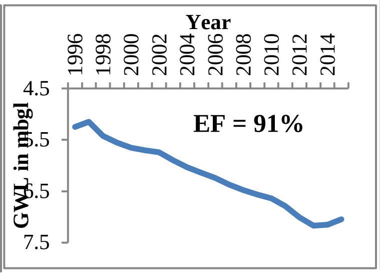
20. Ramdurg1



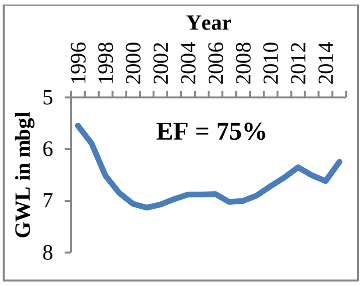
21. Mugad



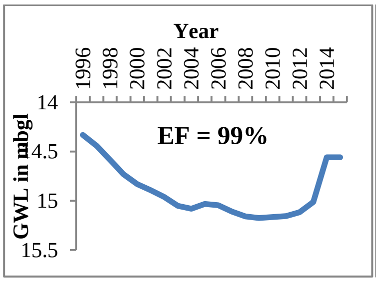
22. Amminabhavi



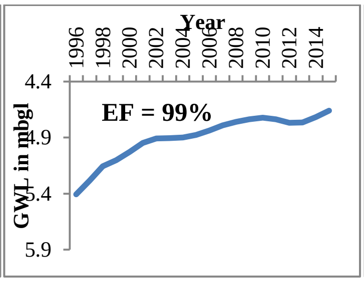
23. Morab



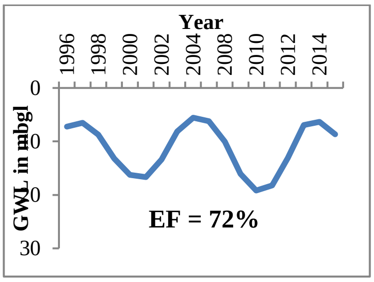
24. Shanawad



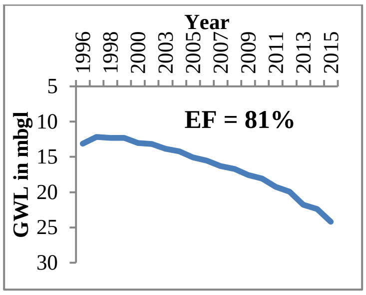
25. Basapur



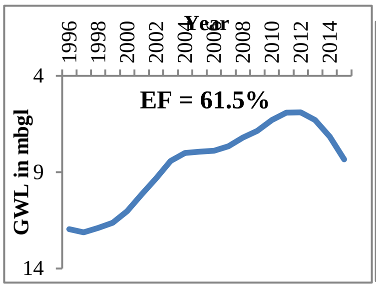
26. Hebsur1



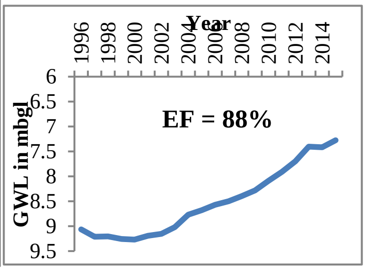
27. Kundgol



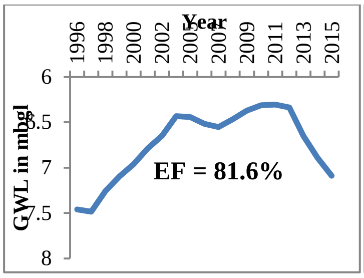
28. Gudgeri



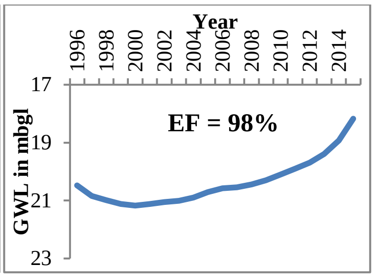
29. Wadarahalli



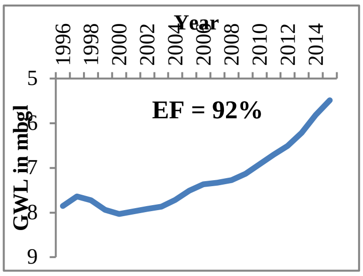
30. Tumminakatti



31. Kuppelur



32. Ramgeri



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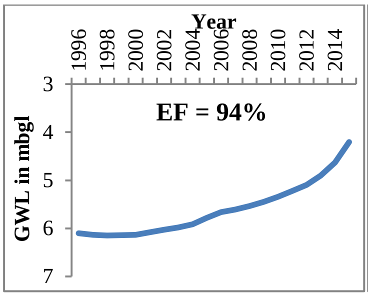

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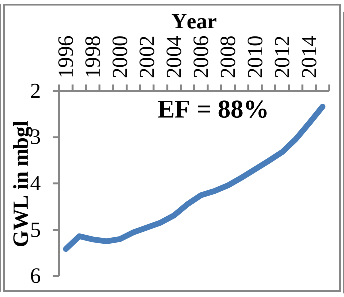

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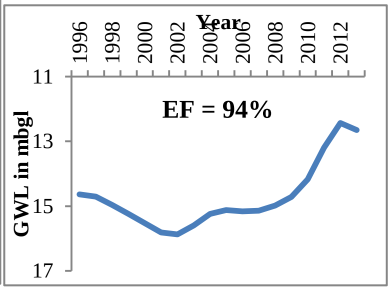

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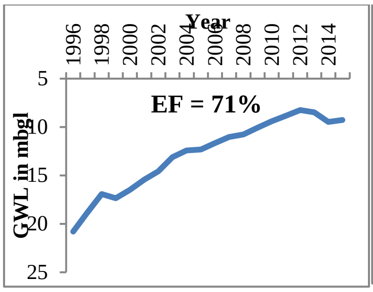

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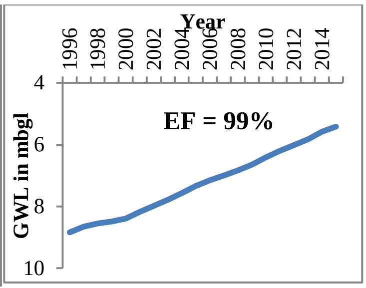

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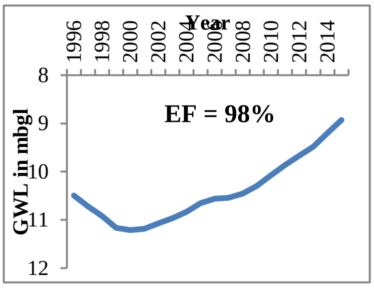

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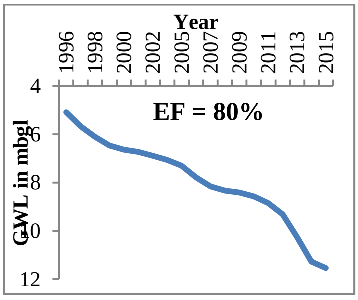

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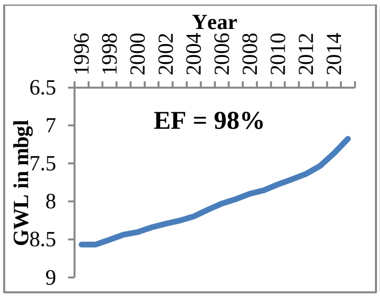

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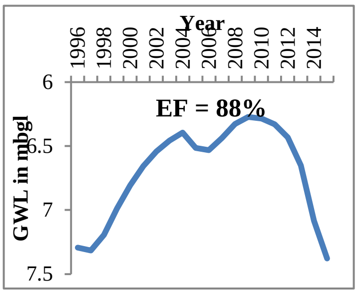
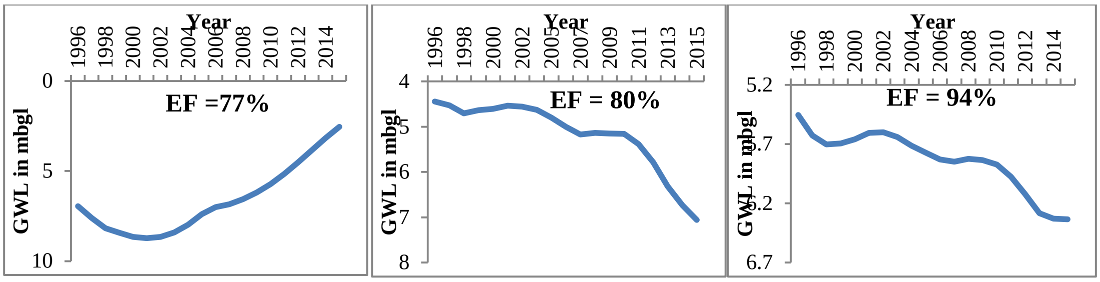


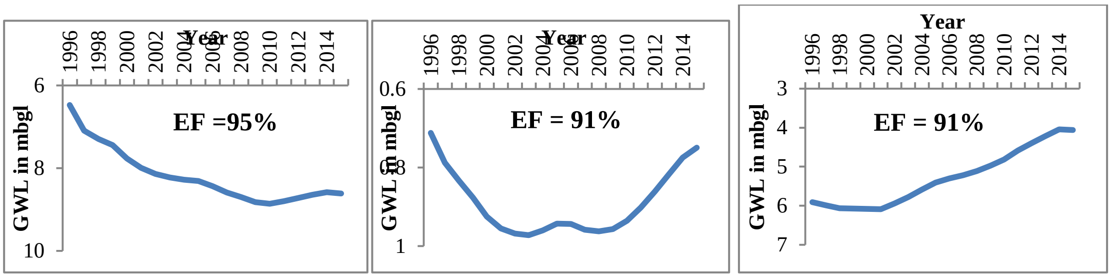
42. Guledagudda



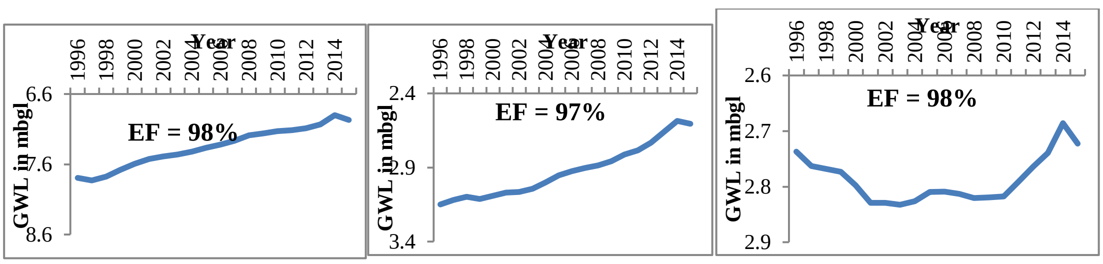
43. Amingad 44. Vadageri 45. Nagur

Figure 5.20: Nonlinear trends extracted for annual POMRB season GWLs using SSA method

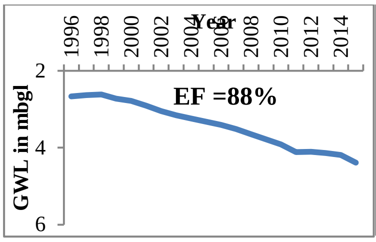
The SSA extracted non-linear trends for GWLs of wells in the Malaprabha river basin for post-monsoon rabi season (POMRB) are depicted Figure 5.20. Wells 4 (Khanapur 1), 11 (Kittur 1), 20 (Ramadurga) and 42 (Guledagudda) showed higher variation compared to other wells. As it is observed from the Figure 5.20, only 12 wells out of 45 showed decreasing trends, the reason could be during rabi season irrigation takes place in fewer regions and thus less variability in GWLs as compared to POMKH season.

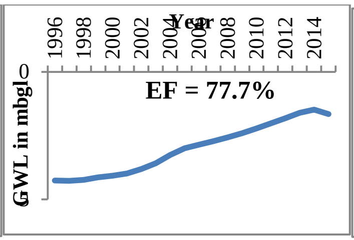


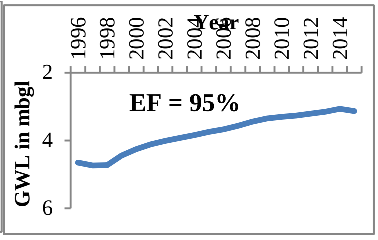
1. Londa1 2. Gunji 3. Bidi



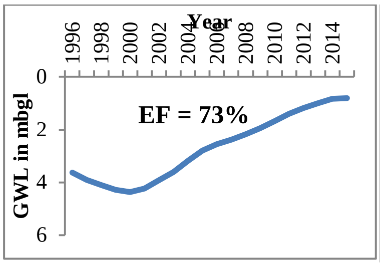
4. Khanapur1 5. Prabhunagar 6. Peerwadi

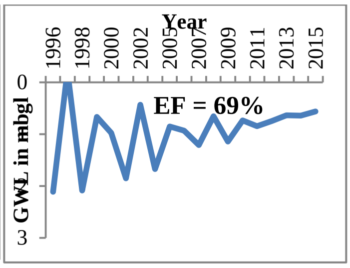


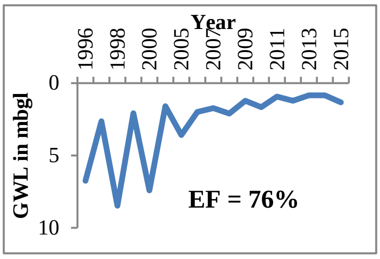




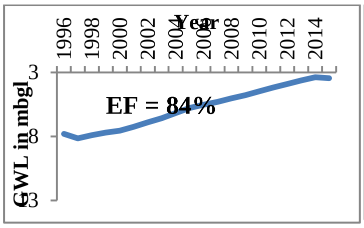
7. Uchagaon 8. Halaga 9. Belgaum1

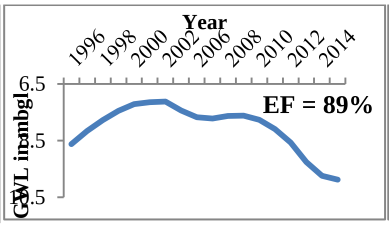


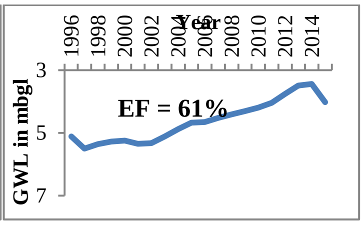




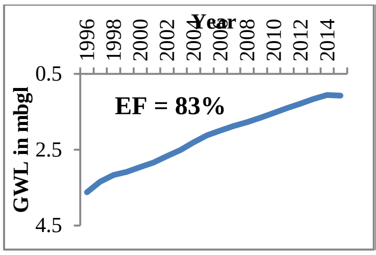
10. Kudachi-2 11. Kittur1 12. Hire bagewadi

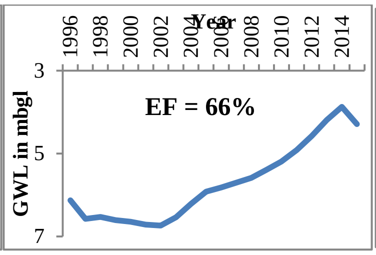


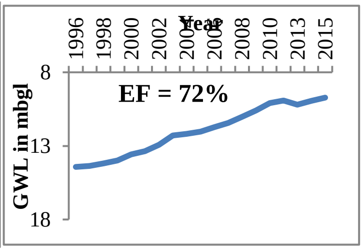




13. Sutagatti1 14. Nesaragi1 15. Halaki







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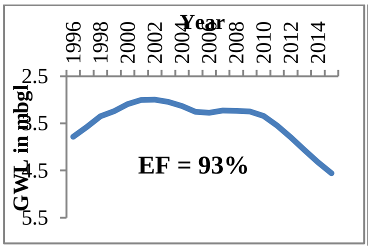
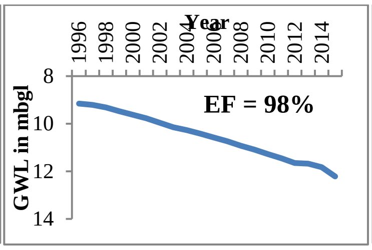
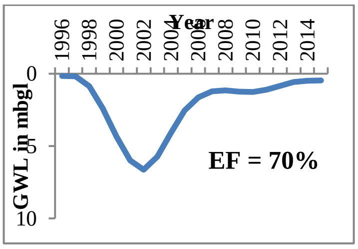
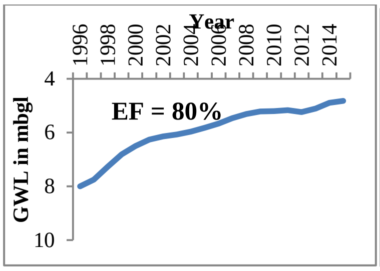






19. Saundatti 20. Ramdurg1 21. Mugad



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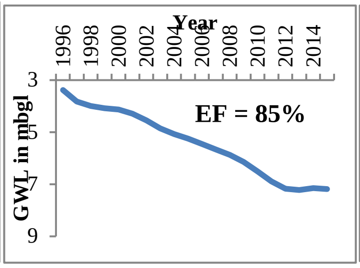

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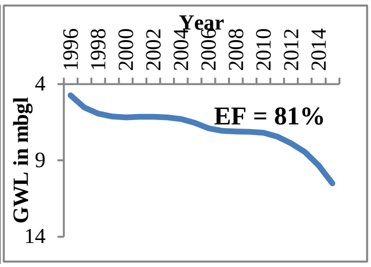

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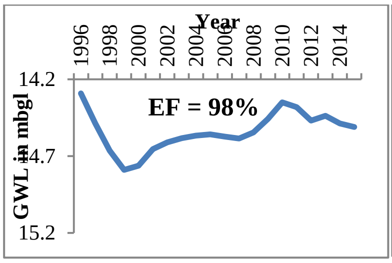

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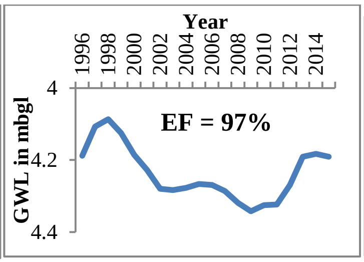

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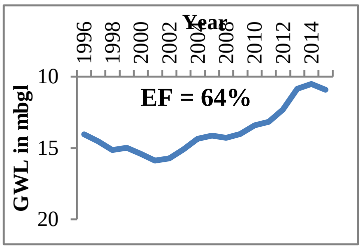

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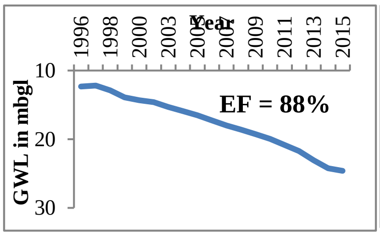

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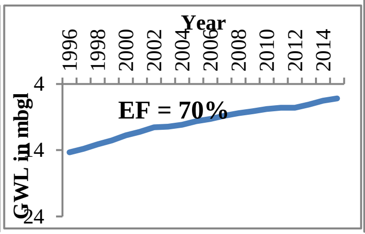

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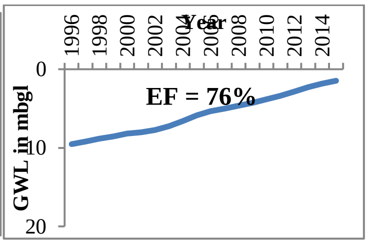

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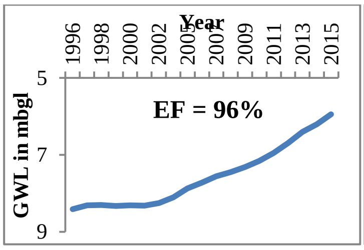

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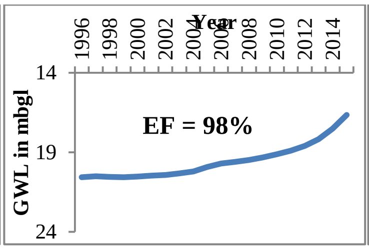

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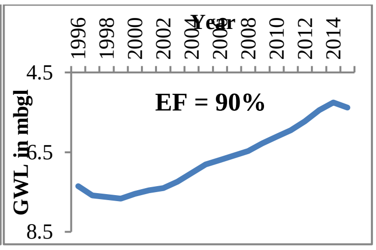

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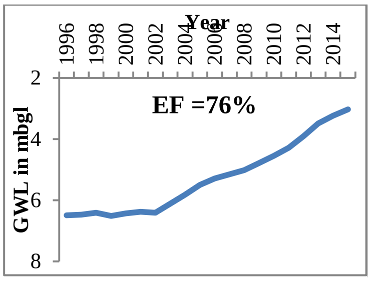

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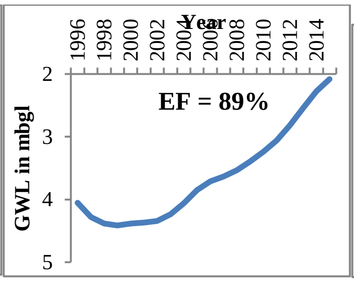

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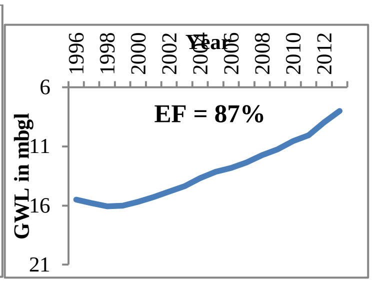

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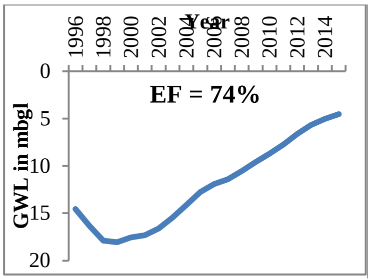

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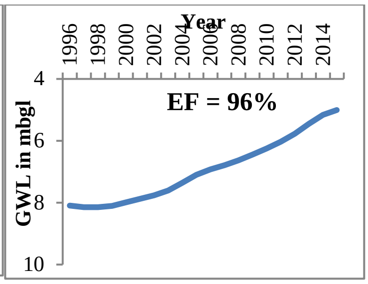

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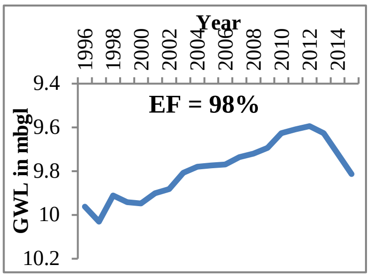

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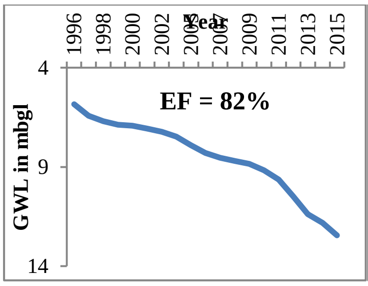

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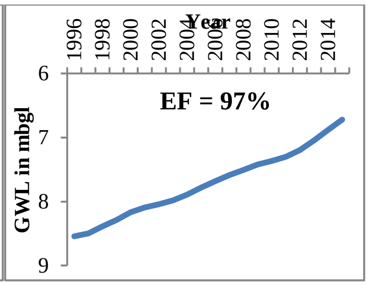
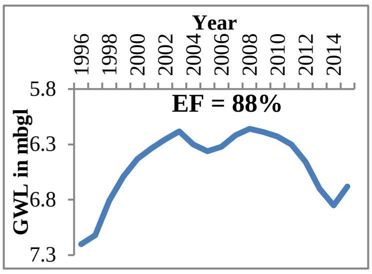
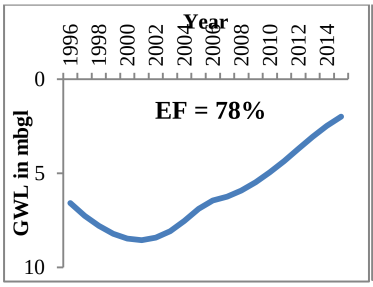


41. Pattadakal



42. Guledagudda



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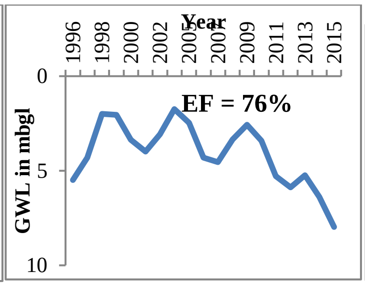

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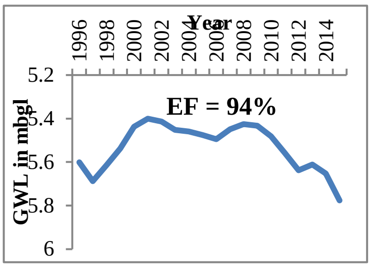
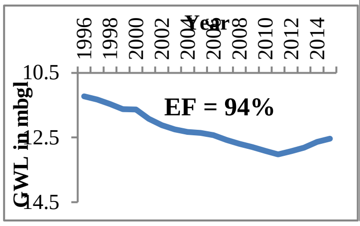


45. Nagur

Figure 5.21: Nonlinear trends extracted for annual POMKH season GWLs using SSA method

During the post-monsoon kharif (POMKH) season, maximum number of wells showed decreasing trends (20 out of 45). Also some wells exhibited greater variability (7.Uchagaon, 11.Kittur 1, 12. Hirebagewadi, 21. Mugad). This may be the result of extensive irrigation activities in the Malaprabha river basin using ground water source during the month of November.



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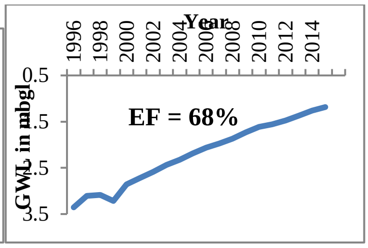

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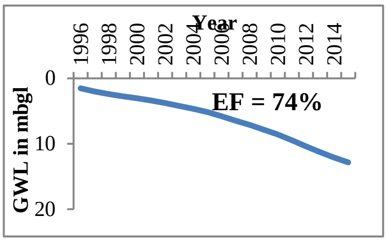
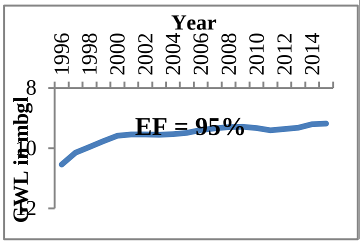
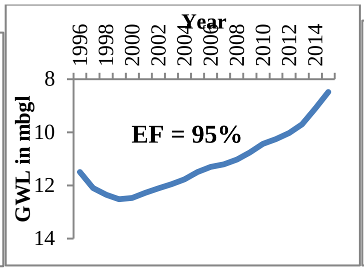


3. Bidi



4. Khanapur1



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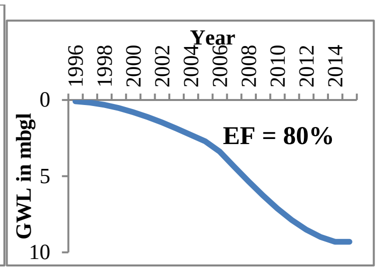

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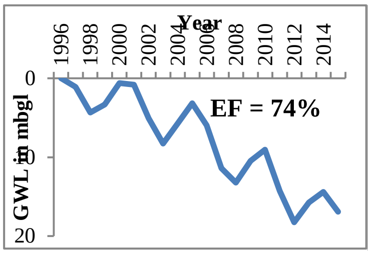

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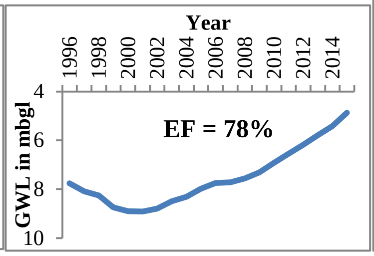
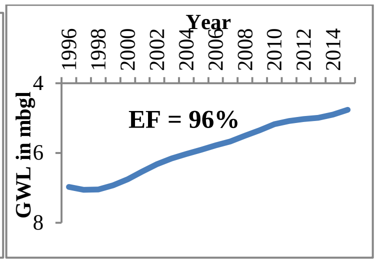
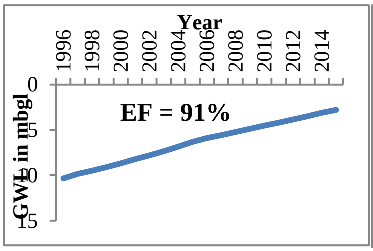


8. Halaga



9. Belgaum1



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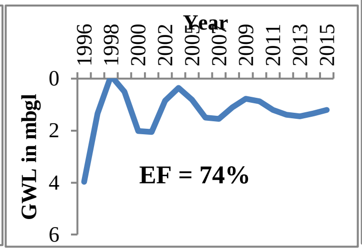
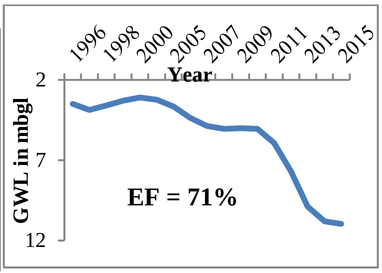
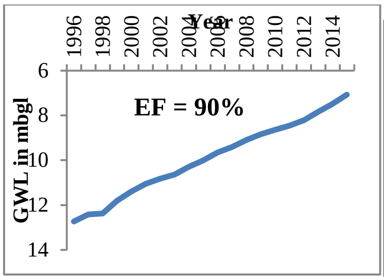
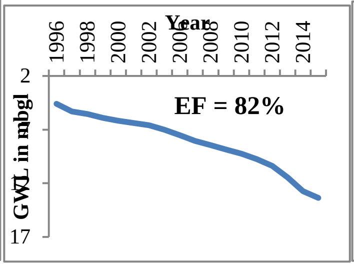


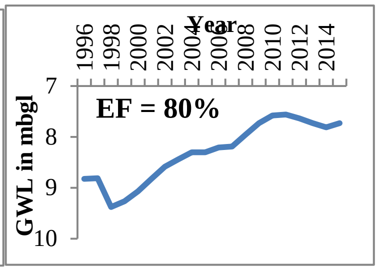
11. Kittur1



12. Hire bagewadi



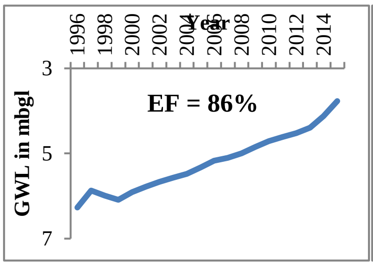


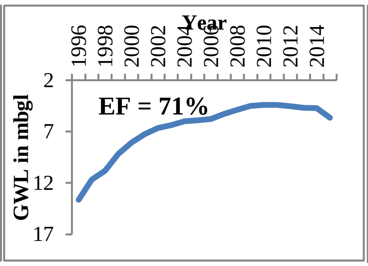


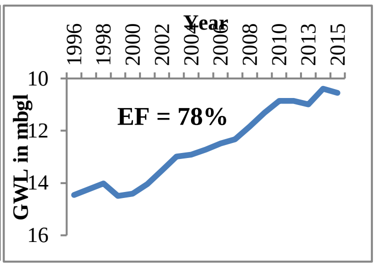
13. Sutagatti1

14. Nesaragi1

15. Halaki







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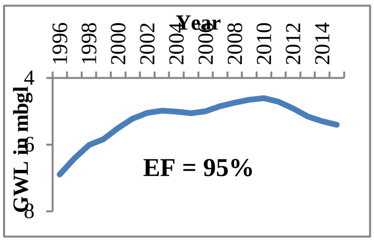
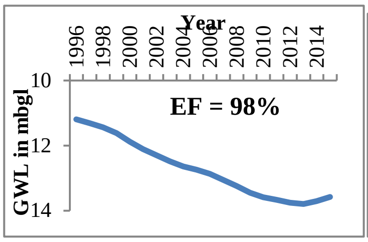
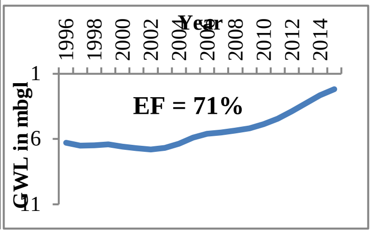
18. Achamatti







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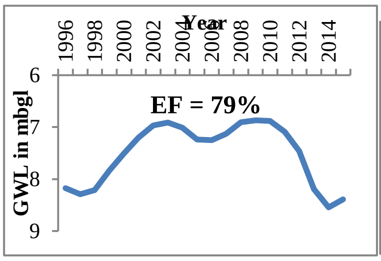

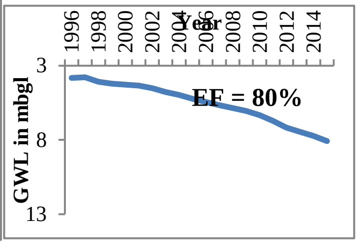

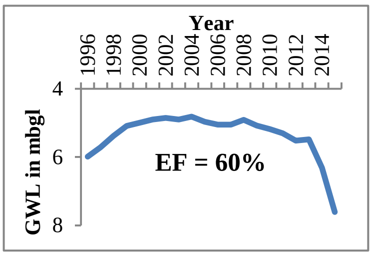

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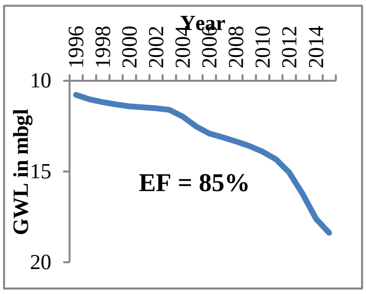

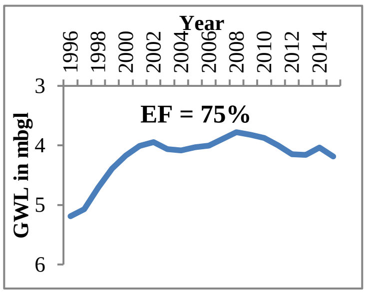

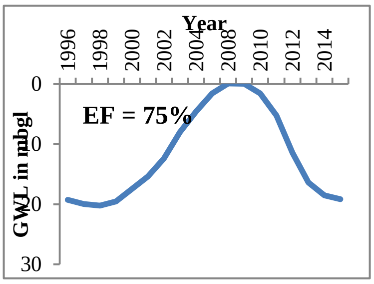

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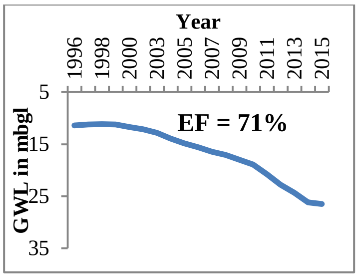

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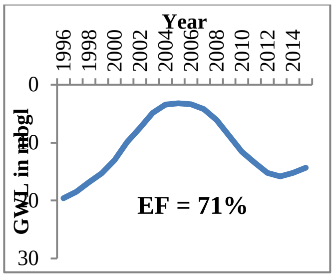

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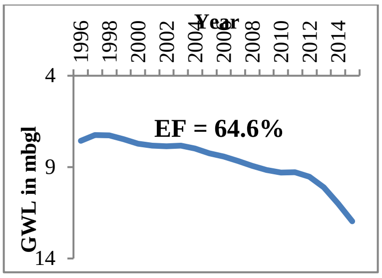

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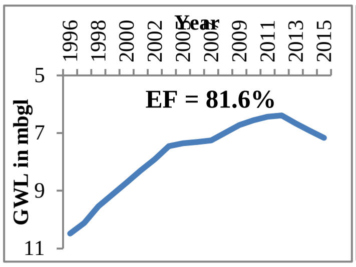

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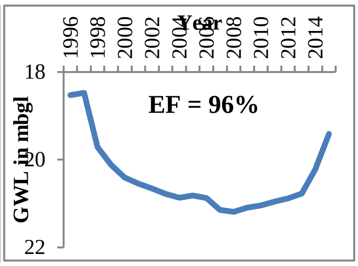

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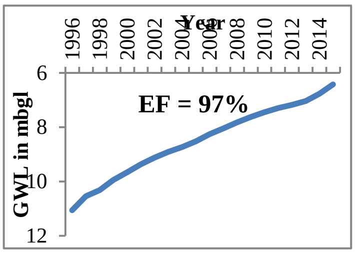

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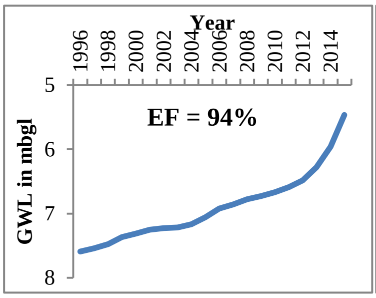

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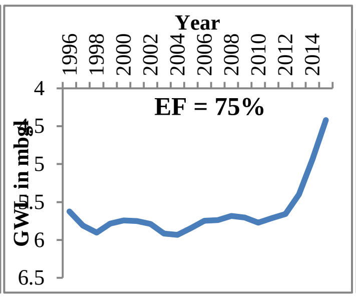

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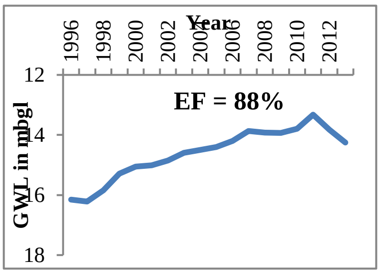

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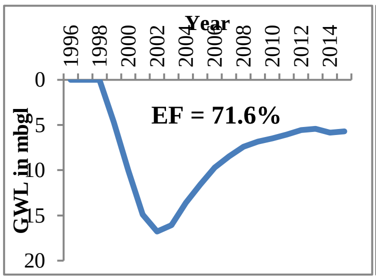

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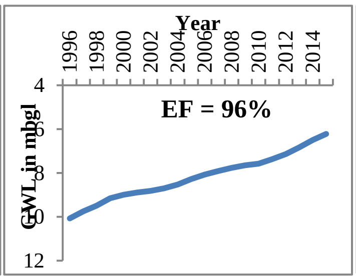

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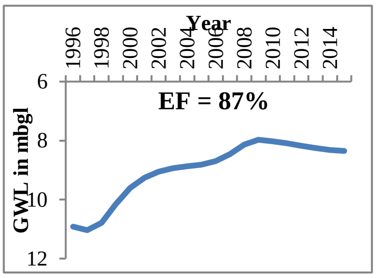

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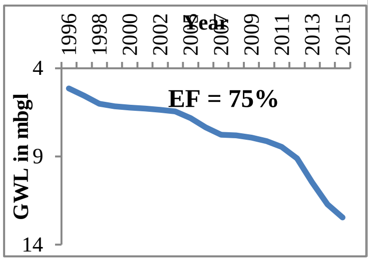

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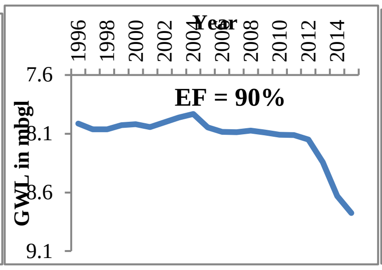

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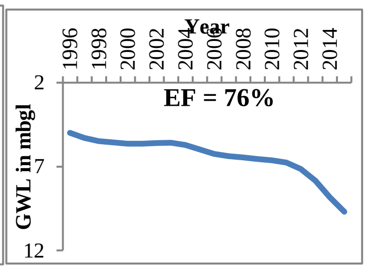

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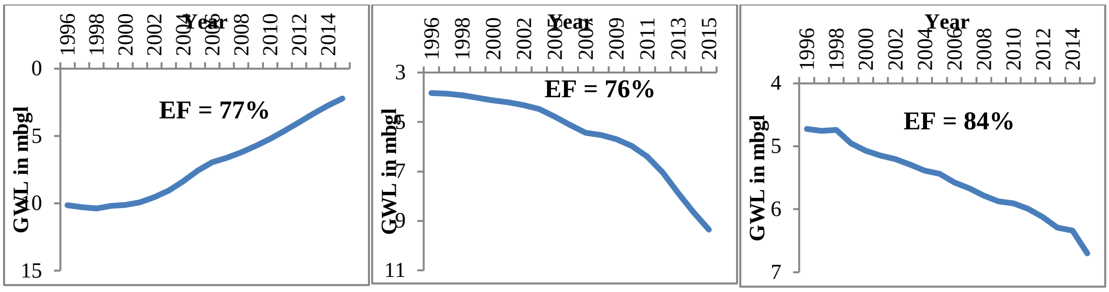


43. Amingad 44. Vadageri 45. Nagur

Figure 5.22: Nonlinear trends extracted for annual PREMON season GWLs using SSA method

Figure 5.22 represents SSA non-linear trends extracted for GWLs of wells in the Malaprabha river basin during the pre-monsoon (PREMON) season. The wells which showed no-trend (well id 3 and 6) and slightly increasing trends (well id 7, 12, 22, 23, 28) in SE and MK test (Table 5.5), showed decreasing trends in SSA. This demonstrates that SE and MK test capture true nature of trend only when there is steep change in the slope of trend. Otherwise, the method fails to capture the true nature of trend and it may misinterprete the direction of trend. On the otherhand SSA method captures the true variation of trend even when there is insignificant change in slope.

5.5 Closure

The present chapter focused on analyzing trends and variability of historical hydro-meteorological variables (rainfall, rainy days, average temperature, stream flows, and groundwater levels) over the Malaprabha river basin. Also, the likely effects of irrigation on the results were analyzed. A nonparametric Singular Spectrum Analysis (SSA) and conventional Sen’s slope Estimator (SE) methods were used for trend analysis. The statistical significance of non-linear and linear trends was identified using Monte-Carlo SSA and Mann-Kendall methods for 95% significance levels respectively. The temporal variability of the data was analyzed using the Coefficient of Variation (CV) statistic.

For the region close to the downstream of the Malaprabha dam, the number of rainy days for annual and monsoon periods exhibit higher variabilities. This is in contrast to the finding that CV values for annual and monsoon rainfall totals are lower in this part of the basin. This implies that it is likely that the presence of the reservoir has resulted in the occurrence of rainfall events with higher intensities in its vicinity. The downstream river gauging stations for post dam conditions showed greater variabilities as compared to pre-dam conditions.

The two rain gauge stations (Badami and Ramadurga) located immediately downstream of the Malaprabha dam showed increasing annual rainfall trends. However, the remaining stations showed decreasing annual trends. The SSA results indicated decreasing trends for basin average annual rainfall and rainy days trends since the commissioning of the Malaprabha dam and a steep increase in these trends from the year 2004.

The annual stream-flow trends for downstream gauging stations were subjected to variability as these are regulated flows and showed decreasing trends corresponding with the progression of irrigation in the command area. On the other hand, increased trends for annual and seasonal average air temperature were noticed in the study area. Groundwater levels of most of the wells in the upstream region showed increasing annual trends. The two wells located in close vicinity of the Malparabha dam towards the downstream side showed significantly decreasing trends. On the other hand, the wells in the downstream command area indicated a combination of significantly increasing and decreasing trends.

Results of this study also demonstrate the ability of SSA to capture the trajectory of nonlinear trends over the entire time series of hydro-meteorological variables. The traditional SE and MK methods, on the other hand, provide information on linear monotonic trends. Also, SSA permits identification of “change points” of trend reversal brought about by anthropogenic activities which, in this particular case, was found to correspond to the introduction of large-scale irrigation activities in the study area. Therefore, it is proposed that SSA is an attractive statistical tool that permits the identification of non-stationary and extraction of trajectories of nonlinear trends and change points in time series of hydro-climatic variables which exhibit non-stationarity.

CHAPTER 6

HISTORICAL GROWTH OF IRRIGATED AGRICULTURE IN THE MALAPRABHA RIVER BASIN

6.1 GENERAL:

Agriculture is the main occupation of about 85% of the population in the Malaprabha region, the success of which is very uncertain due to untimely, inadequate, and undependable rainfall. The talukas of Badami, Nargund, Navalgund, and Ron have been known to suffer from severe droughts and scarcity conditions in the past (Madar 1993). Therefore, the Malaprabha irrigation project was commissioned in the year 1972 to provide irrigation facilities to those talukas of the basin which suffered from severe droughts and scarcity conditions.

The Malaprabha irrigation project is protective in nature and was proposed for irrigation mainly for dry crops in the command area. However, the availability of additional surface and groundwater encouraged farmers to cultivate more water-intensive crops such as sugarcane, paddy, and tobacco (Reshmi et.al. 2008, Biswas and Venkatachalam 2010). This violation in cropping pattern and adoption of flood-irrigation has resulted in several water-related problems in the basin such as water shortage for the tail-end users, lowering of groundwater table under irrigated areas (Reshmidevi and Nagesh Kumar 2014), mismanagement among inter-sectoral water distribution, and leaching problems in agricultural regions close to the reservoir (Chitragar 2018). Accordingly, the optimal functioning of the irrigated project is questionable. Thus, there is a need for performance evaluation of the project to provide solutions to these issues.

A few previous studies have assessed water use efficiencies and agricultural productivity of major Indian irrigation projects (Rani et al. 2011, Singh et al. 2013, Thiruvengadachari and Sakthivadivel 1997, Srinivasulu 2003, Kadam 2015, Chandran and Ambili 2016, Chandran et.al. 2016). However, these studies have focused on issues related to crop and irrigation water requirements, growth of irrigated areas, and cropping patterns. A limited number of studies have evaluated spatiotemporal changes in irrigated areas, cropping patterns, water requirements, and sources of irrigation water in command areas over long periods following the commissioning of major irrigation projects.

Accordingly, the present study was taken up to analyze the historical development of irrigated agriculture in the Malaprabha irrigation project which was commissioned in 1972. CROPWAT model was used in the present study to estimate crop and irrigation water requirements. Several previous studies have successfully applied the CROPWAT model in Indian conditions (Chatterjee et.al. 2012, Babu et.al 2015, Gangwar et.al. 2017, Surendran et.al. 2017, Trivedi et.al. 2018, Verma et.al. 2019). This model uses procedures suggested by Allen et al. (1998) to estimate crop and irrigation water requirements using data pertaining to climate, crops, and soils.

The present chapter focuses on implementing a scientific approach to characterize the development of irrigation in the Malaprabha river command area. The main objective of the work is to 1) assess the spatiotemporal changes in the extent of irrigated area and cropping patterns, 2) explore the role of groundwater in providing irrigation water supplies, 3) compute crop water requirements (CWR) and irrigation water requirements (IWR) of crops grown in the command area using the CROPWAT model over the period 1965-2014 in the command area of the project.

6.2 MALAPRABHA IRRIGATION PROJECT

The Malaprabha irrigation project was planned to create a total irrigation potential of 1, 96,132 ha in the Malaprabha command area through two main canals namely Malaprabha Right Bank Canal (MRBC-1, 21,392 ha), Malaprabha Left Bank Canal (MLBC-47,769 ha), and 11 foreshore lift irrigation schemes (LIS-26,971 ha) (Detailed Project Report (DPR) 2008). The mean annual rainfall in the command area is 591 mm for the period 1965 to 2015.

The Malaprabha command area spreads over nine talukas of Belgaum, Bagalkot, Dharwad, and Gadag districts. However, only six talukas are included for analysis

(Figure 6.1) in the present work. The remaining three talukas were not considered since their irrigated area is less than 4 percent. Thus, the talukas considered for the study are Saundatti, Ramadurga, Naragunda, Rona, Navalagunda, and Badami. The total geographical area of the talukas considered is 6,98,008 ha and the total irrigation potential created under the Malaprabha irrigation project for these talukas is 1,83,393 ha (Table 6.1).

Table 6.1 Taluk wise Geographical area under Malaprabha command area

Sl.no	Taluka name	Geographical area in Sq.km	Taluka area under River basin		Irrigation potential area in Sq.km
			Area (km^2)	Area %	
1	Soundatti	1,580.94	1237.46	78.27	360.83
2	Ramadurga	1215.72	860.75	70.80	181.64
3	Nargund	435.62	435.62	100	277.61
4	Rona	1290.91	1261.27	97.70	342.68
5	Navalgund	1082.18	1081.49	99.94	385.52
6	Badami	1,374.71	1102.67	80.21	285.65

Source: District at a Glace of Belgaum, Bagalkot, Dharwad, and Gadag, 2016-17

6.3 MATERIALS AND METHODOLOGY

The taluk is considered as the spatial unit for analysis in the present study. Accordingly, taluk-wise relevant data for the historical period extending over 50-years (1965-2014) was procured from various published government reports and doctoral thesis (Table 6.2). Daily rainfall (DES, Govt. of Karnataka), maximum and minimum temperature (NASA-GDDP) data were obtained for the locations in and around the Malaprabha command area (Figure 6.1) for the period of analysis. However, for highlighting temporal changes (based on the availability of data) in the variables considered over a decadal time step, results are presented separately for the years 1965-66, 1975-76, 1985-86, 1993-94, 2003-04 and 2013-14. While 1965-66 represents the pre-dam condition, the other years are representative of evolving conditions after the commissioning of the Malaprabha project in 1972.

Table 6.2. Datasets procured for the study

Sl.No	Data Type	Period	Resolution	Source
1	Cultivated area, Irrigated area, Crop area, and Sources of irrigation in Malaprabha command area	1965-2014	Taluk wise Decadal	District at a glance reports, Government of Karnataka and Published values from Madar 1993, S.L. Chitragar 2018 doctoral theses from the Department of Agriculture and Geography, University of Dharwad, Karnataka
2	Canal water releases	1972-2014	Monthly	Executive engineer, Malaprabha left bank canal construction (MLBCC) Department, Division II, Navilutheertha, Belgaum
3	Rainfall	1965-2014	Daily	Directorate of Economics and Statistics (DES), Government of Karnataka
4	Maximum and Minimum temperatures	1965-2014	Daily $0.25^0 \times 0.25^0$	NASA Earth Exchange Global Daily Downscaled Projections -NEX-GDDP (ACCESS1-0 model)

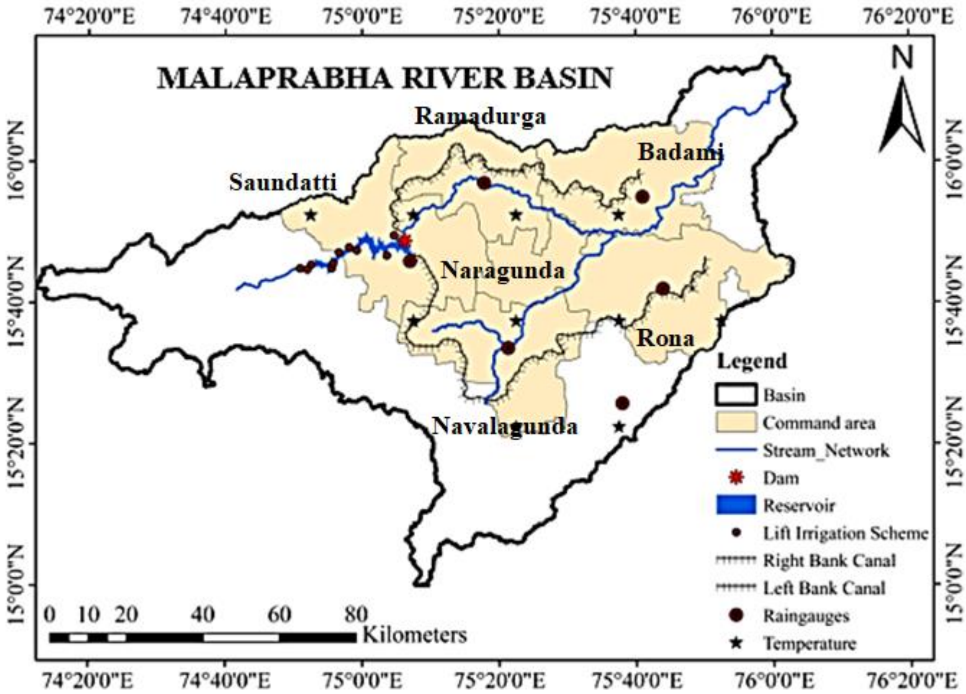


Figure 6.1: Talukas of Malaprabha river basin command area considered for the study

6.3.1 CROPWAT 8.0:

CROPWAT is a decision support system developed by the Land and Water Development Division of the United Nations Food and Agricultural Organization for planning and management of irrigation activities. The model is envisioned as a practical tool to carry out standard calculations for reference crop evapotranspiration (ET_0), effective rainfall (P_{eff}), CWR, and IWR, and more explicitly for the design and management of irrigation schemes. It is capable of planning irrigation schedules under changing water supply conditions and assessing crop production under rainfed or deficit irrigation circumstances.

6.3.2 Climate data

Daily rainfall data for the period of analysis was collected from the Directorate of Economics and Statistics (DES), Government of Karnataka for the six rain gauges located in and around the Malaprabha command area (Figure 6.1). Daily maximum and minimum temperature values for 10 grid points at 0.25^0 resolutions were obtained from the ACCESS1-0 model of NEX-GDDP (Thrasher et.al. 2013, Jain et.al. 2019, Kumar 2020) for the period of analysis. Validation of grid data with monthly data recorded at climate stations yielded a minimum correlation coefficient of 0.78 which was considered to be acceptable.

6.3.3 Cropping pattern

The cropping pattern in the Malaprabha command area has evolved in response to the irrigation project, socio-economic development in the area and establishment of agriculture processing industries, etc. (Madar 1993). The irrigation project was envisaged to provide irrigation for less water-intensive crops in the Kharif season only (DPR 2008). Table 6.3 represents the proposed cropping pattern and that existing in 2013-14 in the command area from which significant differences are evident.

Application of CROPWAT also requires specification of the season-wise cropping pattern in the command area. However, this is a complex task on account of the heterogeneity in crops grown and the dynamics involved in the present cropping patterns. Thus, for the sake of reducing complexity, logical approximations were made regarding the cropping pattern in the basin and the same pattern was assumed to be valid for all six decades. As Jowar, Maize, Pulses, and Cotton are grown in both the Kharif and rabi seasons, a share of 60% and 40% of their sown areas were distributed to the two seasons respectively. The planting date for the two seasons was selected as 15th June and 15th October respectively for all the crops (following CADA information).

Table 6.3: Cropping pattern in the Malaprabha Command area

		Proposed cropping pattern	Existing cropping pattern	
Sl.No.	**Crop name**	**Kharif**	**Kharif**	**Rabi**
1	Paddy	-	100%	-
2	Jowar	100%	60%	40%
3	Maize	100%	60%	40%
4	Wheat	-	-	100%
5	Green gram	-	60%	40%
6	Bengal gram	-	60%	40%
7	Groundnut	100%	100%	-
8	Sunflower	-	-	100%
9	Cotton	-	60%	40%
10	Sugarcane	-	100%	

6.3.4 Reference Crop Evapotranspiration (ET_0)

Since historical climatic data required for estimating reference crop evapotranspiration (ET_0) by the preferred Penman-Montieth method were unavailable, the temperature-based Hargreaves method (Allen et.al. 1998) was used instead. Daily temperature values were converted to monthly averages and used to compute monthly ET_0 values using the Hargreaves equation which is given by,

$$ET_0 = 0.0023\,(\overline{T}+17.8)\,(T_{max}-T_{min})^{0.5} \times Ra \qquad (6.1)$$

Where ET_0 is reference crop evapotranspiration in the mm/day; T_{max}, T_{min} and $\overline{T}$ are the maximum, minimum, and mean monthly air temperatures in ^0C, Ra is extra-terrestrial radiation in MJ m^{-2} d^{-1} calculated as per procedures are given in Allen et al. (1998). Monthly ET_0 values were provided as input to the CROPWAT model.

6.3.5 Crop Evapotranspiration and Crop Coefficients:

CROPWAT computes crop evapotranspiration values (ET_c) which represent CWR using the single crop coefficient (K_c) approach as,

$$CWR = ET_c = ET_0 \times K_c \qquad (6.2)$$

Subsequently, IWR is computed as follows,

$$IWR = CWR - P_{eff} \qquad (6.3)$$

Gross IWR is obtained by assuming an irrigation efficiency of 50%. Effective precipitation (P_{eff}) is calculated in CROPWAT using the USDA-Soil Conservation Service approach,

$$P_{eff} = \frac{(P \times (125 - 0.2P))}{125} \quad \text{for } P \leq 250\text{mm}$$

$$P_{eff} = 125 + 0.1P \quad \text{for } P > 250\text{mm} \qquad (6.4)$$

where P is the total rainfall (mm).

Growth stage-wise K_c values for each crop are needed to estimate CWR. Curves showing the temporal variation of K_c over the growing season for each of the selected crops were derived using values of durations of initial (L_{ini}), development (L_{dev}), mid-season (L_{mid}), and late-season (L_{late}) and corresponding values of crop coefficients for initial (Kc_{ini}), mid-season (Kc_{mid}) and harvest (Kc_{end}). Standard values of durations and crop coefficients (Table 6.4) and data regarding crop characteristics such as yield response, crop height, minimum and maximum rooting depths, were obtained from Allen et al. 1998, Doorenbos, and Pruitt 1977 and Doorenbos and Kassam 1979.

Table 6.4: Crop coefficients (Kc) and length of growth stages of crops

Name of Crop	Kc values			Length of crop stages (days)				
	Kc_{ini}	Kc_{mid}	Kc_{end}	L_{ini}	L_{dev}	L_{mid}	L_{late}	Total
Paddy	1.05	1.2	0.7	30	30	60	30	150
Jowar	0.7	1.15	1.05	20	35	40	30	125
Maize	0.7	1.15	1.05	20	35	40	30	125
Wheat	0.3	1.15	1.4	15	25	50	30	120
Green gram	0.4	1.15	0.35	20	20	50	20	110
Bengal gram	0.4	1.15	0.35	20	20	50	20	110
Ground nut	0.4	1.15	0.6	35	35	35	35	140
Sunflower	0.35	1.15	0.35	25	35	45	25	130
Cotton	0.35	1.2	0.7	30	50	60	55	195
Sugarcane	0.4	1.25	0.75	15	70	220	140	445

6.4 RESULTS AND DISCUSSION

6.4.1 Growth of Irrigated agriculture:

Figure 6.2 depicts changes in the net cultivated and the irrigated area along with average rainfall for the past six decades over the Malaprabha command area. Although not much change was observed in the net cultivated area, the rapid growth of irrigated agriculture can be noticed in the region since the commissioning of the irrigation project during 1972. The irrigation intensity (ratio of net irrigated area to cultivated area) has increased from 0.76% during 1965-66 to 56.82% during 2013-14.

It is interesting to note that the planned potential was not achieved even after 33 years (2003-04) of commissioning of the project. In fact, the net irrigated area decreased in 2003-04 in comparison to 1993-94 when it registered a value of 1,47,855 ha. This decrease may be attributed to a decrease in rainfall (369mm) during 2003-04 and consequent reduction of inflows into the Malaprabha reservoir. As of 2013-14, the net irrigated area was 2,40,039 ha which is significantly higher than the planned irrigation potential of 1,83,393 ha for the area under consideration. This surplus irrigated area is an outcome of increased groundwater-based irrigation in the region (Figure 6.4).

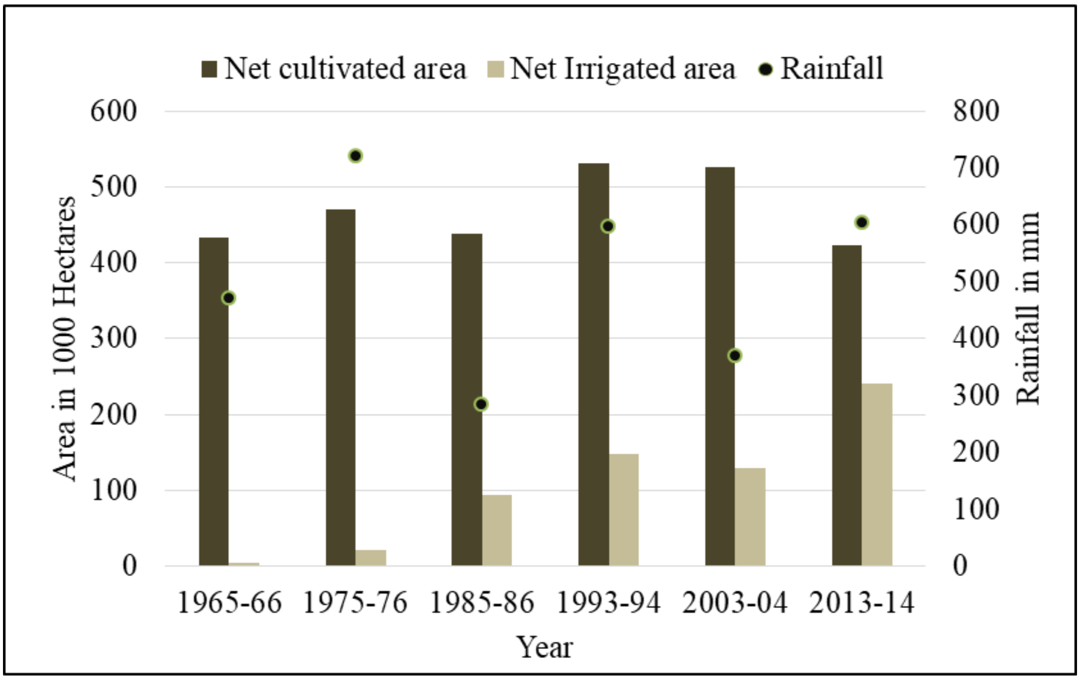


Figure 6.2: Growth of net cultivated area and irrigated area in the Malaprabha command area. ***(Source: Data compiled from Madar 1993, S.L. Chitragar 2018 and District at a glance reports of Bagalkot, Belgaum, Dharwad, and Gadag)***

6.4.2 Sources of irrigation water supply:

The main sources of irrigation water in the Malaprabha command area are canals, tanks, wells, and other sources which consist of mainly lift irrigation (Figure 6.3). It can be noticed from Figure 6.3 that tanks and dug/open wells catered to 20% and 70% of the irrigated area respectively during 1965-66 which represents the pre-project condition.

The irrigated area under canal supply showed an abrupt increase with the commissioning of the project and served 9,169 ha in 1975-76. It continued to be the major source of irrigation till 1993-94 and its maximum contribution (61%) was in the year 1985-86. However, by 2013-2014 the share of canal reduced to 41% although it catered to the largest extent of irrigated area (98,339 ha) during the period of analysis.

The next important source of irrigation is groundwater extracted through the bore and dug wells. With falling groundwater levels, tube wells are gradually replacing dug/open wells. Despite the introduction of canal water supplies in 1972, the irrigated area under groundwater supplies has registered a steady and steep increase in the last 40 years. It is interesting to note that during 2003-04 and 2013-14, groundwater replaced canal supplies as the highest contributor (46% and 48% respectively) to irrigated agriculture in the region.

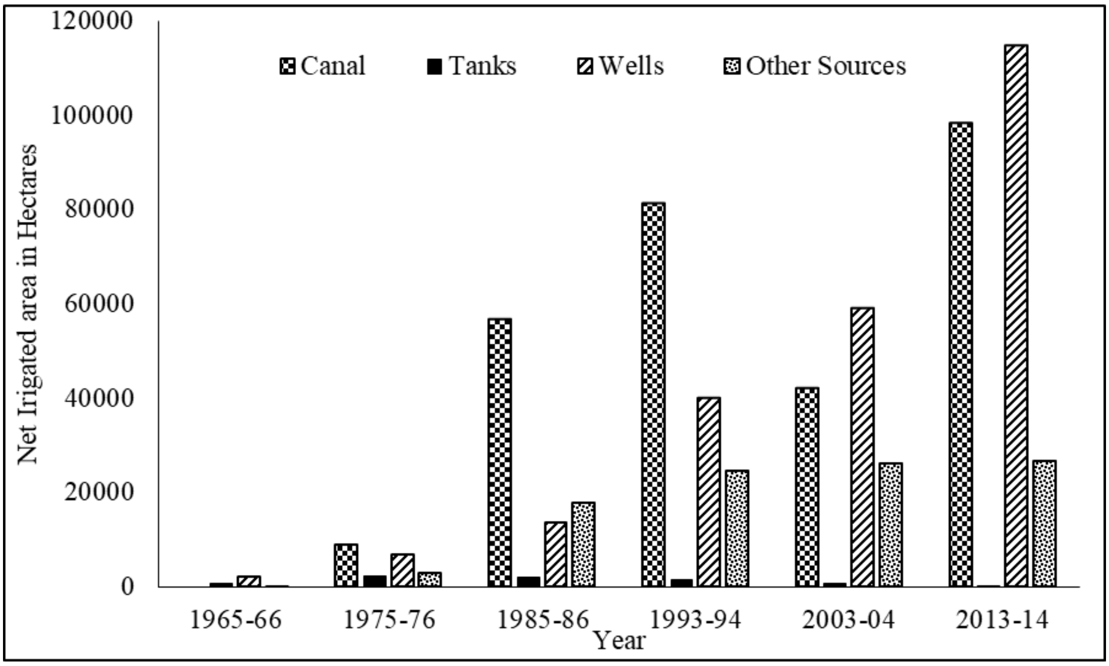


Figure 6.3: Source-wise irrigated area in the Malaprabha river command area.
(Source: Data compiled from Madar 1993, S.L. Chitragar 2018 and District at a glance reports of Bagalkot, Belgaum, Dharwad, and Gadag)

Other sources of irrigation include minor transfers from small barrages constructed across the river to fields and major transfers through lift irrigation from the reservoir. Also, illegal pumping of water from canals and supply to the fields through pipelines. The irrigated area under this source increased from 306 ha in 1965-66 to 26,794 ha in 2013-14. Tanks were important sources of irrigation before dam construction. Though their contribution has decreased from 648 ha in 1965-66 to 163 ha in 2013-14, they continue to play a significant role in irrigation supply in highland regions where the canal network is not present. From these results, it can be seen that as of 2013-14 the total irrigated area in the command under canal (41%) and lift schemes (11%) works out to 1,25,133 ha whereas the planned irrigation potential was 1,83,393 ha. The fact that even after 43 years of commissioning the project has not been able to meet the planned objective may be attributed to a variety of reasons such as violation of planned cropping pattern, flood irrigation practice, non-delivery of water to tail-enders, the poor performance of canal and associated structures and increasing conveyance losses. It is probably for these reasons that farmers have shifted to groundwater as a more reliable and readily available source of irrigation water supply in the command area. This has resulted in an increase in the irrigated area especially in areas not served by the canal system and also in tail-end regions of the canal network.

6.4.3 Spatiotemporal variation of Irrigated agriculture:

Figure 6.4 displays the taluk-wise spatiotemporal development of the irrigated area (in percentage) under different sources across the Malaprabha command area from 1965-66 to 2013-14. It is evident from Figure 6.4a that before the commissioning of the irrigation project during 1965-66, groundwater wells and tanks were the major sources of irrigation throughout the region. Ramadurga taluk to the north-west had the largest number of tanks in the past (Madar 1993) and the area under this irrigation source was 35% of the total irrigated area. During this period, Rona taluk was completely under groundwater irrigation mainly through open and dug wells. Saundatti with an irrigated area of 1,076 ha had supplies from groundwater, tanks, and other sources whereas Naragund taluka had the least irrigated area of 170 ha with groundwater supplies. Details for the Navalgund taluk were unavailable for this period.

Figure 6.4b represents clearly the advent of canal irrigation during 1975-76 to talukas close to the reservoir (Soundatti, Ramadurga, Navalgund, and Naragund,). On the other hand, Rona and Badami talukas are lacking canal water as the construction of canal structures was still in progress. It is also observed that the talukas that experienced a rapid increase in canal irrigation have naturally registered a decrease in the area under tank and well irrigation.

During 1985-86 (Figure 6.4c), further extension of canal irrigation took place and canal water supplies reached up to the Rona taluk. Also, the total area under lift irrigation and others (19%) were becoming significant at this stage which was the main source of irrigation at the tail end regions of command area such as Badami taluk (59%). Also, the reservoir water was supplied to the upstream command area in Saundatti taluk through lift irrigation. In the year 1993-94 canals and associated works were fully developed and supply of canal water to all the talukas of the command area was attained (Figure 6.4d). However, by this time a major shift was observed in the source of irrigation as a result of a change in cropping pattern (growing highly water-intensive crops instead of proposed dry crops), flood irrigation, illegal withdrawal of water from canals to fields, and also decrease in canal efficiency due to poor operation and maintenance (Biswas and Venkatachalam 2010). All these factors resulted in an inadequate supply of canal water to tail-end regions. Therefore, exploitation of groundwater sources for irrigation increased in the command area especially in Rona (77%) and Badami (36%) talukas. A decrease in total canal (61 to 54%) and lift irrigated (19 to16%) areas were accompanied by an increase in well-irrigated areas (14 to 27%) during this period.

The year 2003-04 is one of the deficit (drought) years in the river basin with a decreased annual rainfall of 369mm in the command area. The amount of total canal irrigated area decreased to 32% and consequently, groundwater irrigated area increased up to 46% in the command area (Figure 6.3). The decreased canal and significantly increased groundwater irrigated area is observed in all the talukas except Navalagunda (99%) and Naragunda (83%) during this period (Figure 6.4e).

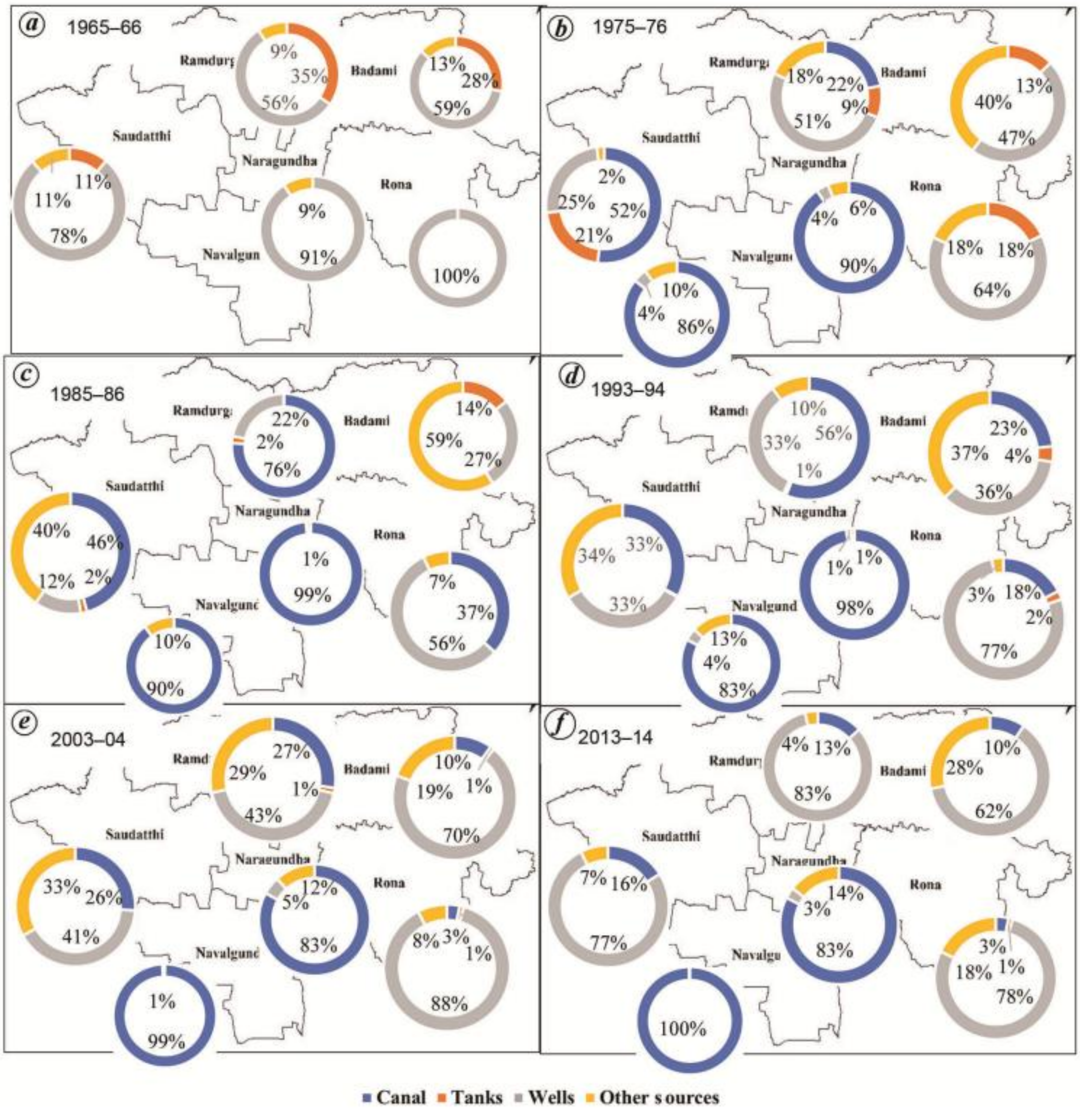


Figure 6.4: Spatiotemporal development of the source-wise irrigated area in the Malaprabha command area. ***(Source: Data compiled from Madar 1993, S.L. Chitragar 2018 and District at a glance reports of Bagalkot, Belgaum, Dharwad, and Gadag)***

During 2013-14 the command area received higher rainfall (603mm) and the total irrigated area increased to 2,40,039 ha (Figure 6.3). However, the contribution of the canal and lift irrigation together (1,25,133 ha) is still less than the proposed irrigation potential (1,83,393 ha.) of the project. On the other hand, groundwater becomes the dominant source of irrigation in all the talukas of the command area except Navalgunda and Naragunda where canal irrigation is significant (Figure 6.4f).

Overall, the efficiency of the Malaprabha irrigation project appears to have decreased in the last two decades considered in this analysis and only the talukas close to the reservoir seem to get the maximum benefit of the project. Talukas located further away are greatly dependent on groundwater and lift irrigation sources for crop cultivation.

6.4.4 Cropping Pattern:

The changes in the area under major crop classes cultivated in the Malaprabha command area are depicted in Figure 6.5. The cropping intensity (percent ratio of gross cropped area to net cropped area) in the region increased from 125% to 165% in the past five decades, indicating an increase in the number of crops grown from the same field. Cereals share the maximum amount (>40%) of cropped area among all other classes followed by pulses (25%). The production of pulses has increased in the last two decades of this analysis. Though not significant, the crop area under other food crops which include mainly vegetables has increased continuously from 1 to 8% since 1965-66.

The cash crops which mainly consist of cotton and sugarcane seem to decrease till 2003-04 but increased in the year 2013-14. As of 2013-14 the percentage area under various crops were as follows: cereals - 40%, pulses - 25%, cash crops - 14%, oilseeds - 13% and other crops - 8%. More than 15 types of crops are grown in the Malaprabha command area. Figure 6.6 represents the cultivated area of selected important crops under each major crop category. Although the overall increase in cropping area over the six decades is 28%, there exist huge deviations among the type of crops and their extent of growth in the region during the period of analysis. The major shifts observed are a decrease in area under cotton (40%) and an increase in the sugarcane area (286%) from 1965 to 2014, which is an annual crop consuming around 2500 mm of water. The area under paddy cultivation also increased up to 60% by the year 1993-94 and decreased thereafter. Also, in the oil-seeds category, a decrease in groundnut and increase in comparatively water-intensive sunflower crop was noted. Overall, the major deviations observed in the cropping pattern are a shift from traditional crops to high-yielding, water-intensive crops and an increase in commercial and cash crops in the place of proposed dry crops.

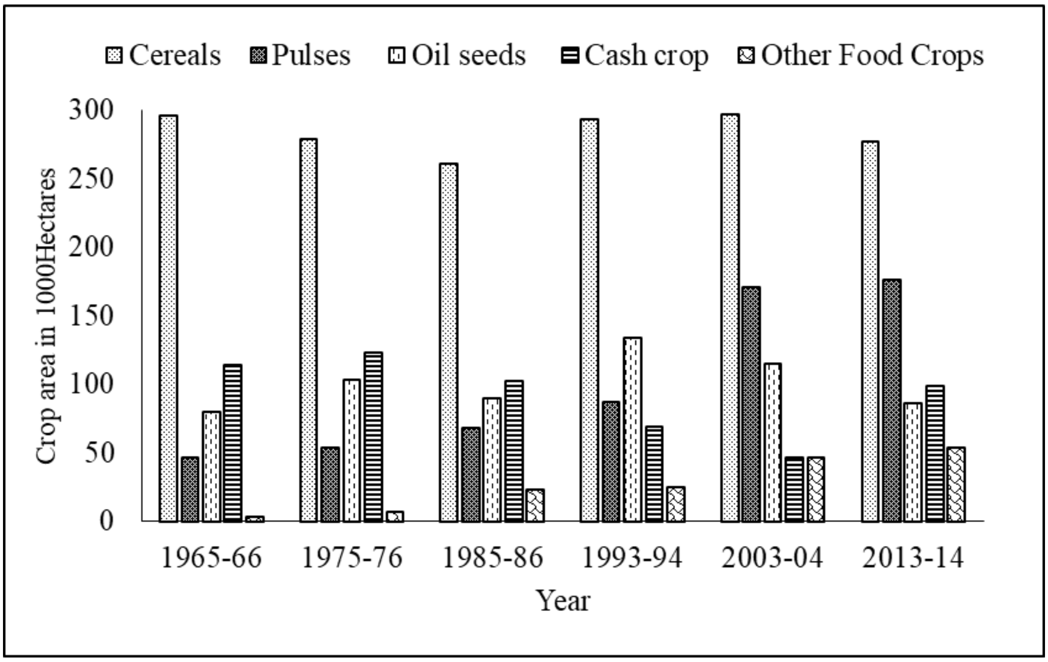


Figure 6.5: Changes in the area under major crop classes in the Malaprabha Command Area. ***(Source: Data compiled from Madar 1993, S.L. Chitragar 2018 and District at a glance reports of Bagalkot, Belgaum, Dharwad, and Gadag)***

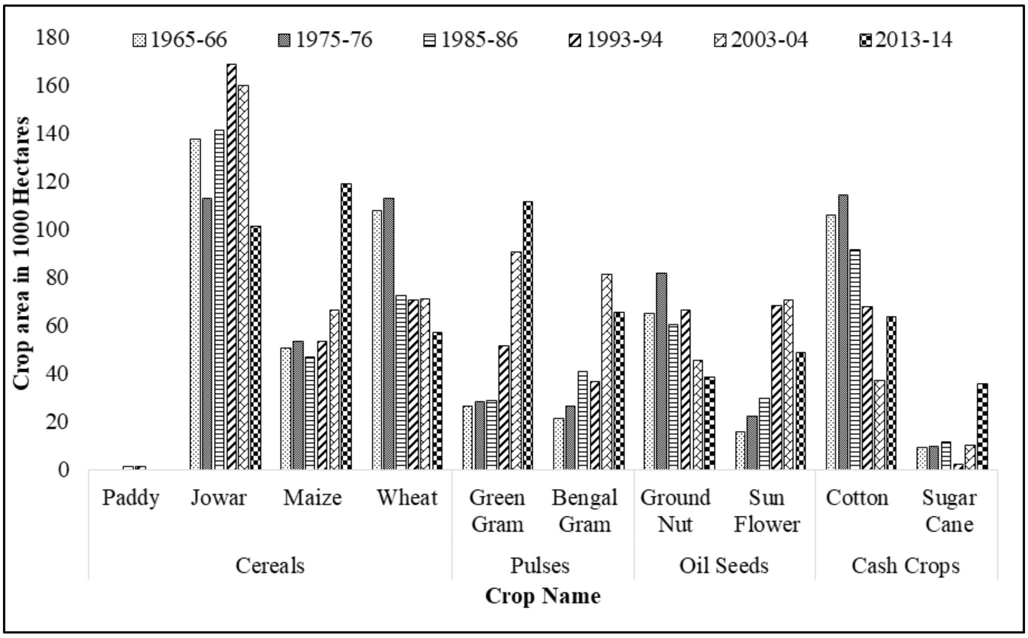


Figure 6.6: Cultivated area of major crops grown in the Malaprabha river command area. ***(Source: Data compiled from Madar 1993, S.L. Chitragar 2018 and District at a Glance report of Bagalkot, Belgaum, Dharwad, and Gadag)***

6.4.5 Historical Crop and Irrigation Water Requirements:

The CWR and IWR for the major crops grown in the study area were estimated using the CROPWAT 8.0 model for proposed and existing cropping-pattern for the historical period of analysis. The calculated basin average monthly ET_0 values using the Hargreaves method were incorporated into the model. Considering rainfall records for 6 rain gauges (Figure 6.1), Thiessen's average rainfall over the Malaprabha command area for the historical period was also given as input to the model to estimate P_{eff}. The cropping pattern shown in Table 6.3 and crop-coefficients shown in Table 6.4 were provided as inputs to CROPWAT.

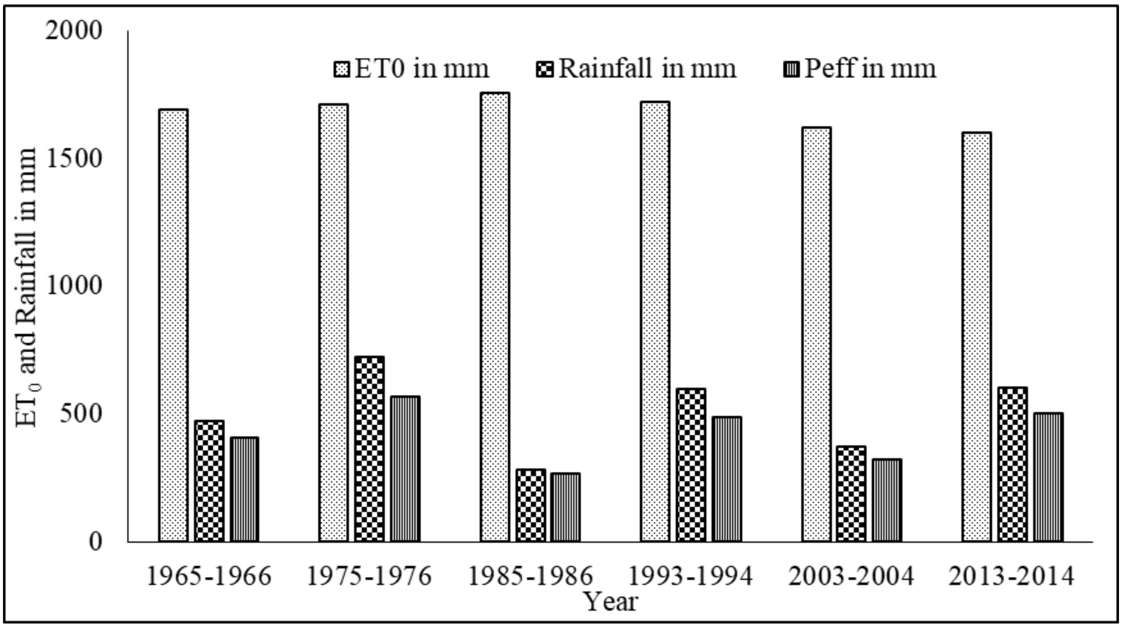


Figure 6.7: Reference evapotranspiration, Rainfall, and Effective rainfall over the Malaprabha command area.

Figure 6.7 represents the variation of annual ET_0, $P_{eff,}$ and rainfall over the command area for the past six decades. The average annual ET_0 in the command area is 1683 mm and the average P_{eff} was about 84% of the rainfall in the region with the maximum P_{eff} occurring for the year 1993-94 (93%) and minimum for the year 1975-76 (78%). Figures 6.8 and 6.9 represent the variations of estimated CWR and IWR for proposed and existing cropping-pattern throughout the analysis. The average CWR of the existing cropping pattern is around 170% higher than the proposed (Figure 6.8).

Also, the CWR of the proposed cropping pattern remained more or less constant with an average value of 1264 MCM and CWR for the existing cropping pattern has increased from 3,189 MCM to 4,024 MCM (26%) between the years 1965-66 and 2013-14.

The IWR for the proposed cropping pattern (Figure 6.9) is estimated considering 100% irrigation in Kharif season for the entire irrigable command as envisaged originally has never been practiced in the study area. However, IWR for existing cropping-pattern estimated only for the actual area irrigated during the respective year. Since the proposed cropping pattern is assumed to be implemented over the entire irrigable command area of 1,83,393ha every decade, it works out to be higher IWR in comparison to the IWR for the existing cropping pattern for the years 1975-76 and 1985-86. Further, for the later years, IWR for the existing cropping pattern is higher than the proposed, though the actual irrigated area is less than the proposed. This is due to the cultivation of more water-intensive crops in the command area. IWR for Existing cropping-pattern soon after commissioning of the project was about 138 MCM and increased to 824 MCM, 884MCM, and 1044 MCM in 1985-86, 1993-94, and 2003-04 respectively. It is interesting to note that the IWR for the recommended cropping pattern in the Malaprabha project proposal was 764.5 MCM (DPR 2008) although, canal releases are subjected to vary depending on storage available in the reservoir. However, during the year 2013-14, the existing IWR increased significantly to 2410 MCM due to the widespread adoption of more water-intensive crops.

Figure 6.9 also provides a comparison between IWR and canal releases for the period of analysis. During 1975-76 the release far exceeds the proposed and existing IWR, validating the fact that excess water has supplied in the initial stages of the Malaprabha project, and farmers who were provided with canal supplies for the first time over irrigated their fields using the flood-irrigation method. The situation improved during the subsequent decades with releases being somewhat close to the proposed IWR for 1993-94. During 2003-04 canal release was only 30.6 MCM, probably because it was a drought year with low storage levels in the reservoir.

Consequently, the area under canal irrigation reduced (Figure 6.3) in 2003-04 farmers turned to groundwater as an alternative source and the area under groundwater irrigation increased significantly. During 2013-14 canal releases returned to normal levels but fell far short (233%) of satisfying the IWR for the changed cropping pattern.

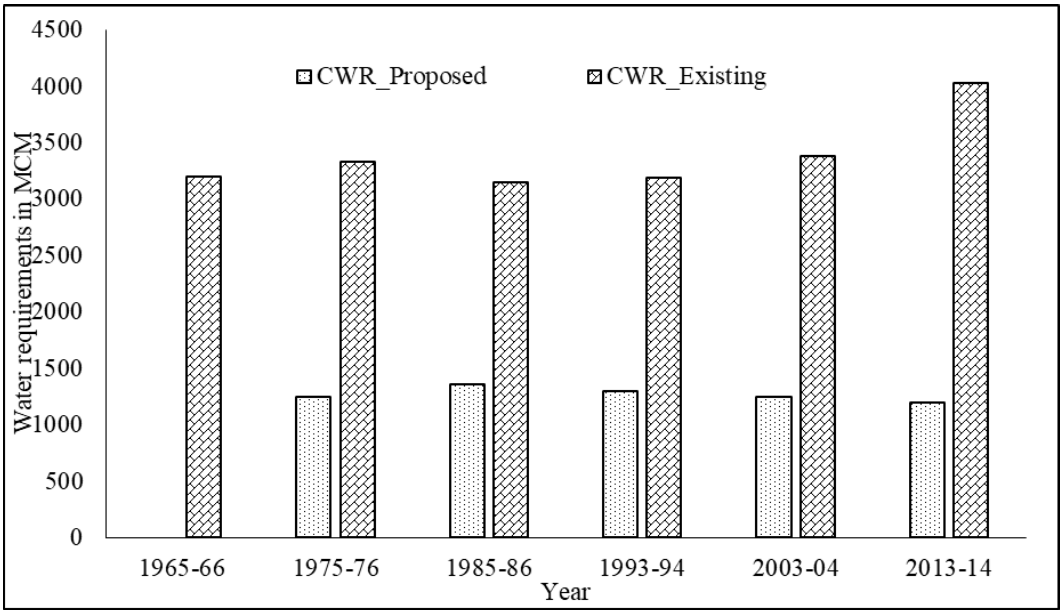


Figure 6.8: Crop water requirements for proposed and existing cropping pattern in the Malaprabha command area.

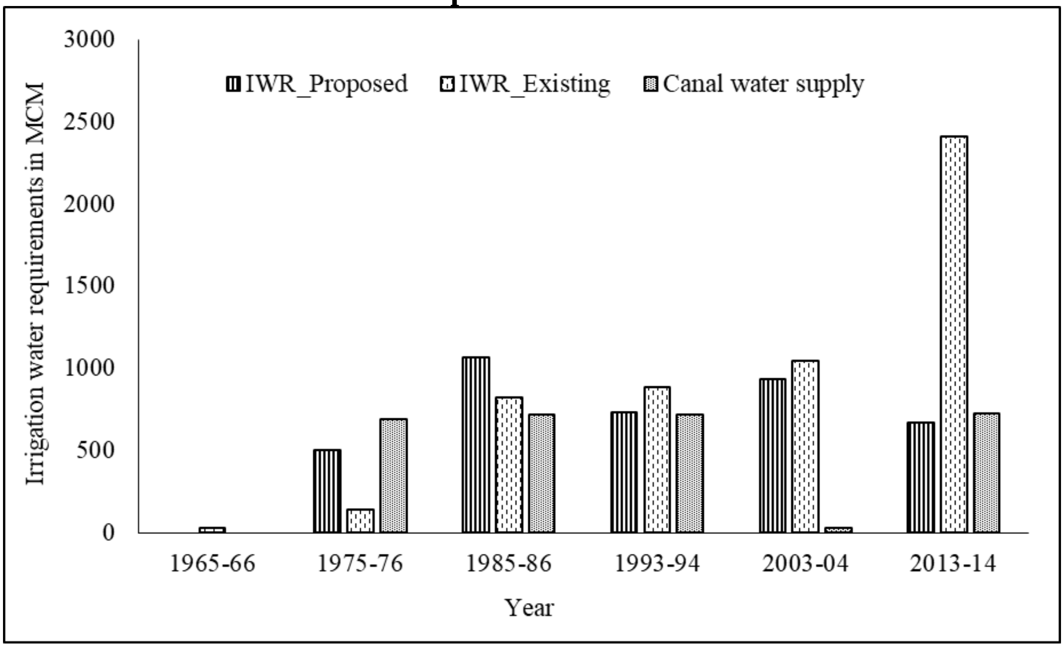


Figure 6.9: Irrigation water requirements for proposed and existing cropping-pattern and measured canal releases in the Malaprabha command area.

Overall, it appears that the Malaprabha project since 2003-04 has not been able to achieve the demands imposed by farmers on account of the significant divergence between the original objectives and the existing situation on the ground in terms of the cropping patterns. While deficient rainfall and reduced reservoir inflows may have contributed to this situation, the more important factors appear to be a drastic change in cropping patterns favoring cash crops and expansion of irrigated agriculture with groundwater as the main source of water. The results obtained in the present work conform to outcomes presented in the previous studies carried out for the same study area (Madar 1993, Reshmi et.al. 2008, Reshmidevi and Nagesh Kumar 2018, Chitragar 2018). However, since the present analysis is based on data procured from a variety of independent sources, results and conclusions may have been influenced by inherent errors in the data sets despite the best efforts made to eliminate them. Also, the assumption of a constant cropping pattern throughout the study period is a limitation of the study, but it is believed that this aspect may not have influenced the results as much as variations in other variables. Future studies may incorporate finer resolution data on temporal and spatial variabilities in cropping patterns.

6.5. CLOSURE:

The analysis of the historical growth of irrigation in the Malaprabha command area revealed that the commissioning of the irrigation project has a significant role in the development of irrigated agriculture in the region. From the spatiotemporal analysis of the growth of irrigated agriculture, it is evident that the contribution of canal supplies to irrigated agriculture was maximum until 1985-86 (61%) and decreased thereafter. On the other hand, the contribution of groundwater to irrigation increased subsequently since 1993-94. Also, the regions close to the reservoir appear to be fully benefitted by canal water supplies whereas regions located away from the reservoir seem to be benefitting from groundwater supplies. A shift from low water consuming crops to water-intensive crops is observed and the area under cash crops has increased significantly. Canal releases not conforming to estimated IWR and an increase in irrigation intensity (57%) was noticed in the study area at the end of 2013-14. Cropping-pattern violations, flood-irrigation, illegal water withdrawals, and poor maintenance of canal and associated structures are likely causing the current status. Overall, it appears from the performance analysis that the Malaprabha irrigation project has not been able to enforce the planned objectives and goals. Results of this study depict the real status of irrigation development in the Malaprabha command area highlighting the differences between project planning and farmer aspirations. The quantitative information provided by this study will be useful in solving water scarcity issues in the river basin through the development of effective management strategies to improve the efficiency of the project and promote sustainable development of natural resources.

CHAPTER 7

IDENTIFICATION OF MAJOR DRIVERS AFFECTING STREAMFLOW IN MALAPRABHA RIVER BASIN

7.1 GENERAL

The main focus of the present chapter is to understand the overall response of hydrological processes to large-scale irrigation practice in the Malaprabha river basin using a modeling approach. Before analyzing the impact of irrigation on hydrological processes over the study area, it is necessary to first identify the major drivers causing changes in stream flows, as it is one of the most significant and sensitive variables in basin hydrology which depicts the impact of natural and anthropogenic factors.

Earlier studies have suggested that climate and land-use changes are the major reasons for river flow changes in a basin (Mudbhatkal et al., 2017; Marhaento et al., 2017; Mekonnen et al., 2018). However, the introduction of large-scale irrigation structures and associated irrigation management activities in the basin will also play a crucial role in streamflow variations (Haddland et al., 2006; Tebakari et al., 2012; Huang et al., 2015). Thus, an attempt was made to understand the contributions of these drivers towards the variability of river flows in the Malaprabha river basin. The Soil and Water Assessment Tool (SWAT) hydrological model was used to simulate major hydrological processes in the study area using available hydrometeorological data and other data related to topography, LULC, and soils. After calibrating/validating the model for historical conditions, it was used to simulate changes in streamflow brought about by plausible future scenarios of climate change, LULC, and with and without reservoir conditions.

Accordingly, the main objective of the work was to 1) analyze LULC changes over the decades 1985, 1995, and 2005 2) examine the streamflow responses to combined and isolated effects of LULC, climate change, and presence and absence of Malaprabha reservoir 3) identify and evaluate the contribution of major drivers causing streamflow variation in the Malaprabha river basin using the SWAT hydrological model for the period 1983-2006.

This chapter includes a description of the SWAT hydrological model, input data used and the methodology implemented to analyze the combined as well as isolated effects of climate change, land-use changes, and presence of the Malaprabha reservoir on river flows. Results obtained are discussed and inferences are drawn.

7.2 DESCRIPTION OF SWAT MODEL

SWAT is a comprehensive, continuous-time, semi-distributed, physically-based hydrological model developed by USDA (United States Department of Agriculture)-ARS (Agricultural Research Service), designed to simulate hydrological processes, nutrient dynamics, and sediment transport at river basin or watershed scale (Arnold et al., 1998). The model can be applied using a daily, monthly, and annual time step in a distributed manner by delineating the catchment into sub-basins which are further discretized into Hydrologic Response Units (HRUs). The HRUs are unique interactions of land use, elevation, and soil types, and all model computations are performed at the level of individual HRUs. SWAT splits hydrological simulations of a watershed into two major phases: land phase and routing phase. The land phase of the hydrological cycle controls the amount of water, sediment, nutrient, and pesticide loadings to the main channel in each watershed. While the routing phase considers the movement of water, sediment, and agricultural chemicals through the channel network to the watershed outlet.

The hydrology component of the model requires inputs of rainfall, climate, LULC, soils, and elevation data. Simulation of hydrological processes for each HRU is based on the water balance equation:

$$SW_t = SW_O + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (7.1)$$

Where SW_t is the final soil water content in mm, SW_o is the initial water content on the day i in mm, i is a time in days for the simulation period t.R_{day}, Q_{surf}, E_a, W_{seep} and Q_{gw} are daily precipitations, surface runoff, actual-evapotranspiration, percolation, and return flow respectively.

7.2.1 Surface Runoff:

Surface runoff occurs whenever the rate of precipitation exceeds the rate of infiltration. The Surface runoff (Q_{surf}) for each HRU is calculated by using SCS-CN (USDA-SCS, 1972) method. The general form of the method is given by

$$Q_{surf} = \frac{P_e^2}{(P_e + S_e)} \tag{7.2}$$

Where P_e in mm, is the depth of effective precipitation (precipitation minus initial abstractions), S_e in mm, is the depth of effective available storage in the watershed when runoff begins and it's defined as

$$S_e = 25.4 * \left(\frac{1000}{CN} - 10\right) \tag{7.3}$$

Curve Number (CN) is a function of land use, soil permeability, and antecedent soil water conditions.

7.3 Study Area and Data Sources Used for SWAT Model

The area of the Malaprabha River basin considered for modeling is up to Cholachgudda (15.87^0N latitude and 75.72^0E longitude) streamflow gauging station, having a basin drainage area of 9867 km^2 (Figure 7.1). This is the only working gauging station on the downstream side of the Malaprabha dam having daily flow records from 1983 to 2006.

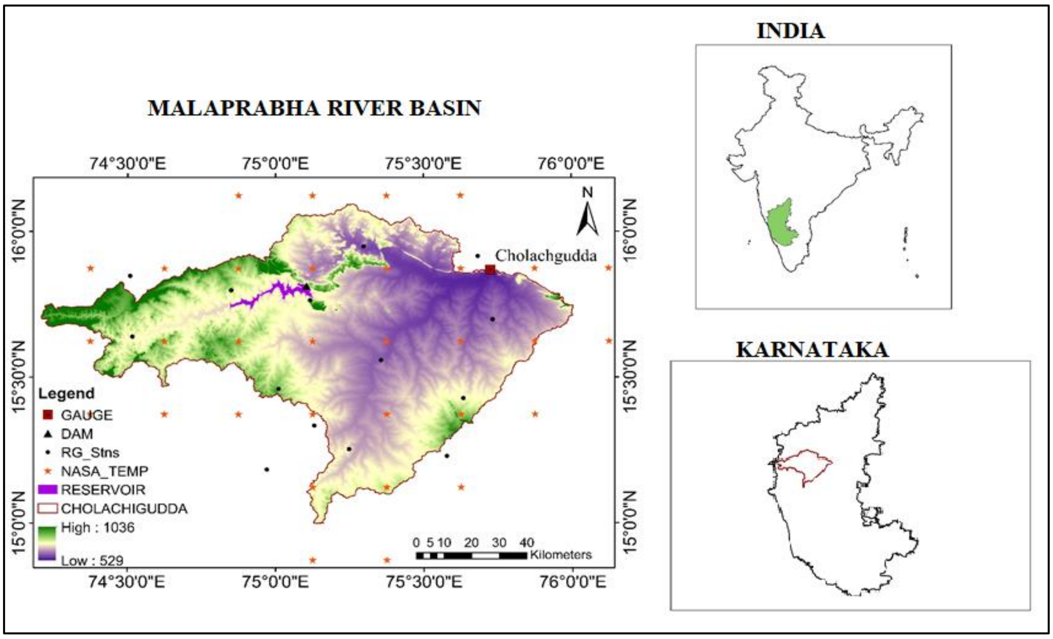


Figure 7.1 Location map of a portion of Malaprabha River basin considered for the hydrological modeling

Basic input data required for SWAT hydrological model includes topography, weather, rainfall, LULC, and soil data. Topographic data was obtained in the form of DEM (Digital Elevation Model) at 30 m resolution from SRTM (Shuttle Radar Topography Mission) and it was used to delineate the watersheds into multiple sub-watersheds. Topography-based parameters such as slope class and stream length were calculated from DEM. Soil map along with the associated physical properties database is obtained from the Food and Agricultural Organization of the United Nations, FAO (Figure 7.2).

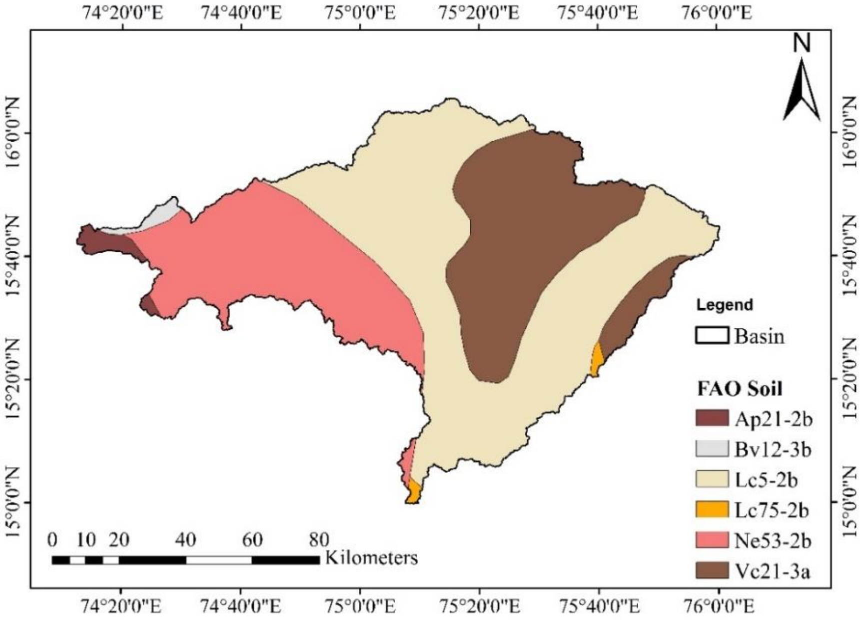


Figure 7.2 FAO Soil map of Malaprabha River basin

The decadal LULC maps for the years 1985, 1995, and 2005 at 100 m resolution from the Indian Space Research Organization (ISRO) (Roy et al., 2016) were used in this study (Figure 7.3) to analyze LULC changes. The images of the basin showed 12 different land use classes, dominated by cropland and followed by fallow and shrublands. Table 7.1 shows the proportions of various land use categories for the three years and also the percentage changes in these proportions between 1985-1995 and 1995-2005.

Daily rainfall data was collected from the Directorate of Economics and Statistics (DES) Department, Government of Karnataka for 14 rain gauge stations located in and around the watershed (Figure 7.1). Daily minimum and maximum air temperature values were obtained from NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) (Thrasher et al., 2013) at 0.25^0 resolution. Daily inflow records for the dam in the river basin were collected from the Malaprabha Dam division at Navilutheertha, Karnataka State Irrigation Department, and streamflow records at Cholachgudda gauging station were obtained from Central Water Commission (CWC), India.

Table 7.1 Land use Land cover change in the Malaprabha river basin

	Classification	Land use area in Watershed %			% Change		
		1985	1995	2005	1985 to 1995	1995 to 2005	1985 to 2005
1	Cropland	86.85	83.77	85.38	-3.08	1.61	-1.47
2	Fallow land	4.14	6.03	4.23	1.89	-1.80	0.09
3	Shrub-land	3.47	3.59	3.53	0.12	-0.06	0.06
4	Mixed Forest	1.36	1.32	1.38	-0.04	0.06	0.02
5	Water bodies	1.38	2.22	2.23	0.84	0.01	0.85
6	Evergreen Broad leaf Forest	0.50	0.64	0.62	0.14	-0.02	0.12
7	Built up land	0.29	0.51	0.82	0.22	0.31	0.53
8	Deciduous Broad leaf Forest	1.48	1.25	1.20	-0.23	-0.05	-0.28
9	Barren land	0.44	0.43	0.44	-0.01	0.01	0.00
10	Plantations	0.04	0.19	0.13	0.15	-0.06	0.09
11	Waste land	0.02	0.02	0.02	0.00	0.00	0.00
12	Grass land	0.03	0.03	0.03	0.00	0.00	0.00

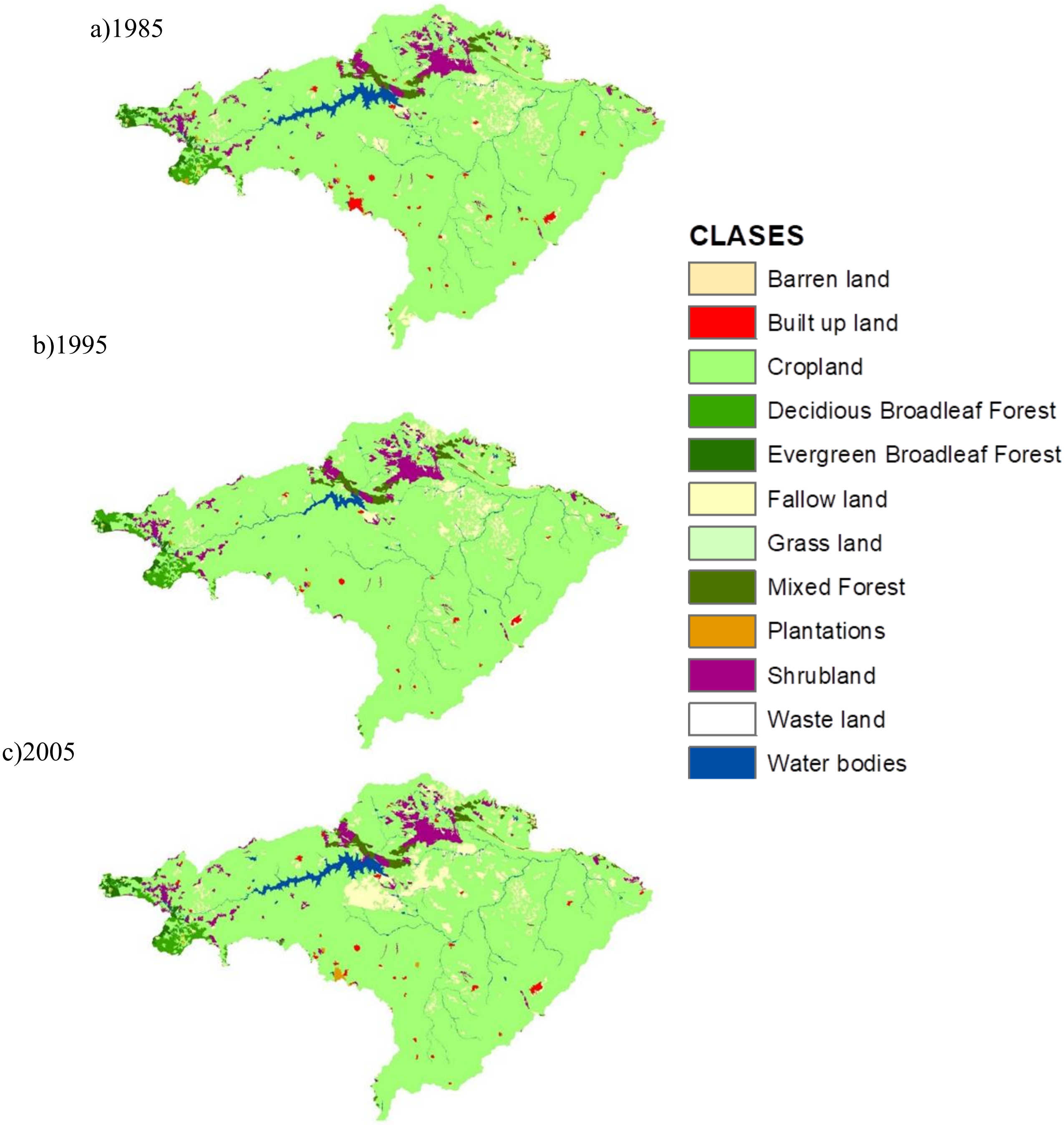


Figure 7.3 Land Use-Land cover maps of Malaprabha river basin for the years a) 1985 b)1995 and c) 2005. ***Source: Roy et al., 2016***

It is evident from Table 7.1 that, cropland shares the major portion (>83%) of the Malaprabha river basin, followed by fallow land (>4%) and shrub-land (>3%). During the three decades (1985-2005), no extensive change was observed in the land use patterns. However, decreasing cropland by 3.08% is noticed in 1995 and increased by 1.61% in 2005. Correspondingly an increase in fallow land was noticed by 1.89% and decrease by 1.80% during the respective decades. Built-up area increased from 0.29% in 1985 to 0.82% in 2005 and no changes were detected in wasteland and grassland areas.

7.4 METHODOLOGY

The overall methodology to analyze the combined and isolated effects of climate, LULC change, and effect of the reservoir on streamflow using SWAT hydrological model included the following steps: 1) input data preparation 2) sub-basin discretization 3) HRU definition 4) parameter sensitivity analysis 5) calibration, validation and performance evaluation of the model including uncertainty analysis. The SWAT model set-up and data preparation were done using the ArcSWAT2012 tool in the ArcGIS10.1 environment. During model set-up, the observed daily weather and monthly stream-flow data from the given period were divided into three different periods: the first to warm up the model, the second to calibrate it, and the third to validate it.

7.4.1 SWAT Simulation

Four different approaches were applied for assessing the effects of LULC changes, climate changes, and the presence of Malaprabha reservoir on stream flows.

1) The first approach (SIM_1) was to assess the response of streamflow to combined effects of the presence of reservoir, LULC, and climate change. The approach as given by Mahaento et al., (2017) and Mekonnen et al., (2018) was followed in the study. The total analysis period from 1983 to 2006, was divided into three periods of equal length representing three decades. The first period 1983-1990 (the 1980s), was regarded as the baseline period. The other periods 1991-1998 (the 1990s) and 1999-2006 (2000s) were regarded as altered periods 1 and 2 respectively. The LULC maps of 1985, 1995, and 2005 represented the land use patterns during the 1980s, 1990s, and 2000s respectively. For the analysis, the SWAT model was calibrated and validated for each respective period using the respective LULC map and weather data

(Table 7.2). The DEM and soil data sets remained unchanged. The differences between the simulation results of baseline and altered periods represent the combined effects of the reservoir, LULC, and climate change on streamflow.

2) The second approach (SIM_2) included simulations without considering the dam and its regulation operations. The three sets of calibrated and validated models for the respective decades were forced to simulate results without consideration of the dam while keeping the calibrated parameters intact. The difference between simulated results of the first and second approaches represents the effect of reservoir and dam regulation activities on streamflow variability.

3) The third approach (SIM_3) consists of simulations that assess the effects of LULC changes alone. The aim was to investigate whether LULC change was the main driver for changes in stream flows in the basin. The calibrated and validated SWAT model and its parameter settings in the baseline period (SIM_1) were forced by weather data from the baseline period while changing only the LULC maps from 1995 and 2005, keeping DEM and soil data constant. The calibrated SWAT model was run three times for the baseline period (the 1980s), only changing the LULC map for the years 1985, 1995, and 2005 and retaining the constant weather data set from the 1980s (Table 7.2). The difference in results of approaches one and three represents the contribution of LULC change on streamflow variability.

Table 7.2 Data sets of Baseline and altered periods for SWAT simulation

Sl. No	Combined Effect		Reservoir Effect		Isolated LULC change Effect		Isolated Climate change Effect		Remarks
	Climate data	LULC map	Climate data	LULC map	Climate data	LULC map	Climate data	LULC map	
1	1980s	1985	1980s	1985	1980s	1985	1980s	1985	Baseline period
2	1990s	1995	1990s	1995	1980s	1995	1990s	1985	Altered period 1
3	2000s	2005	2000s	2005	1980s	2005	2000s	1985	Altered period 2

4) The fourth approach (SIM_4) is similar to the third, but the simulations assessed the impact of climate change only. The calibrated model for the baseline period was run again three times, corresponding to 1980s, 1990s, and 2000s periods using the LULC map of the year 1985 but altering the three different periods of weather data sets for their respective periods.

The difference in results of approaches one and four represents the contribution of climate change on streamflow variability. Lastly, a comparative analysis of results obtained from all four approaches revealed the major driver causing variability in streamflow.

7.4.2 Sensitivity Analysis

Determining the most sensitive parameters is the first step in the model calibration and validation process, and is performed using the global sensitivity analysis option (Arnold et al., 2012) in the SWAT-CUP (Calibration and Uncertainty procedures) interface. This interface combines the Latin Hypercube (LH) sampling to determine the global sensitivity rank of the selected model parameters. Using this approach, sensitivity analysis was performed on 13 different model parameters (Table 7.3) by using default upper and lower boundary parameter values (Van Griensven et al., 2006). The parameters were tested for sensitivity using observed stream-flow data at Cholachgudda station for the period 1983-2006.

Table 7.3 Parameters and their ranges considered in the Sensitivity Analysis

Name	Min	Max	Definition	Process
Alpha_Bf	0	1	Baseflow alpha factor (day)	Gw
Alpha_Bnk	0	1	Baseflow alpha factor for bank storage (day)	Channel
Ch_K2	0	150	Effective hydraulic conductivity in main channel alluvium(mm/h)	Channel
Ch_N2	-20	20	The Manning coefficient for channel*	Channel

CN2	-20	20	SCS runoff curve number for moisture condition II*	Runoff
Epco	-20	20	Plant evaporation compensation factor*	Evap
Esco	0	1	Soil evaporation compensation factor	Evap
Gw_delay	0	100	Groundwater delay	Gw
Gw_revap	0.02	0.2	Groundwater revap coefficient	Gw
Gwqmn	0	1000	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	Gw
Revapmn	0	500	Threshold depth of water in the shallow aquifer for revamp to occur (mm)	Gw
Sol_Awc	-20	20	Available water capacity (mm/mm) *	Soil
Sol_K	-20	20	Soil conductivity (mm/h) *	Soil

Relative percentage change

7.4.3 Model Calibration, Validation, and Performance Evaluation

Model calibration entails the modification of parameter values and the subsequent comparison of simulated streamflow with observed data until the defined objective function is minimized. In this study, automatic calibration was carried out using the datasets of observed monthly stream-flow at Cholachgudda gauging station from 1983 to 2006. To calibrate the SWAT model, the auto-calibration tool SWAT-CUP was used with SUFI-2 mode. In the present work, the historical data from 1983 to 2006 was divided into three-time steps representing three decades the 1980s, 1990s, and 2000s to capture the presence of reservoir, LULC, and climate change effect. The details of the calibration and validation periods of each time step are presented in Table 7.4.

Table 7.4 Calibration and Validation periods of three decades 1980s, 1990s and 2000s

	Decade	LULC	Warm-up period	Calibration	Validation
Baseline period	1980s	1985	1980-1982	1983-1988	1989-1990
Altered period1	1990s	1995	1988-1990	1991-1996	1997-1998
Altered period2	2000s	2005	1996-1998	1999-2004	2005-2006

To evaluate the performance of the model across the simulation period, four model performance statistics were used 1) Coefficient of determination (R^2) 2) Nash-Sutcliffe Efficiency (E_{NS}) (Nash and Sutcliffe, 1970) 3) Percent bias (PBIAS) (Yapo et al., 1996) and 4) Ratio of root mean square error (RMSE) to the standard deviation (RSR).

The R^2 describes the proportion of the variance in measured data explained by the model (Equation 7.4). The E_{NS} value measures how well the simulated values coincide with the observed values (Equation 7.5). PBIAS shows how much the simulated data is larger or smaller than their observed values (Equation 7.6). RSR- the RMSE values can be used to compare the performance of a given model with other predictive models. RSR is the ratio of RMSE and the standard deviation of measured data (Equation 7.7).

$$R^2 = \frac{[\sum_{i=1}^{n}(Q_{O,i}-\overline{Q_O})(Q_{S,j}-\overline{Q_S})]^2}{\sum_{i=1}^{n}(Q_{O,j}-\overline{Q_O})^2 \sum_{i=1}^{n}(Q_{S,i}-\overline{Q_S})^2} \quad (7.4)$$

$$E_{NS} = 1 - \left[\frac{\sum_{i=1}^{n}(Q_O-Q_S)_i^2}{\sum_{i=1}^{n}(Q_{O,i}-\overline{Q}_O)^2}\right] \quad (7.5)$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(Q_i^{obs}-Q_i^{sim})*100}{\sum_{i=1}^{n}(Q_i^{obs})}\right] \quad (7.6)$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{sim})^2}}{\sqrt{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{mean})^2}} \qquad (7.7)$$

In the above equations, Q_O is observed discharge (m^3/s), Q_S is simulated discharge (m^3/s), $\overline{Q_O}$ is the average observed discharge (m^3/s) and $\overline{Q_S}$ is the average simulated discharge (m^3/s).

7.4.4 Uncertainty Analysis

Hydrological modeling invariably leads to considerable uncertainty in the model predictions due to a number of sources of error. Thus, it is important for a modeling study to quantify such uncertainties in predictions and provide the user with information regarding the confidence with which model results may be used.

In the present work uncertainty analysis of the SWAT model is carried out using the Sequential Uncertainty Fitting (SUFI-2) technique (Abbaspour, 2008) integrated with the SWAT-CUP tool. SUFI-2 accounts for all sources of uncertainties through parameter uncertainty in the hydrological modeling. The degree to which all uncertainties are accounted for is quantified by measuring the P-factor, which is the percentage of observed data bracketed by the 95% prediction uncertainty (95PPU) (Abbaspour, 2007). Another measure quantifying the strength of uncertainty analysis is the R-factor, which is the average thickness of the 95PPU band divided by the standered deviation of the measured data. The efficiency of the calibration uncertainty is evaluated based on the closeness of the P-factor to 100% and R-factor to 1 (Kumar Raju, 2016).

7.5 RESULTS AND DISCUSSION

Table 7.5 presents the long-term trend analysis results for rainfall and temperature for the Malaprabha river basin and also streamflow at the Cholachgudda gauging station. The methodologies for trend analysis were explained in Chapter 5. However, for the sake of completeness, the results of trend analysis for the modeling period (1983-2006) are presented in this section. The annual negative trend was observed for rainfall in the river basin. However, no significant trends were observed for rainfall in the basin at annual and seasonal time scales. On the other hand, average temperature shows a significant increasing trend at annual as well as seasonal scales. Annual streamflow at Cholachgudda gauging station showed a negative trend though not significant. However, a significant negative trend was noticed for pre-monsoon streamflow at a 90% significance level.

Table 7.5 MK test Z statistic values for hydroclimatic variables at a 90% significance level over the Malaprabha river basin

	Rainfall	Average Temperature	Streamflow
Annual	-0.91	**5.40**	-0.63
Pre-Monsoon	-0.61	**4.31**	**-1.64**
Monsoon	-0.72	**4.57**	-0.69
Post-Monsoon	-0.30	**2.92**	0.74
Winter	0.70	**4.04**	No Trend

**Bold letters indicate significant trends*

7.5.1 Sensitivity Analysis

The SWAT model's most sensitive parameters for simulating streamflow for three model set-ups (1985, 1995, and 2005) were identified using the global sensitivity analysis method provided in SWAT-CUP (Figure 7.4). The figure represents sensitivity ranks of the 13 hydrological parameters (Table 7.3), characterized based on their relative magnitude of response (Van Griensven et al., 2006). For the analysis, parameters with_rank 1 were classified as 'Very important, those with ranks between 2-6 as 'important', parameters with ranks between 7-11 as 'slightly important and those with rank greater than 12 as 'unimportant.

Accordingly, among the 13 model parameters selected (Table 7.3), it can be observed that the parameter representing the thresh-hold depth of water in the shallow aquifer required for return flow to occur (Gwqmn) was very important (rank 1) for decades 1990s and 2000s. Whereas curve number (CN_2) was observed to be very important (rank 1) for the 1980s. The curve number fell under the important category (rank 2) for the 1990s and 2000s. The results indicate the significance of base flow contribution to runoff.

Available water capacity (Sol_Awc) and groundwater revamp coefficient (Gw_Revap) were shown to be important parameters (rank 3 to 5). The four parameters namely, soil compensation factor (Esco), plant evaporation compensation factor (Epco), Soil conductivity (Sol_K), and Baseflow alpha-factor (Alpha_Bf) showed to be slightly important with the remaining parameters being unimportant.

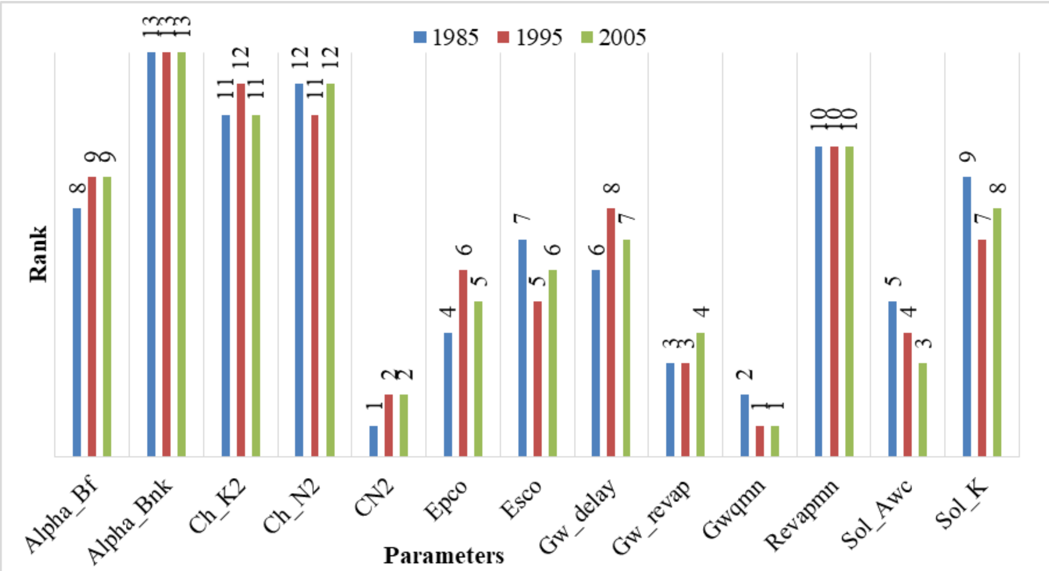


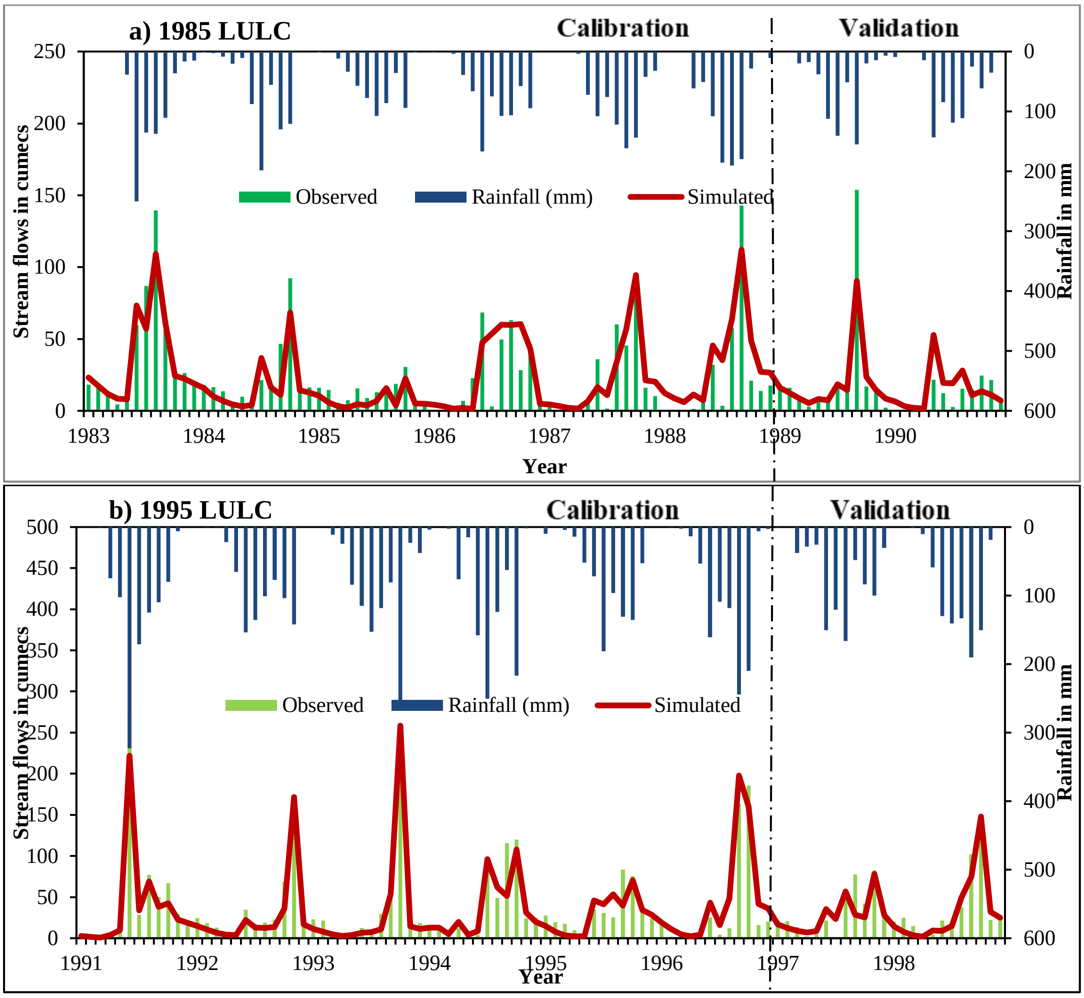
Figure 7.4 Sensitivity ranks for hydrological parameters of the SWAT model for the periods 1980s, 1990s, and 2000s

7.5.2 Combined Effect on stream flows (SIM_1)

Table 7.6 represents the SWAT model's calibration and the validation results of monthly streamflow for the three decades. As per Santhi et al., (2001) and Moriasi et al., (2007), the acceptable ranges for model performance statistics are R^2 >0.75, NSE >0.7, P-BIAS (±15%), and RSR < 0.7. Also, the uncertainty in the model simulations has to be minimum and indicated by parameters P >0.65 and R closer to 1.

From table 7.6 it is found that during the calibration period the value of R^2 is 0.76, 0.88, and 0.76 for the decades 1980s (LULC-1985), 1990s (LULC-1995), and 2000

(LULC-2005) and R^2 value for the validation period for the same decades is 0.78, 0.82 and 0.89 respectively. Likewise, NSE values range between 0.7 to 0.87 during calibration and 0.72 to 0.88 during validation. P-BIAS varied from -4.9 to 4.1 during calibration and -0.2 to 10.8 during validation. While RSR values range from 0.35 to 0.52 for the calibration period and 0.34 to 0.44 for validation periods for the three decades. The uncertainty parameters R-factor ranges from 0.85 to 1.46 and P-factor ranges from 0.65 to 0.83, indicating SWAT model able to predict about 65 to 85% of observed monthly stream-flows.



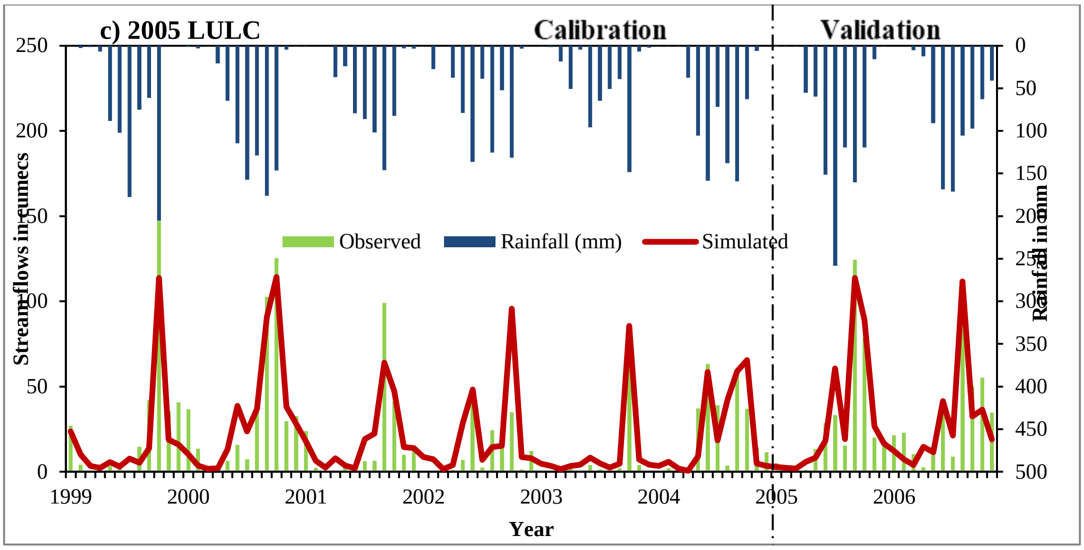


Figure 7.5 SWAT simulations for calibration and validation period at monthly timescale for the decades a) 1980s b) 1990s and c) 2000s

Table 7.6 Performance statistics of SWAT simulations

LU/LC		**Period**	**R^2**	**NSE**	**P-BIAS**	**RSR**	**P factor**	**R-factor**	**Remark**
	Calibration	1983-1988	0.76	0.70	2.7	0.52	0.75	0.85	
1985	Validation	1989-1990	0.78	0.72	-0.2	0.41	0.75	1.20	**Base period**
	Calibration	1991-1996	0.88	0.87	4.1	0.35	0.75	0.92	
1995	Validation	1997-1998	0.82	0.81	10.8	0.44	0.83	1.54	**Altered period 1**
	Calibration	1999-2004	0.76	0.76	-4.9	0.49	0.65	0.96	
2005	Validation	2005-2006	0.89	0.88	4.2	0.34	0.70	1.46	**Altered period 2**

Figure 7.5 represents the hydrographs of observed and simulated average monthly stream flows at the Cholachgudda gauging station along with monthly rainfall over the three decades. The results revealed that the SWAT model simulates monthly

stream-flows reasonably well across calibration and validation during three decades. The model-derived stream-flows for high flows events are well captured for the three decades, except for the years 1983, 1984, 1988, and 1989 (figure 7.5a) and 1999 and 2001 (Figure 7.5c) where the model underestimated the high flows. Similarly, the model simulates well the low-flows for the entire simulation period except for the years 1988, 2003, and 2004, where it overestimated the low-flows.

The monthly stream-flow hydrographs of simulated flow match well with the observed flow (Figure 7.5). The annual average rainfall for the three decades over the basin is assessed to be 669mm, 864mm, and 707mm during 1980s, 1990s, and 2000 respectively. Consequently, from the simulation results, it was found that simulated mean annual streamflow increased by 56% between 1980s and 1990s, while the observed mean annual streamflow increased by 60% for the same period. Similarly, the simulated mean annual stream flows decreased by 38% between the 1990s and 2000s, while the observed streamflows decreased by 34%. Also, the simulated average annual stream-flows were estimated to be 2151 m^3/sec, 3373 m^3/sec, and 2177 m^3/sec for the decades 1980, 1990, and 2000 respectively. These are found to be within the close range of the corresponding values for the observed data which are 2157 m^3/sec, 3470 m^3/sec, and 2136 m^3/sec respectively.

The simulation results obtained for the three independent, decadal time scale model setups (Baseline period, altered period_1, and altered period_2) reflect the combined effects of LULC, climate change, and reservoir operations on stream-flows during the simulation period. The results of these simulations become the base for analyzing the isolated effects of reservoir operation, LULC, and climate change on stream-flows.

7.5.3 Reservoir Effect on stream flows (SIM_2)

As described earlier in section 7.4.1, the isolated effect of the reservoir and its operation on stream-flows are simulated using three calibrated models (SIM_1) for the respective decades. However, in this phase the calibrated models were run without considering the reservoir and its operation for the same simulation period, keeping calibrated parameters obtained in SIM_1 intact. The difference in results between

SIM_1 and SIM_2 enables us to understand the effect of the reservoir and its operation on stream-flows.

Figures 7.6, 7.7, 7.8, and 7.9 represent the SWAT simulations without considering dam and reservoir operations for mean annual, monthly, mean monthly, and seasonal scales respectively for the three decades (1983 to 2006).

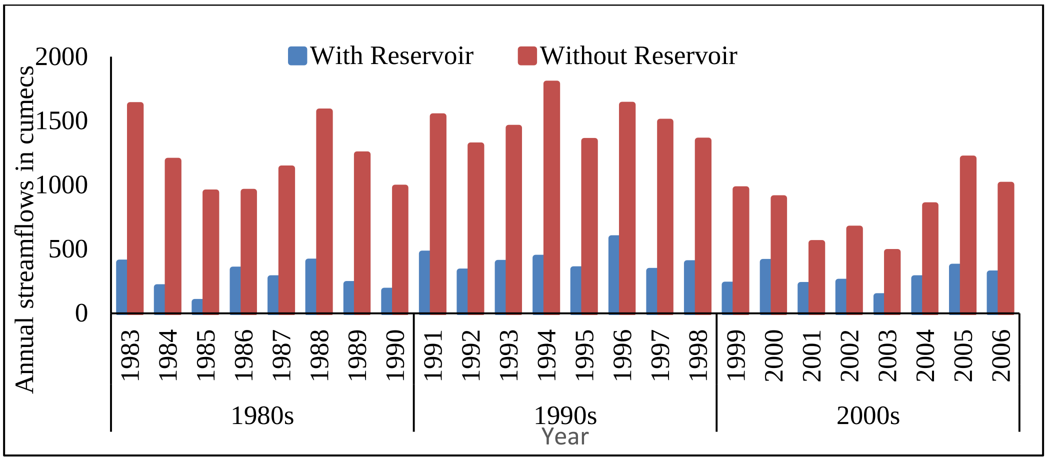


Figure 7.6 SWAT simulations of Annual streamflow for Reservoir effect

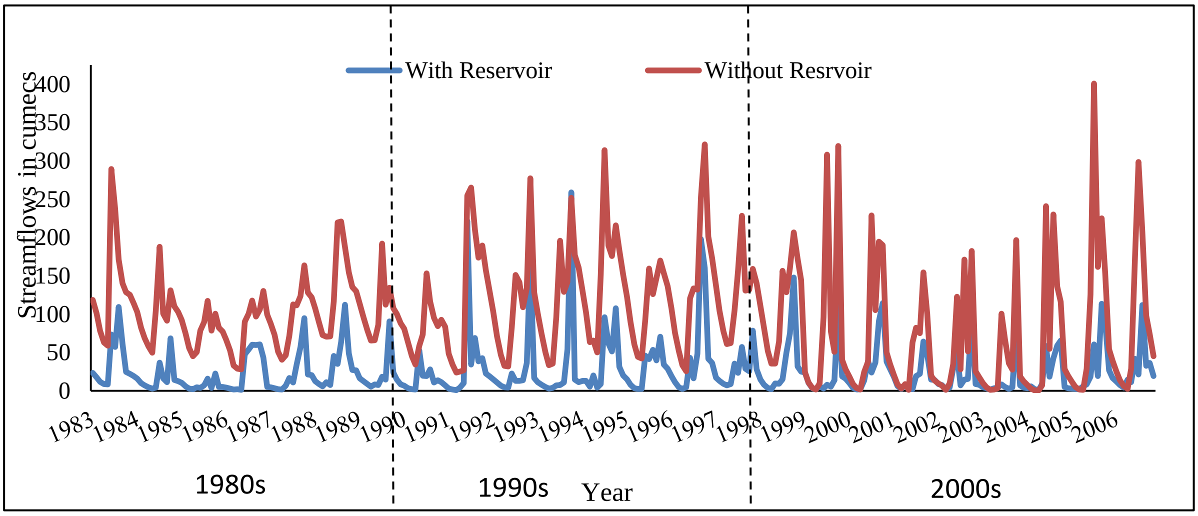


Figure 7.7 Monthly SWAT simulations for with and without reservoir operation condition for the period 1983 to 2006

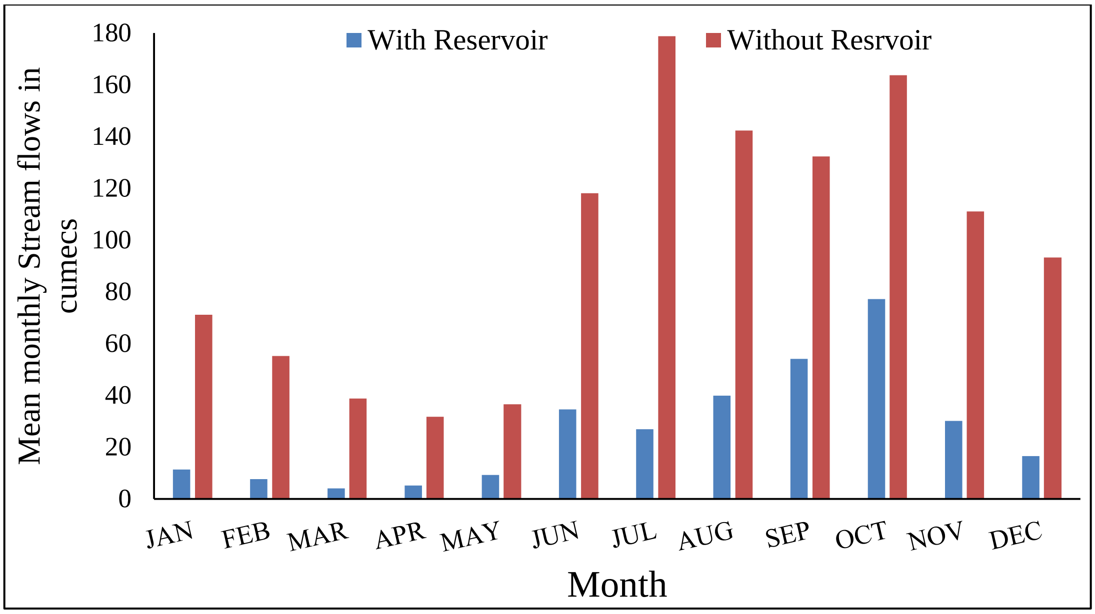


Figure 7.8 SWAT simulations of Mean monthly stream flows for Reservoir effect

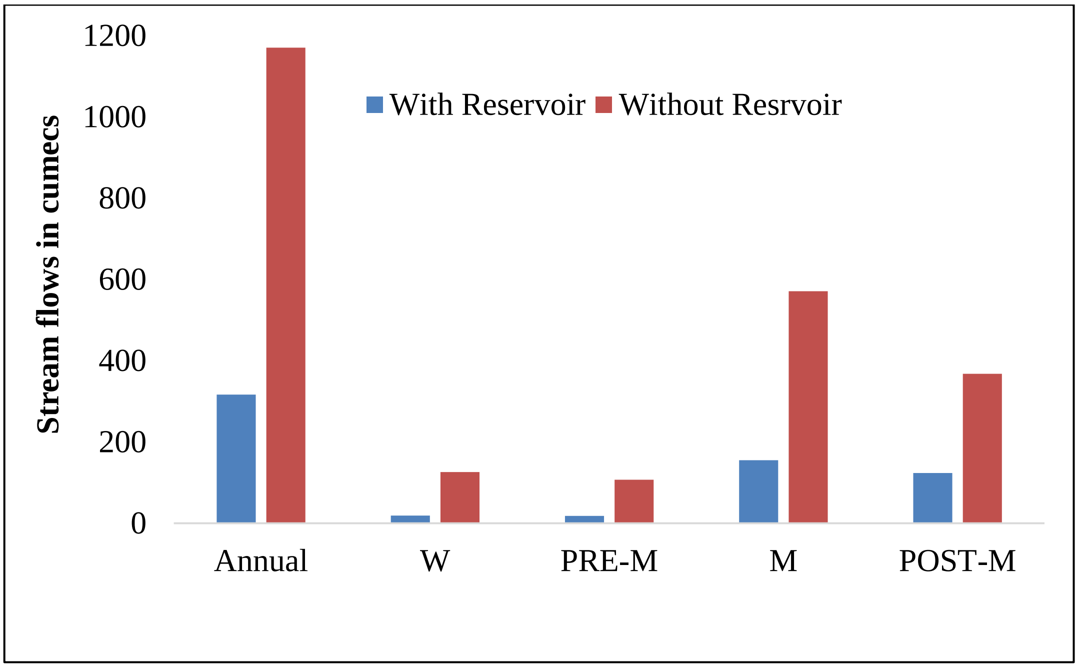


Figure 7.9 SWAT simulations of seasonal streamflow for Reservoir effect

SWAT simulations without considering dam and reservoir operations showed increasing annual stream flows to an extent of 200% in all three decades (Figure 7.6). The highest difference occurred in the year 1985 and the least difference was recorded for the year 2000. Figure 7.8 displays the mean monthly SWAT simulations for with and without reservoir conditions for the period 1983-2006. The difference between the two conditions increases greatly during monsoon and post-monsoon flows (Figure 7.9), as the only excess storage water will be released downstream during this period. Further, the difference is less during non-monsoon (winter and pre-monsoon) months, as the minimum reservoir outflows and return flows from irrigation fields will contribute to downstream flows (Figure 7.9). Overall, the results indicate that the reservoir storage and operational activities have significantly affected downstream river flows.

7.5.4 Effects of Isolated LULC change on stream flows (SIM_3)

In this phase, the isolated effect of decadal LULC change was analyzed. The calibrated and validated SWAT model and its parameter settings in the baseline period were forced by weather data from the baseline period (Table 7.4) 1983-1998 while changing only LULC maps from 1995 and 2005, keeping DEM and soil data constant.

Figures 7.10 and 7.11 depict the variations in annual and mean monthly stream flows for the altered periods 1 and 2 concerning the baseline period (Table 7.4). An increase of average annual stream flows by 102% and 72% for LULC 1995 and 2000 respectively were recorded. The increase in stream flows between the 1980s and 1990s is mainly the consequence of a decrease in cropland by 3% and an increase in fallow land by 1.88% between these decades. Further, the increase in stream flows between the 1980s and 2000s is also the result of a decrease in cropland by 1.47% and an increase in Built-up area by 0.5% during this period (Table 7.1).

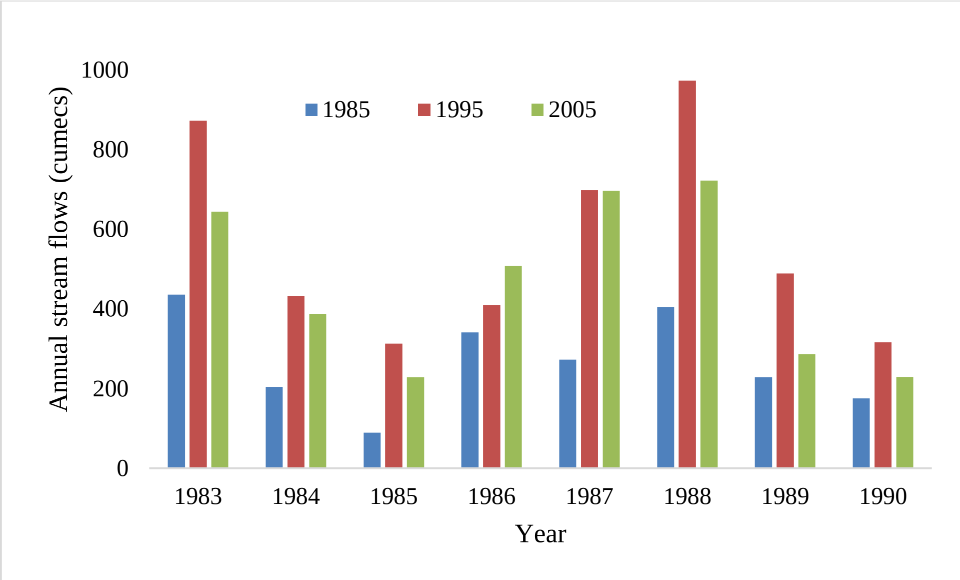


Figure 7.10 SWAT simulations of annual streamflow for isolated LULC change effect

The monthly differences showed an increase in monsoon flows by 77% between the 1980s and 2000s. However, the winter, pre-monsoon, and post-monsoon flows increased by 38%, 23%, and 83% respectively.

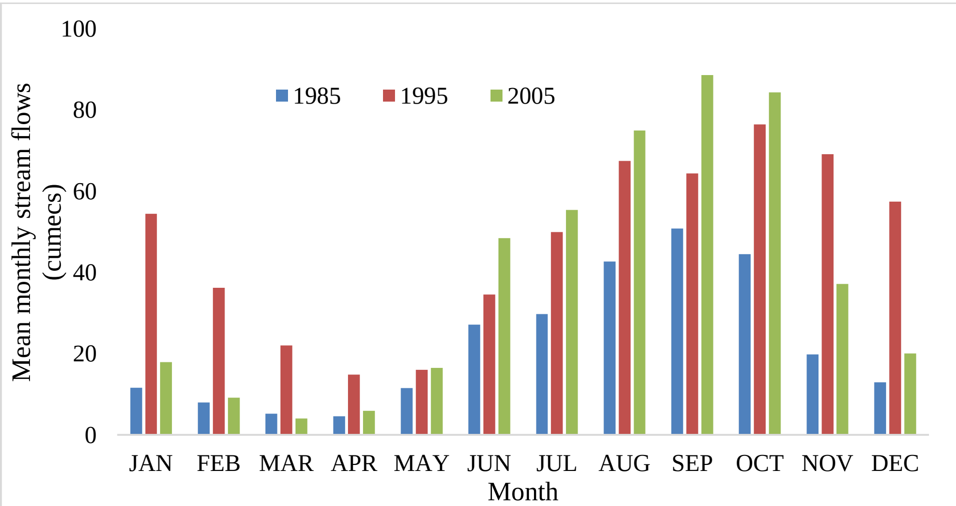


Figure 7.11 SWAT simulations of mean monthly streamflow for isolated LULC change effect

7.5.5 Effects of Isolated Climate change on stream flows (SIM_4)

In this phase, the isolated effect of decadal climate change was analyzed. The calibrated and validated SWAT model and its parameter settings in the baseline period were forced by land use data from the baseline period of 1985 while changing only climate data from the 1990s and 2000s (refer to Table 7.4). Figures 7.12 and 7.13 depict the variations in annual and mean monthly stream flows for the altered periods concerning the baseline_period.

An increase of average annual stream flows by 30% and decrease by 2.6% for the climates 1990s and 2000s respectively is observed concerning the 1980s. The increase in stream flows between the 1980s and 1990s is mainly due to the increase in average annual rainfall by 29%. However, an increase in annual rainfall by 5% was observed between the 1980s and 2000s. The occurrence of severe drought during 2002-2003 in the basin resulted in an overall decrease in stream flows during the 2000s. The monthly differences showed an increase in monsoon and post-monsoon flows by 44% and 3% for the decades 1990s and 2000s respectively concerning baseline period climate. However, the winter and pre-monsoon flow decreased by 2.8% and 16% respectively for the decades 1990s and 2000s concerning 1980s climate.

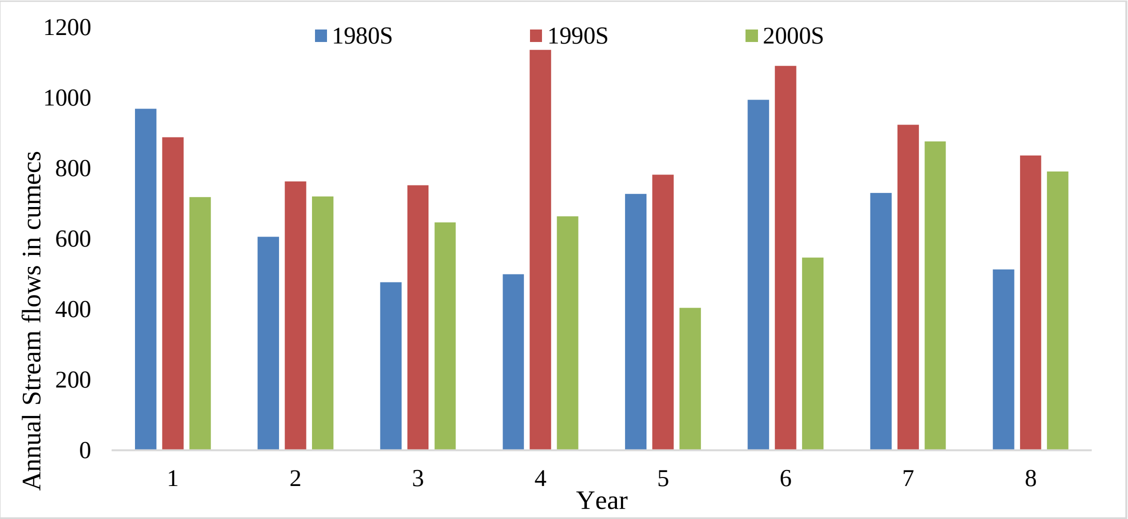


Figure 7.12 SWAT simulations of annual streamflow for isolated climate change effect

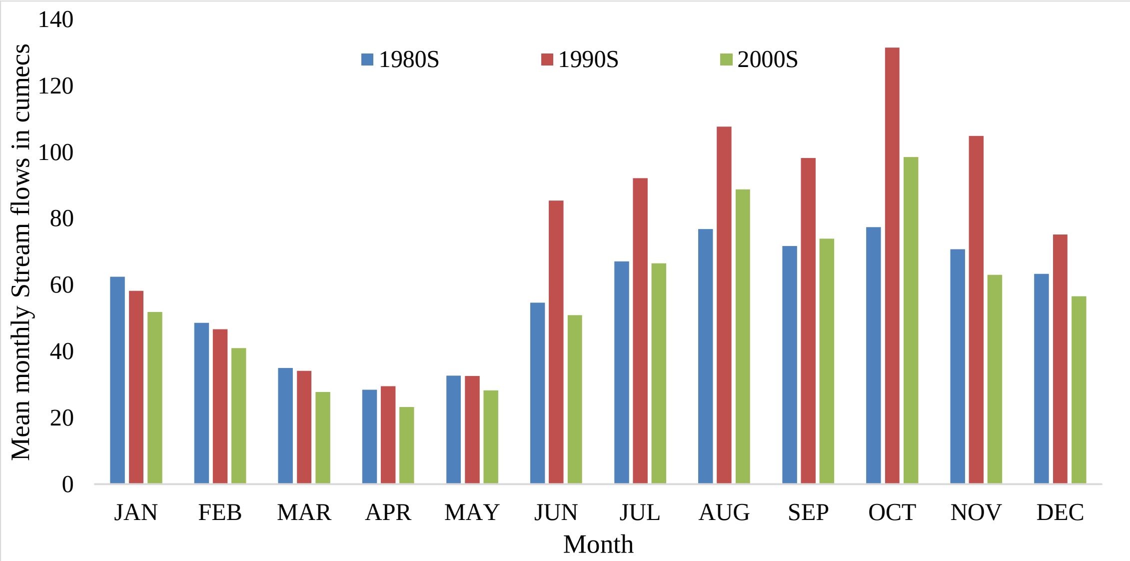


Figure 7.13 SWAT simulations of mean monthly streamflow for isolated climate change effect

7.6 CLOSURE

The present work was taken up to analyze decadal LULC change and recognize the major drivers causing variations in stream flows of the Malaprabha river basin. The combined and isolated effects of Malaprabha reservoir, LULC change, and climate change were analyzed for the decades 1980s, 1990s, and 2000s. The combined effect of changes in all three drivers caused an increase in annual streamflow in the basin by 53% between the 1980s and 1990s and a decrease in streamflow by 38% between the 1990s and 2000s. The combined effect caused an increase in annual stream flows in the basin by 53% between the 1980s and 1990s and a decrease in stream flows by 38% between the 1990s and 2000s. The presence of the Malaprabha reservoir was found to have the largest impact, reducing streamflow by more than 200%. Changes in LULC increased streamflow by 102% and 72% between the 1980s to 1990s and 1980s to 2000s respectively whereas climate changes increased streamflow by 30% and 2.6% during the same periods. This study reveals that in a tropical river basin the presence of an irrigation reservoir can significantly alter the temporal variability of streamflow which is further exacerbated by changes in LULC and climate.

CHAPTER 8
HYDROLOGICAL IMPACTS OF IRRIGATED AGRICULTURE

8.1 GENERAL

In this chapter impacts of irrigation practice on hydrological processes in the Malaprabha river basin are analyzed. As discussed in Chapter 2, several earlier studies have analyzed this effect at various spatial scales. The majority of the works have adopted the approach of studying this effect mostly through incorporating an irrigation module in a hydrological model (Haddland et al., 2006; Kienzle and Schmidt 2008, Sorooshian et al 2014; Tatsumi and Yamashiki, 2015, etc,). In the present study, SWAT hydrological model was used to analyze this effect. The model simulates the major elements and processes of hydrological cycle and it is sensitive to land cover changes and has the ability to incorporate elements of the infrastructure for irrigated agriculture likely to affect catchment hydrology.

Due to increasing unsustainable land-use practices, the Malaprabha basin is experiencing water scarcity and water availability in the lower catchment is constrained by land-use practices and water extraction in the upstream regions (Reshmi et al 2008). The main aim of the present study is to 1) highlight differences in the basin hydrological responses under the conditions with and without irrigated agriculture 2) develop and analyze the effects of different plausible future irrigation and land-use scenarios on stream-flows.

8.2 Materials and Methodology:

8.2.1 Model setup, calibration, sensitivity, and uncertainty analysis

Complete details of the working of the SWAT model and input data are previously described in Sections 7.2 and 7.3 of Chapter 7 respectively. The precipitation data is obtained from DES and temperature data from NASA (Figure 8.1). Soil map from FAO and DEM (SRTM) is used for the study. However, in order to satisfy the objective of this exercise, the LULC input had to focus primarily on the agricultural/crop land portion of the command area. Accordingly, the LULC image for the present objective was obtained from National Remote Sensing Centre (NRSC) for the year 2005-06 (Figure 8.2). This particular image was selected since it contains seasonal crop land classification which is essential for the identification of irrigated lands. The image contains total of 13 LULC classes, among which three are seasonal crops i.e., Kharif, Rabi, and annual (double/triple) crops. However, the type of crop and source of irrigation information is not available with the image. Thus, the major crop type grown in the respective season is assumed based on local practices (Table 8.1) and each LULC classes were assigned to a corresponding SWAT class.

Table 8.1 major seasonal crops considered for the study

Crop season	**Crop type**	**Source of Irrigation for command area**
Kharif	Corn	Reservoir
Rabi	Wheat	Reservoir
Annual	Sugarcane	Groundwater

Also, irrigation is assumed to be provided only for irrigable command area of Malaprabha reservoir and the rest of the river basin is assume to be under rained condition. Thus, out of 63 sub-basins formed for the river basin, 32 sub-basins were considered under irrigation in the study, and the rest under rained conditions (Figure 8.3). Crop management practices like, beginning and end of the cropping period, irrigation application etc., were manually defined for each HRU under irrigable command area. Information regarding crop characteristics was obtained from Allen et al. (1998) and Doorenbos and Pruitt (1997), planting dates for Kharif and rabi seasons were selected as June 15^{th} and October 15^{th} respectively for the selected crops. Irrigation water for the command area is supplied from the reservoir. Groundwater source is provided from the deep aquifer as discussed in Chapter 6 and also, from Reshmidevi and Nageshkumar (2014), deeper confined aquifer system is the major source for ground water withdrawal for irrigation in the study area. The deeper confined aquifer system for respective sub-basins was selected as a groundwater source. Irrigation was assumed to be provided when the plant water stress reached the threshold value of 0.9 and assuming flood irrigation method, the average irrigation efficiency of 0.5 was assumed (Narayanamrthy, 2006; Reshmidevi and Nageshkumar 2014).

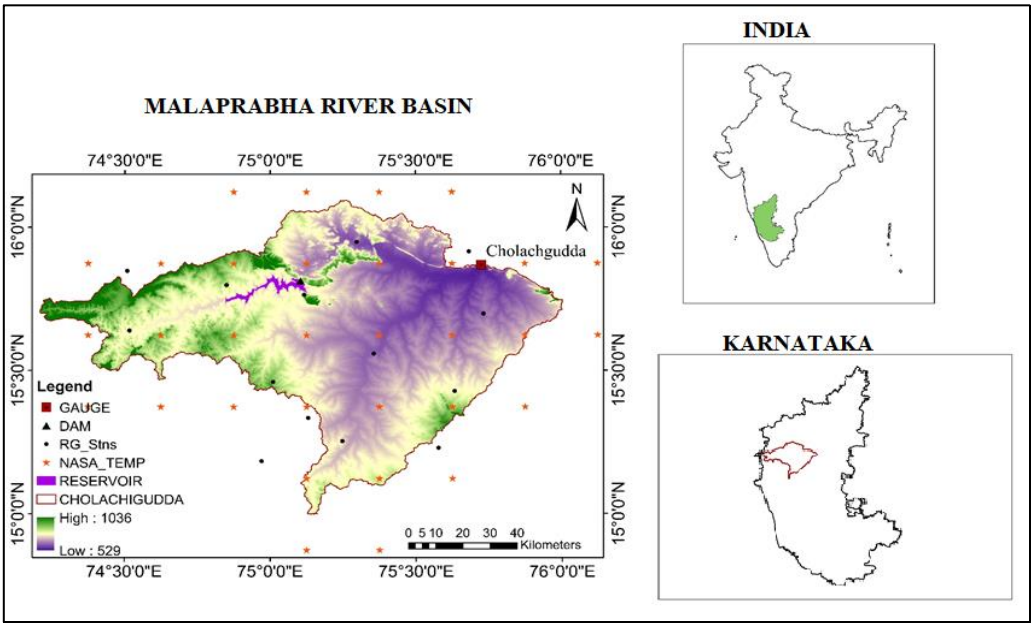


Figure 8.1: Malaprabha River basin considered for the hydrological modeling

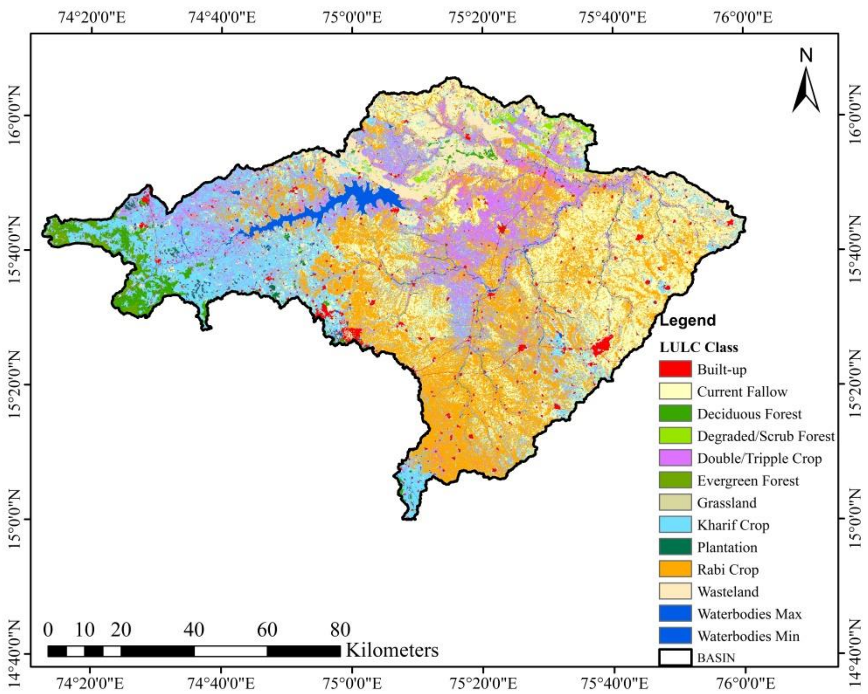


Figure 8.2: LULC image from NRSC considered for the present study

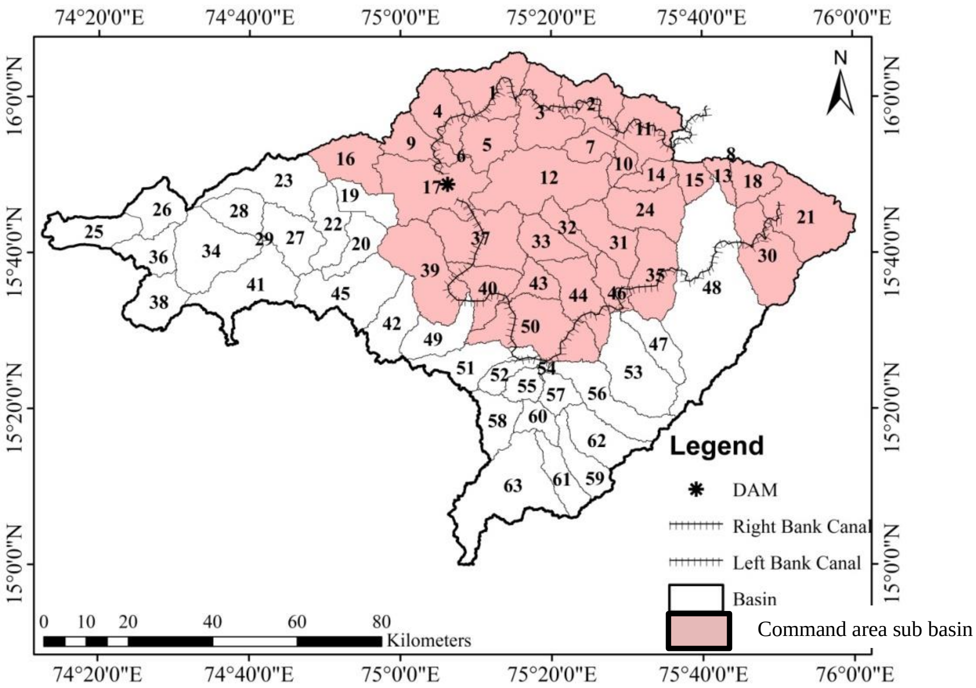


Figure 8.3: Sub basins under Irrigable command area of the Malaprabha river basin

From the ArcSWAT interface, the modified Curve Number method (USDA-SCS, 1972) and the Hargreaves methods (Hargreaves and Samani, 1985) were selected for estimation of the surface runoff and the potential ET respectively. The model simulations were carried out for the period 1992 to 2005 (14 years) for which observed monthly stream-flow data was available at the Cholachgudda gauging station. The monthly stream-flow data for the 10 years (1992-2001) was used for calibration and the remaining 4 years (2002-2005) was used for model validation. In the SWAT model, the hydrologic processes are calibrated only concerning the flow at the sub-basin outlets. Based on the model efficiency to simulate the flow, the other components are assumed to be reasonably well simulated in the model.

Model calibration, sensitivity, and uncertainty analysis were performed using the SWAT-CUP interface. The sensitivity analysis for the parameters selected (Table 8.2) for the present study was performed using the global sensitivity analysis option (Arnold et al., 2012) in the SWAT-CUP (Calibration and Uncertainty procedures) interface which combines Latin Hypercube (LH) sampling to determine the global sensitivity rank of the selected model parameters. The parameters were tested for sensitivity using observed stream-flow data at Cholachgudda station for the period 1997-2006. In the present work uncertainty analysis of SWAT model is carried out using Sequential Uncertainty Fitting (SUFI-2) technique (Abbaspour, 2008) integrated with SWAT-CUP tool. The degree to which all uncertainties are accounted for is quantified by measuring P-factor and R-factor. (Refer sections 7.4.2, 7.4.3, and 7.4.4). To evaluate the performance of the model across the simulation period four model performance statistics were used 1) Coefficient of determination (R^2) (Eq. 7.4) 2) Nash-Sutcliffe Efficiency (E_{NS}) (Nash and Sutcliffe, 1970) (Eq. 7.5) 3) Percent bias (PBIAS) (Eq. 7.6) and 4) Ratio of root mean square error (RMSE) to the standard deviation (RSR) (Eq. 7.7)

8.2.2 Scenario analysis

The three plausible future scenarios studied here for the impact analysis of irrigated agriculture are 1) existing irrigation scenario 2) no irrigation scenario 3) proposed cropping pattern irrigation scenario.

Existing irrigation scenario – the model is calibrated for the existing LULC (NRSC image 2005-06) and current irrigation scenario. The sub-basins under the irrigable command area of the Malaprabha project were only subjected to irrigation in the present study. The total analysis period from 1992 to 2005, was divided into calibration (1992-2001) and validation (2002-2005) period. The results show the stream flow under existing conditions in the river basin.

Base scenario (No irrigation scenario) - the calibrated model parameters are used to develop further scenarios. The base scenario is developed by using the existing LULC map but assuming rain-fed cultivation in all agricultural areas. However, the reservoir storage condition is included in this condition, to highlight the impact of irrigation practice alone. The effect of reservoir storage and operation on stream-flows is already discussed in chapter 7. This scenario represents the stream-flows without irrigation conditions and shows the maximum water available. The difference in stream-flows between existing and base scenarios will emphasize the impact of irrigation.

Proposed cropping pattern irrigation scenario – the proposed cropping pattern for irrigation considered while commissioning the reservoir was entirely different than the existing practicing cropping pattern. The differences in cropping patterns are well explained in Chapter 5. However, this scenario intends to analyze the effect of the proposed cropping pattern and irrigation on stream-flows. For this scenario, the entire command area is assumed to be of less water-intensive crops (corn) irrigated only during Kharif season with the reservoir water. The difference between results of existing and proposed cropping pattern irrigation scenarios will highlight the alterations caused due to violations in the proposed cropping pattern.

8.3 Results and Discussion

8.3.1 Sensitivity analysis

In the study, relative sensitivity of 15 parameters that control the surface flow and groundwater flow for simulations were analysed using global sensitivity analysis method provided in SWAT-CUP (Table 8.2). The criteria for the classification of the most sensitive parameters were explained in section 7.5.1 of Chapter 7.

From the analysis, the Plant evaporation compensation factor (Epco) was observed as a very important parameter (rank 1). However, in chapter 7, referring to figure 7.4, the parameters Epco falls under the 'important' category, this may be non-consideration of irrigation activity in the basin.

Curve number (CN2) was observed as an important parameter (rank 2). Groundwater revap coefficient (Gw_revap), threshold water depth in shallow aquifer required for return flow to occur (GWqmn), Soil evaporation compensation factor (Esco), and Available water capacity (Sol_Awc) are also shown to be important parameters (rank 3 to 6).

Deep aquifer percolation co-efficient (RCHRG_DP), the Manning coefficient for channel (Ch_N2), Baseflow alpha-factor (Alpha_Bf), Effective hydraulic conductivity in main channel alluvium (Ch_K2), were found to be slightly sensitive parameters and remaining as non-sensitive parameters.

Table 8.2 Parameters and their ranges considered in the Sensitivity Analysis

Name	Min	Max	Definition	Rank
CN2	-20%	20%	SCS runoff curve number for moisture condition II*	2
Alpha_Bf	0	1	Baseflow alpha factor (day)	9
Gw_delay	0	100	Groundwater delay	12
Gwqmn	0	1000	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	4
Alpha_Bnk	0	1	Baseflow alpha factor for bank storage (day)	11
Ch_K2	0	150	Effective hydraulic conductivity in main channel alluvium(mm/h)	10
Ch_N2	-20	20	The Manning coefficient for channel*	8
Gw_revap	0.02	0.2	Groundwater revap coefficient	3
Revapmn	0	500	Threshold depth of water in the shallow aquifer for revamp to occur (mm)	15
Sol_Awc	-20%	20%	Available water capacity (mm/mm) *	6
Epco	-20%	20%	Plant evaporation compensation factor*	1
Esco	0	1	Soil evaporation compensation factor	5
Sol_K	-20%	20%	Soil conductivity (mm/h) *	14
RCHRG_DP	-20%	20%	Deep aquifer percolation co-efficient*	7
SURLAG	0	10	Surface runoff lag coefficient	13

Relative percentage change

8.3.2 Existing irrigation scenario

In this case, the SWAT model was initially setup for existing irrigation scheduling and existing LULC conditions defined by the NRSC satellite image (Figure 8.2). Cultivated areas were classified as corn (Kharif crop), wheat (rabi crop), and sugarcane (annual crop). The crop land under the irrigable command area of the Malaprabha project was considered for irrigation in the present study. The corn and wheat crops were assumed to be irrigated from the reservoir water and sugarcane from the deep aquifer. However, in the reality cultivated areas in the upstream area are also irrigated using stream water directly and from bore wells which in turn alter the quantity of inflows to the reservoir.

The simulated daily average monthly stream-flows from the SWAT model and observed data for calibration and validation periods are compared in Figure 8.4.

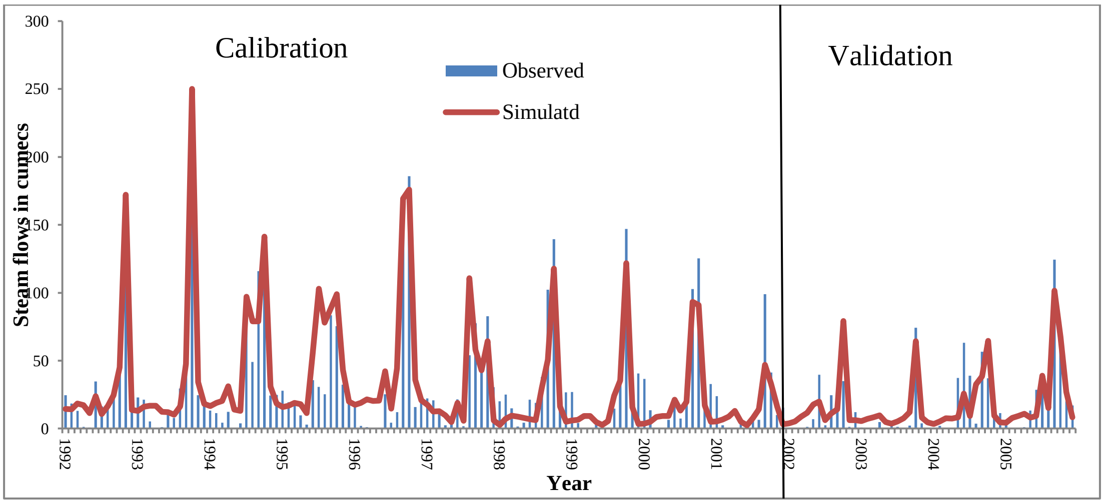


Figure 8.4:_Comparison of simulated vs. observed daily average monthly flows during model calibration and validation.

These results revealed that the model simulates monthly flows reasonably well, as indicated by favorable values of R^2 (>0.70), NSE (>0.6), P-BIAS (±15%), and RSR (Table 8.3). The uncertainty in the model simulations was also minimum as indicated by parameters P (>0.6) and R (closer to 1) factors. The model performance for the validation period is somewhat poorer compared to calibration. This is due to the occurrence of severe drought years in the validation period and the inability of the model to simulate extreme low flows.

Table 8.3 SWAT model performance statistics for existing irrigation scenario

LU/LC		Period	R^2	NSE	P-BIAS	RSR	P factor	R-factor
2005	Calibration	1992-2001	0.82	0.79	-2.1	0.4	0.61	1.10
	Validation	2002-2005	0.70	0.65	-14.2	0.5	0.50	1.03

8.3.3 Base (no-irrigation) scenario

To find the effect of irrigation in the study area, the base scenario was built in the model, where the entire command area was assumed to be under rain-fed cultivation. Assuming no irrigation extraction from the water sources, this scenario indicates the maximum stream-flows that can be generated under the current LULC condition. The differences between average annual and monthly stream-flows at Cholchigudda gauging station for the current and base scenarios are presented in Figures 8.5 and 8.6 respectively. When irrigation is withdrawn, surface water availability was found to improve significantly.

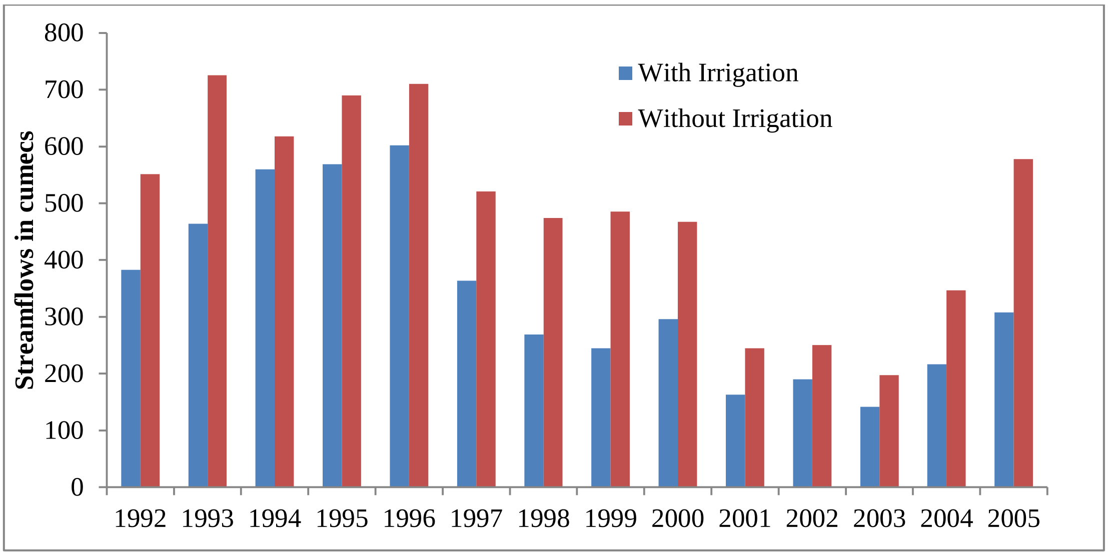


Figure 8.5: Comparison between average annual stream-flows at Cholachigudda for with and without irrigation condition

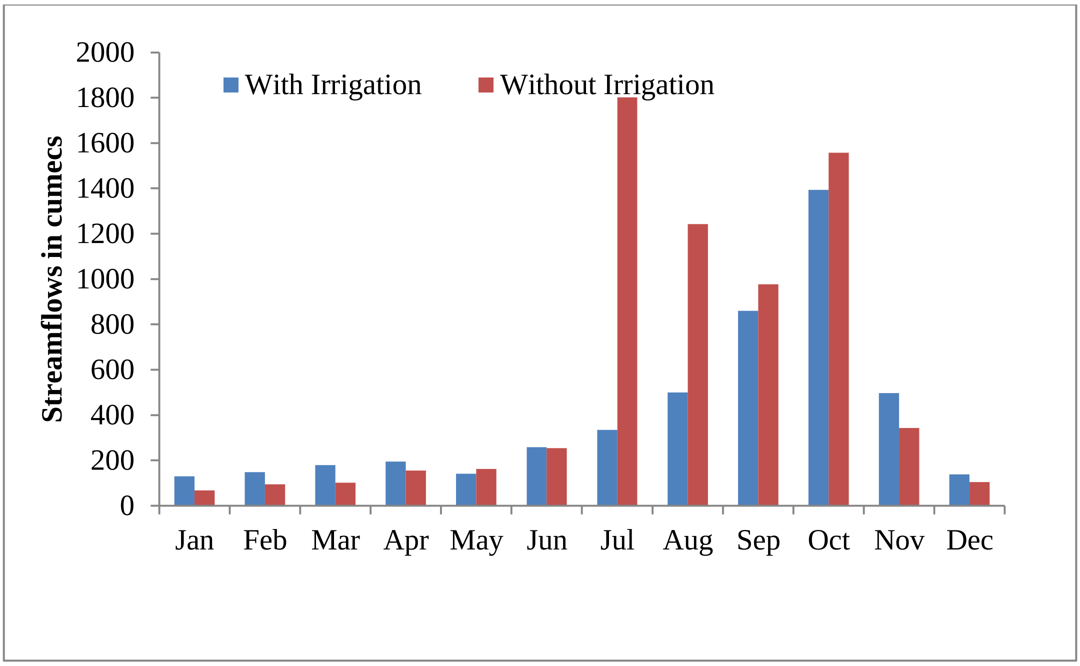


Figure 8.6: Comparison between average monthly stream-flows at Cholachigudda for with and without irrigation condition

An increase of average annual stream flows by 9 to 50% was observed (Figure 8.5) for base scenario i.e., without irrigation condition for the period 1992 to 2005. On the other hand, Figure 8.6 depicts that the monsoon flows increased by 33% and non-monsoon flows decreased by 45% for the base scenario concerning the existing scenario.

8.3.4 Proposed cropping pattern scenario

The Malaprabha project is envisaged to be protective in nature. The irrigation project was originally designed for cultivating less water-intensive crops in the command area and irrigation was provided only for the Kharif season. However, in reality, the proposed cropping pattern was never practiced. The intension of the present scenario is to simulate the stream-flows for the proposed cropping pattern and compare the results with that of existing cropping pattern/irrigation scenario, which enables understanding of changed cropping pattern effects.

The differences between average annual and monthly stream-flows at Cholchigudda for the proposed and existing cropping pattern/irrigation scenarios are presented in

Figures 8.7 and 8.8 respectively. It is interesting to note that, average annual stream flows decreased by 8 to 54% (Figure 8.7) for the proposed cropping pattern scenario with respect to existing. The possible reason could be that, since the entire command area is irrigated from the reservoir, water outflows have decreased significantly. On the other hand, irrigation from groundwater sources for water-intensive crops in the command area results in increasing stream-flows in the study area.

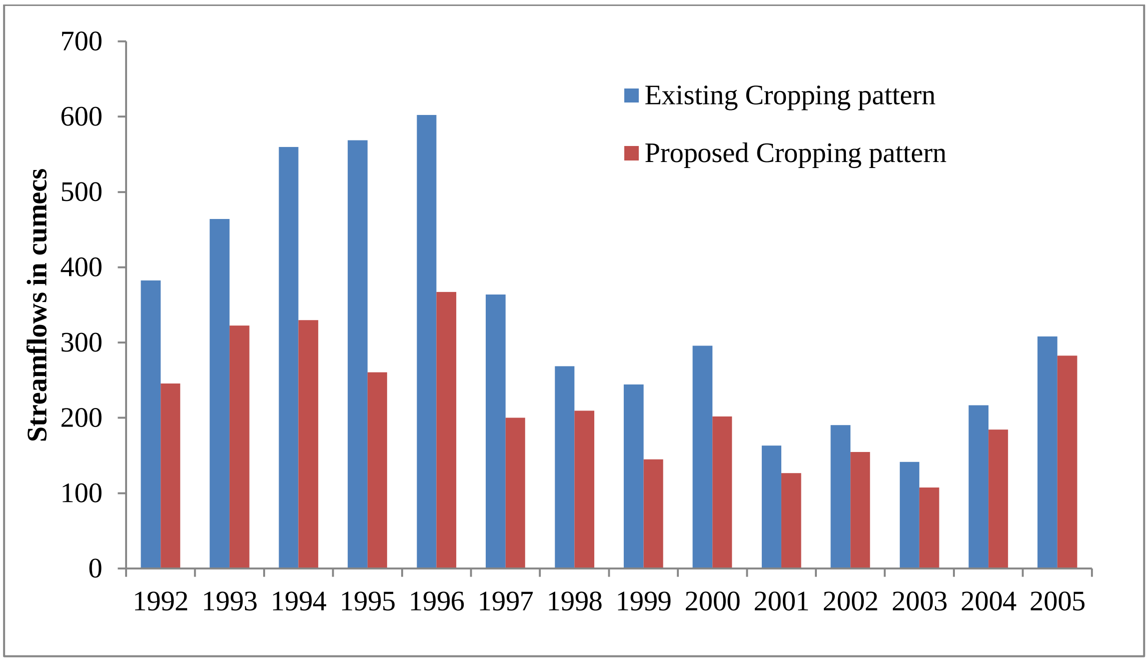


Figure 8.7: Comparison between average annual stream-flows at Cholachigudda for Existing and Proposed cropping pattern condition

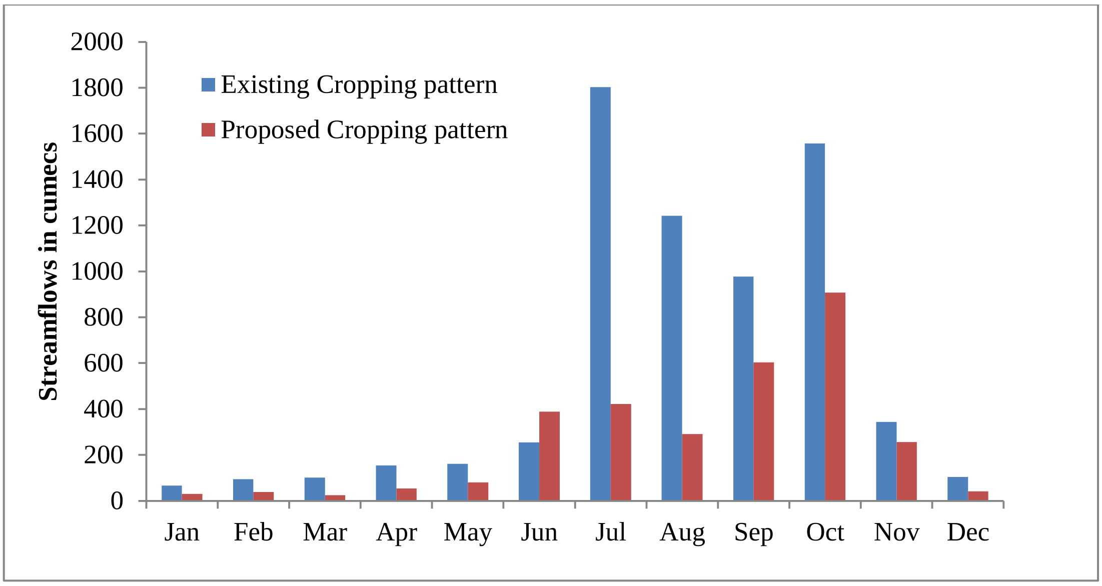


Figure 8.8: Comparison between average monthly stream-flows at Cholachigudda for Existing and Proposed cropping pattern condition

Figure 8.8 depicts the seasonal variation in the stream flows between the two scenarios. The extent of decreased stream-flows for monsoon season is 36% and that for the non-monsoon season is 55% for the proposed cropping pattern/irrigation scenario concerning existing cropping pattern /irrigation scenario for the period of analysis.

8.3.5 Effect of irrigation on AET and SMC

The effect of irrigation on water balance components such as actual evapotranspiration (AET) and soil moisture content (SMC) was analyzed. The analysis was restricted to the command area consisting of 32 sub-basins since irrigation is allowed for the selected sub-basins during model simulation. The average annual potential evapotranspiration (PET) over the command area of the Malaprabha basin is found to be 1756 mm. Figures 8.9a and 8.9b represent the graphical comparison of annual average actual evapotranspiration (AET) and soil moisture content (SMC) for the sub-basins of irrigable command area simulated by the SWAT model for the three scenarios.

The annual average AET increased by 4% to 26% for the existing cropping pattern/irrigation scenario concerning no irrigation scenario. On the other hand, AET for proposed cropping pattern/irrigation scenario decreased by 15% with respect to existing irrigation scenario. However, the annual average SMC increased up to 4% for the existing cropping pattern/irrigation scenario concerning no irrigation scenario. On the other hand, SMC for the proposed cropping pattern/irrigation scenario has a negligible variation (-2% to 1%) concerning the existing irrigation scenario.

Figure 8.9c represents the irrigation water applied for the sub-basins for existing and proposed cropping pattern scenarios. The major part of the excess amount of irrigation water supplied during the existing irrigation scenario is from a groundwater source.

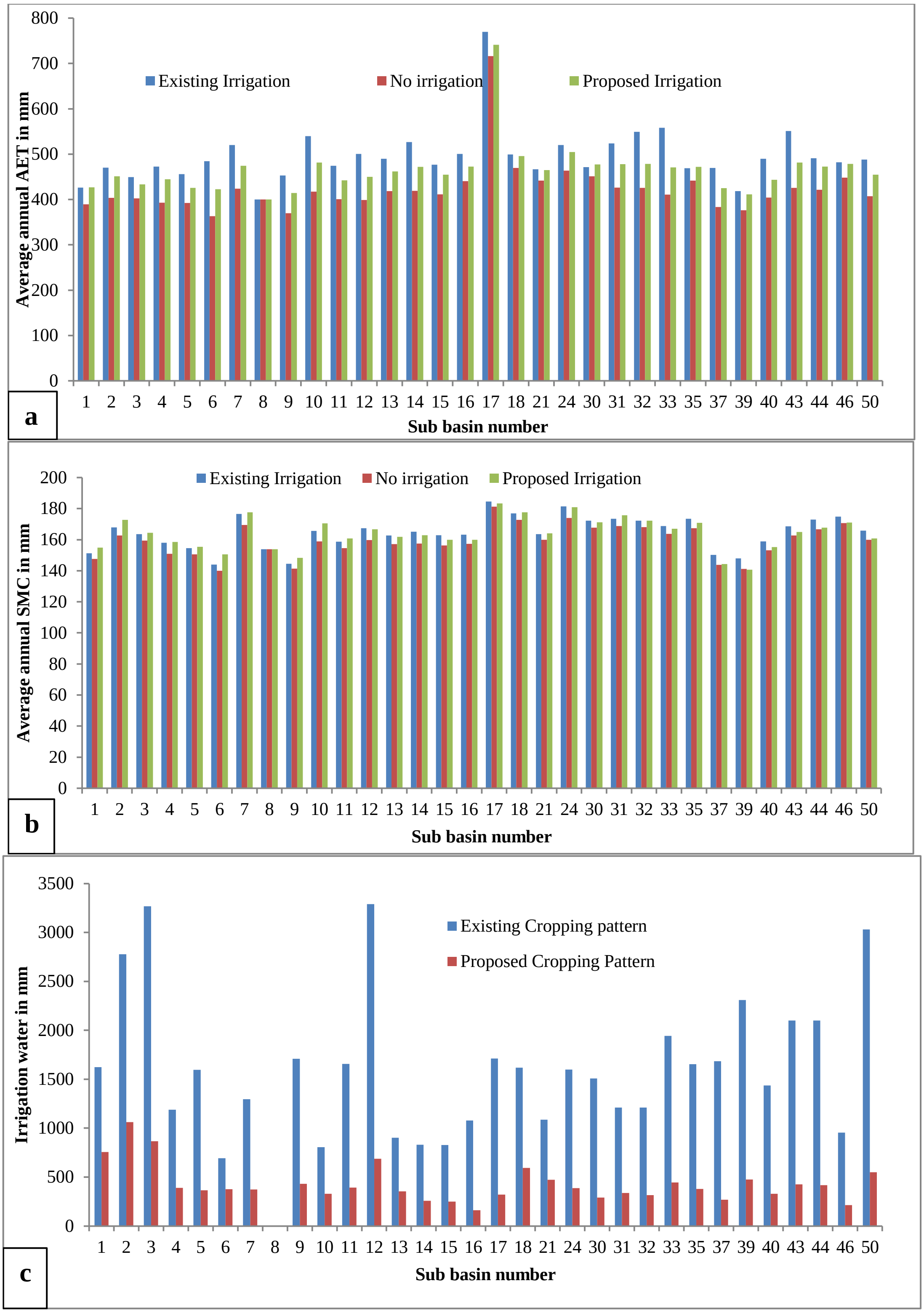


Figure 8.9: Simulated water balance components for sub-basins of irrigable command area of Malaparabha project

8.4 Closure

The present work was taken up to analyze the effect of irrigation on hydrological processes over the Malaprabha river basin using the SWAT hydrological model. Towards this, three hypothetical irrigation scenarios were analysed, namely existing irrigation scenario representing current cropping pattern, base scenario representing no irrigation (rain-fed) condition and proposed irrigation scenario expression cropping pattern and irrigation condition envisaged during project design. The model performed reasonably well during calibration for existing irrigation conditions with $R^2 = 0.82$; NSE =0.79. The calibrated parameters were utilized to develop other irrigation scenarios.

Water availability was found to improve significantly when irrigation is withdrawn. Average annual stream flows increased by 9 to 50% for the base scenario. Also, monsoon flows (high flows) increased by 33% and non-monsoon flows (low flows) decreased by 45% for the base scenario with respect to existing scenario for the period of analysis. For the proposed irrigation condition, average annual stream flows decreased by 8 to 54%. The possible reason could be that, since the entire command area is irrigated from reservoir water outflows have decreased significantly. Irrigation from groundwater sources for water-intensive crops in the command area results in increasing stream-flows in the study area. Irrigation results in increased actual evapotranspiration (AET) in the study area. The AET for existing irrigation condition was increased by 4 to 26% with respect to base scenario and 15% with respect to proposed irrigation scenario over the irrigated sub-basins.

CHAPTER 9
CONCLUSIONS

9.1 GENERAL

The primary objective of the present research work was to analyze the impacts of large-scale irrigation on river-basin scale hydrological processes. Accordingly, the Malaprabha River basin located in a semi-arid Karnataka State, India in which an irrigation project was established in 1972, was selected for the study. The sequential methodology adopted to evaluate the hydrological effects of irrigation consisted of 1) Characterizing the river basin using historical observations of hydro-meteorological variables 2) Analysing the likely effects of irrigation on long-term trend and variability of hydro-meteorological variables 3) Analysing the historical growth of irrigated agriculture in the Malaprabha river basin 4) Identify and evaluating the contributions of major drivers causing the stream-flow change in the river using the SWAT model and 5) Evaluating the hydrological impacts of irrigation using hypothetical cropping pattern scenarios in the river basin.

This chapter summarizes the important findings of this study. Major point-wise conclusions drawn from the results obtained are presented. Also, the limitations of the study and the scope for future study are enumerated.

The quantitative information provided by this study will be useful in solving water scarcity issues in the river basin through the development of effective management strategies to improve the efficiency of the project and promote the sustainable development of natural resources.

9.2 Characterizing the river basin using historical hydro-meteorological variables

In this analysis, historical observations of hydro-meteorological variables such as rainfall and rainy days (17 RG stations), air temperature (23 grids), groundwater level (45 wells), and stream flows (3 gauging stations) were subject to analysis using box-whisker plots and maps depicting spatial variability over Malaprabha river basin were prepared. Also, relationships between rainfall and streamflow and streamflow variability using FDC plots were analyzed. Important findings are:

- Malaprabha river basin comprises of three agro-climatic zones, namely the upper Western Ghats in hilly (Humid) zone, lower-middle in Northern Transition zone (Humid to semi-arid), and a large part of the lower region of the basin in the Northern dry (semi-arid) climatic zone. A large part of the basin experiences annual average rainfall between 544 mm to 700 mm, which is a typical range for a semi-arid climate.
- The exponential nature ($y = 265.55\ e^{0.0207x}$, $R^2 = 0.9115$) of the relationship between rainfall and rainy days is on account of the transitional nature of the climate in the basin and the occurrence of more intense rainfall events in the humid zone.
- The inter-annual variability in annual rainy days is larger than in rainfall magnitudes at each RG station. Stations Soundatti (NW1) and Ramadurga (NE5) which are located in the ND zone in the close vicinity of the reservoir recorded the lowest mean/median annual rainfall and rainy days amongst all the stations considered in this study. The annual average rainfall and rainy days range from 544 to 600 mm and 37 to 40 respectively.
- Examination of data for the period 1960-2015 indicated that the contributions of pre-monsoon, monsoon, and post-monsoon season rainfalls to the annual totals ranged between 5.28-19.13%, 57.04-86.88%, and 7.74-24.03% respectively. Similarly, the contributions of pre-monsoon, monsoon, and post-monsoon season rainy days to the annual rainy days ranged between 8.06-18.33%, 62.08-81.61%, and 10.16-20.26% respectively. However, the contributions of rainfall and the number of rainy days during the winter season to the corresponding annual totals were less than 1% for all the stations.
- The streamflow regime at downstream gauging stations was significantly affected by the Malaprabha irrigation project in the study area causing increased low flows during summer months and decreased peak flows during monsoon.

- The stream-flows of downstream gauging station at Huvanuru indicated an increase in low-flows (LFI up to 111%) during post-monsoon and summer months and a decrease in high-flows (HFI up to 37.4%) during monsoon months of post-dam condition concerning pre-dam. Further, storage of water in the reservoir during monsoon months decreased the extent of high-flows at the gauging station.
- The major portion of the study area comes under the GWL fluctuation range of 6 to 10 mbgl during all seasons. The wells (numbering 18, 19, 20, and 37) located immediately downstream to the dam showed fluctuations of 10 to 15 mbgl during all seasons. This may be a result of excessive groundwater utilization for growing water-intensive crops in the immediate vicinity of the reservoir.

9.3 Analysing the likely effects of irrigation on long term trend and variability of hydro-meteorological variables

Analysis of trends and variability of historical hydro-meteorological variables (rainfall, rainy days, average temperature, stream flows, and groundwater levels) over the Malaprabha river basin were carriedout. Also, the likely effects of irrigation on the results were analyzed. A nonparametric Singular Spectrum Analysis (SSA) and conventional Sen's slope Estimator (SE) methods were used for trend analysis. The statistical significance of non-linear and linear trends was identified using Monte-Carlo SSA and Mann-Kendall methods for 95% significance levels respectively. The temporal variability of the data was analyzed using the Coefficient of Variation (CV) statistic.

- Results revealed that the presence of the reservoir resulted in the occurrence of rainfall events with higher intensities in its vicinity. Also, wells located in irrigable command areas are subjected to greater variability.
- For the region close to the downstream of the Malaprabha dam, the number of rainy days for annual and monsoon periods exhibit higher variability. This is in contrast to the finding that CV values for annual and monsoon rainfall totals are lower in this part of the basin. This implies that it is likely that the

presence of the reservoir has resulted in the occurrence of rainfall events with higher intensities in its vicinity. The downstream river gauging stations for post dam conditions showed greater variability as compared to pre-dam conditions. Also, a profound extent of variation in the groundwater extractions in these regions was observed.

- The trend analysis indicated decreasing rainfall and rainy days till the year 2004 and an increasing trend thereafter. A statistically significant increasing trend in air temperature was noted in the basin. Stream-flow and groundwater at the downstream locations exhibited decreasing trends.
- The two rain gauge stations (Badami and Ramadurga) located immediately downstream of the Malaprabha dam showed increasing annual rainfall trends. However, the rest of the stations showed decreasing annual trends. The SSA results depicted decreasing trends for basin average annual rainfall and rainy days trends since the commissioning of the Malaprabha dam and a steep increase in these trends from the year 2004.
- The annual stream-flow trends for downstream gauging stations were subjected to variability as these are regulated flows and showed decreasing trends corresponding with the progression of irrigation in the command area. On the other hand, increased trends for annual and seasonal average temperature were noticed in the study area.
- Groundwater levels of most of the wells in the upstream region showed increasing annual trends. The two wells located in close vicinity of the Malparabha dam towards the downstream side showed significant decreasing trends. On the other hand, the wells in the downstream command area indicated a combination of significantly increasing and decreasing trends.
- SSA is an effective alternative statistical tool that permits the identification and extraction of trajectories of nonlinear trends and change points in non-stationary time series of hydro-climatic variables.

9.4 Analysing the historical growth of irrigated agriculture in the Malaprabha river basin

The present research work focuses on the application of a scientific approach to characterize the historical development of irrigation in the Malaprabha river command area. The objective was to assess the spatiotemporal changes in the extent of irrigated area and cropping patterns, explore the role of groundwater in providing irrigation water supplies, computing crop water requirements (CWR) and irrigation water requirements (IWR) of crops grown in the command area using the CROPWAT model over the period 1965-2014 in the command area of the project.

- The analysis of the historical growth of irrigation in the Malaprabha command area revealed that the commissioning of the irrigation project played a significant role in the development of irrigated agriculture in the region. The contribution of canal supplies to irrigated agriculture was maximum until 1985-86 (61%) and decreased thereafter. On the other hand, the contribution of groundwater to irrigation increased subsequently since 1993-94. A shift from low water consuming crops to water-intensive crops is observed. Overall, it appears from the performance analysis that the Malaprabha irrigation project has not been able to enforce the planned objectives and goals.
- The Malaprabha dam is situated at a place called Navilutheertha located in the Northern dry zone. The rapid growth of irrigated agriculture has been noticed in the region since the commissioning of the irrigation project in 1972. The irrigation intensity has increased from 0.76% during 1965-66 to 56.82% during 2013-14.
- The contribution of canal supplies to irrigated agriculture was maximum until 1985-86 (61%) and decreased thereafter. On the other hand, the contribution of groundwater to irrigation increased subsequently since 1993-94. Also, the regions close to the reservoir appear to be fully benefitted by canal water supplies whereas regions located away from the reservoir seem to be benefitting from groundwater supplies.

- A shift from traditional low water consuming crops to high yielding, water-intensive crops was observed in the cropping pattern of the command area. Also, the area under cash crops increased significantly.
- The average CWR of the existing cropping pattern is around 170% higher than the proposed. Also, the CWR of the proposed cropping pattern remained more or less constant with an average value of 1264 MCM and CWR for the existing cropping pattern has increased from 3,189 MCM to 4,024 MCM (26%) between the years 1965-66 and 2013-14.
- The IWR of the existing cropping pattern has increased from 138 MCM (1965-66) to 2410 MCM (2013-14) due to the widespread adoption of more water-intensive crops in the command area. Canal releases not conforming to estimated IWR and an increase in irrigation intensity (57%) was noticed in the study area at the end of 2013-14.
- Overall, it appears that the Malaprabha project since 2003-04 has not been able to achieve the demands imposed by farmers on account of the significant divergence between the original objectives and the existing situation on the ground in terms of the cropping patterns.

9.5 Identify and evaluate the contributions of major drivers causing the stream-flow change in the river using the SWAT model

The stream-flow changes induced by irrigation activities have been simulated using modeling approach. The combined and isolated effects of Malaprabha reservoir, LULC change, and climate change were analyzed for decades 1980s, 1990s, and 2000s. The main objective of the work is to 1) analyze LULC changes over the decades 1985, 1995, and 2005, 2) examine the stream-flow responses to combined and isolated effects of LULC, climate change, and presence and absence of Malaprabha reservoir, 3) identify and evaluate the contribution of the major driver causing stream-flow variation in the Malaprabha river basin using SWAT hydrological model for the period 1983-2006.

- Cropland accounts for a major portion (>83%) of the Malaprabha river basin, followed by fallow land (>4%) and shrubland (>3%). Among the three decades, no extensive change was observed in the land use patterns between 1985 and 2005. However, a decrease in cropland by 3.07% was noticed in 1995 and increase by 1.61% during 1995 to 2005. Subsequently, an increase in fallow land was noticed by 1.88% during 1995 and decrease by 1.80% during 1995 to 2005.

- The combined effect of changes in all three drivers caused an increase in annual stream-flow in the basin by 53% between the 1980s and 1990s and a decrease in stream-flow by 38% between the 1990s and 2000s.
- The presence of the Malaprabha reservoir was found to have the largest impact, reducing stream flow by more than 200%. Changes in LULC increased stream-flow by 102% and 72% between the 1980s to 1990s and 1980s to 2000s respectively whereas climate changes increased stream-flow by 30% and 2.6% during the same periods.
- This study reveals that in a tropical river basin the presence of an irrigation reservoir can significantly alter temporal variability of stream-flow which is further exacerbated by changes in LULC and climate.

9.6 Evaluating the hydrological impacts of irrigation along with cropping pattern scenarios in the river basin.

The assessment of the hydrological impacts of irrigated agriculture in the Malaprabha river basin has ben carriedout. Due to increasing unsustainable land-use practices, the area is experiencing water scarcity and water availability in the lower catchment is closely related to the land-use practices and water extraction in the upstream (Reshmi et al 2008). The main aim of the present study is to 1) highlight differences in the basin hydrological responses under the conditions with and without irrigated agriculture 2) develop and analyze the effects of different irrigation and land-use scenarios on stream-flows. The calibrated SWAT model performed reasonably well and was used to analyze the difference between annual and monthly stream-flows for the two conditions.

- Three irrigation scenarios were analyzed, namely existing irrigation scenario representing current cropping pattern, base scenario representing no irrigation (rain-fed) condition, and proposed irrigation scenario expression cropping pattern and irrigation condition envisaged during project design. During the calibration phase, the model performed reasonably well for existing irrigation conditions with R^2 = 0.82; NSE =0.79. The calibrated parameters were ut

- ilized to develop other irrigation scenarios.
- Water availability was found to be improved significantly when Irrigation is withdrawn. Average annual stream flows were increased by 9 to 50% for the base scenario. Also, monsoon flows (high flows) increased by 33% and non-monsoon flows (low flows) decreased by 45% for the base scenario concerning the existing scenario for the period of analysis.
- For the proposed irrigation condition, average annual stream flows decreased by 8 to 54%. The possible reason could be that, since the entire command area is irrigated from reservoir water outflows have decreased significantly. Irrigation from groundwater sources for water-intensive crops in the command area results in increasing stream-flows in the study area.
- Irrigation results in increased actual evapotranspiration (AET) in the study area. The AET for existing irrigation conditions was increased by 4 to 26% concerning the base scenario and 15% concerning the proposed irrigation scenario over the irrigated sub-basins.

9.7 Limitations of the study

Since the present analysis is based on data procured from a variety of independent sources, results and conclusions may have been influenced by inherent errors in the data sets despite the best efforts made to eliminate them. Also, the assumption of a constant cropping pattern throughout the study period is a limitation of the study, but it is believed that this aspect may not have influenced the results as much as variations in other variables. Future studies may incorporate finer resolution data on temporal and spatial variabilities in cropping patterns.

In the present study, the cropland under the irrigable command area of the Malaprabha project was considered for analysis of irrigation effect. The corn and wheat crops are assumed to be irrigated from the reservoir water and sugarcane from the deep aquifer. However, in the reality cultivated areas in the upstream area are also irrigated using stream water directly and from bore wells which in turn alters the quantity of inflow to the reservoir (but may not irrigate from reservoir water).

9.8 Scope for future studies

Different land-use scenarios representing the trend of increased irrigation can be developed and analyze its effects on hydrological processes.

The present study can be analyzed using the hydrological model capable of simulating surface and groundwater interactions, which intern increases the quality of model simulations.

The quantitative information provided by this study will be useful in solving water scarcity issues in the river basin, through the development of effective management strategies to improve the efficiency of the Malaprabha Irrigation project.

REFERENCES

Abbaspour, K. C. (2008): "SWAT Calibrating and Uncertainty Programs, A User Manual". Eawag Zurich, Switzerland.

Abbaspour, K. C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., Zobrist, J. and Srinivasan, R. (2007). "Modelling hydrology and water quality in the pre-alpine Thur watershed using SWAT." *J. of Hydrol.*, 333, 413-430.

Adam J. C. and Lettenmaier D. P. (2008). "Application of new precipitation and reconstructed streamflow products to streamflow trend attribution in Northern Eurasia". *J. Clim.*, *21*(8), 1807–1828.

Adegoke J.O., Pielke R. J. Eastman, R. Mahmood, and K. G. Hubbard, (2003). "Impact of Irrigation on Midsummer Surface Fluxes and Temperature under Dry Synoptic Conditions: A Regional Atmospheric Model Study of the U.S. High Plains," *Mon. Weather Rev.*, vol. 131, no. 1984, pp. 556–564.

Alexandersson, H. (1986). "A homogeneity test applied to precipitation data". *J. Climatol*. 6: 661–675.

Alexandersson, H., and Moberg, A. (1997a). "Homogenization of Swedish temperature data. Part I: homogeneity test for linear trends". *Int. J. Climatol*.17: 25–34

Alexandrov, T. (2009). "A method of trend extraction using singular spectrum analysis." *Revstat Stat. J.*, 7(1), 1–22.

Alexandrov, T., Bianconcini, S., Dagum, E. B., Maass, P. and McElroy, T. S. (2012). "A Review of Some Modern Approaches to the Problem of Trend Extraction". *Econometric Reviews*, *31*(6), 593–624.

Allen, M. R., and Smith, L. A. (1994). "Investigating the origins and significance of low-frequency modes of climate variability" Geophys. Res. Lett. 21, 883-886.

Allen, M. R., and Smith, L. A. (1996). "Monte Carlo SSA: detecting oscillations in the presence of coloured noise". *J. Climate*, *9*,3373–3404.

Allen, R. G., Pereira, L. A., Raes, D. and Smith, M (1998). "Crop evapotranspiration, guidelines for computing crop water requirements". FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization, Rome, Italy, p. 293.

Alpert P, and Mandel M, (1986). "Wind Variability—An Indicator for a Mesoclimatic Change in Israel," *J. Clim. Appl Meteorol*, vol. 25, no. 11. pp. 1568–1576.

Arnold, J. and Fohrer, N.: SWAT2000: (2005) "Current capabilities and research opportunities in applied watershed modeling." *Hydrol. Process*., 19, 563–572.

Arnold, J. G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B. and Neitsch, S.L (2012). "Soil and Water Assessment Tool: User's manual, version 2012."

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R., Van Griensven, A., and Van Liew, M. W. (2012): "SWAT: Model use, calibration, and validation", Trans. Asabe, 55, 1491–1508.

Arnold, J.G., Srinivasan, R., Muttiah, R.S. and Williams, J.R. (1998). "Large area hydrologic modeling and assessment part I: model development." *J. Am. Water Resour. Assoc.,* 34(1), 73–89

Babu, R. G., Babu, G. R. and Kumar, H. V. H (2015). "Estimation of crop water requirement, effective rainfall and irrigation water requirement for vegetable crops using CROPWAT". *Int. J. Agric. Eng.,* 8(1), 15–20

Banacos, P. (2011). "Box and Whisker Plot for Local Climate Datasets: Interpretation and creation using Excel 2007/2010", *Eastern Region Technical Attachment*; January 2011; No. 2011-01. Burlington, VT, USA.

Barkhuizen, M. (2003). "Analysis of process data with singular spectrum methods". M.Sc. Eng. Thesis, University of Stellenbosch, Stellenbosch, South Africa.

Barkhuizen, M., and C. Aldrich. (2003). "Dynamic process analysis with nonlinear Monte Carlo singular spectrum analysis". E. Boje, *J. Tapson (Eds.),* Proceedings of the first African control conference, 0-620-31551-2 (2003), pp. 285-290.

Barston,G.A. and Schichedanz. P.T. (1984). "The effect of Irrigation on Warm season precipitation in the Southern Great Plains.," *J. Climate Sci. and Appl. Meteorol.,* Vol.23, No 6, p.865-888.

Batalla, R. J. and Go, C. M. (2004). "Reservoir-induced hydrological changes in the Ebro River basin (NE Spain)." *J Hydrol*. 290*,* 117–136.

Bigg, T. Gour A. Scott C. Thenkabail P.Teluguntla P.Gumma M K. Acharya S. and Turrral H (2007). "Closing of the Krishna Basin: Irrigation, streamflow depletion and macroscale hydrology., Colombo, Sri Lanka: International Water Management Istitute" (IWIMI reasearch report 111).

Biswas, D. and Venkatachalam, L (2010). "Institutions and their interactions: an economic analysis of irrigation institutions in the Malaprabha dam project area, Karnataka, India". Working Paper 250, *The Institute for Social and Economic Change, Bangalore*, ISBN 978-81-7791-106-0.

Bojar, K. (2011). "Trend extraction from noisy discrete signals by means of singular spectrum analysis and morphological despiking." *Przeglad Elektrotechniczny*, 87(6), 241–244.

Bonfils C.and Lobell D, (2007). "Empirical evidence for a recent slowdown in irrigation-induced cooling.," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 104, no. 34, pp. 13582–13587.

Boucher O, Myhre G, and Myhre A, (2004). "Direct human influence of irrigation on atmospheric water vapour and climate," *Clim. Dyn.*, vol. 22, no. 6–7, pp. 597–603.

Bouwer, L. M., Aerts, J. C. J. H., Droogers, P., and Dolman, A. J. (2006). "Detecting the long-term impacts from climate variability and increasing water consumption on runoff in the Krishna river basin (India)". *Hydrology and Earth System Sciences*, *10*(5), 1249–1280.

Broomhead, D., and King, G. P. (1986). "Extracting qualitative dynamics from experimental data." *Phys. D: Nonlinear Phenomena*, 20(2–3), 217–236.

Central Ground Water Board report (2012): **http://cgwb.gov.in/Annual-Reports/Annual%20Report%202011-12.pdf**

Chandran, K. M. and Ambili, G. K (2016). "Evaluation of minor irrigation schemes using performance indicators: case studies from South India". *Sustain. Water Resour. Manage.*, 2(4), 431–437; https://doi.org/10.1007/s40899-016-0074-3.

Chandran, K. M., Joseph, E. J. and Sushanth, C. M (2016). "Performance evaluation of selected irrigation systems in Kerala state, India". *Irrig. Drain.*, 65(5), 613–619; https://doi.org/10.1002/ird. 2012.

Changnon, S.A. (1973). "Atmospheric Alterations from Man-made Biospheric Changes, Modifying the Weather," *Wetern Geographical Series*, 9, p. 135-184.

Chatterjee, S. K., Banerjee, S. and Bose, M (2012). "Climate change impact on crop water requirement in Ganga River". *In Third International Conference on Biology, Environment and Chemistry (IPCBEE)*, IACSIT Press, Singapore, vol. 46.

Chitragar, S. L. (2018). "Regional imbalances in agricultural development of Malaprabha river basin: a geographical perspective". Doctoral thesis, Department of Geography, Karnataka University, Dharwad. http://hdl.handle.net/10603/201564.

Chow V.T., Maidment, D.R. and Mays, L.W. (1988). "*Applied Hydrology.*" McGraw-Hill: New York

De Luís M, Raventós J, González-Hidalgo J. C, Sánchez, J. R., and Cortina, J. (2000). “Spatial analysis of rainfall trends in the region of valencia (East Spain).” *Int. J. Climatol.*, 20(12), 1451–1469.

De Ridder K. and H. Gallée, (1998). “Land Surface–Induced Regional Climate Change in Southern Israel,” *J. Appl. Meteorol.*, vol. 37, no. 1993, pp. 1470–1485.

De Rosnay P, Polcher J, Laval K, and Sabre M (2003). “Integrated parameterization of irrigation in the land surface model ORCHIDEE. Validation over Indian Peninsula”. *Geophysical Research Lett*, Vol. 30, NO. 1930(19):1-4

Detailed project report of Malaprabha reservoir, revised version in 2008, collected manually from MRBC, Division II, office at Navilutheertha, Belgaum district.

Doll P, Fiedler, K., and Zhang, J. (2009). “Global-scale analysis of river flow alterations due to water withdrawals and reservoirs”, *Hydrol. Earth Syst. Sci.*, 13, 2413–2432.

Döll, Petra, Heike Hoffmann-Dobrev, Felix T. Portmann, Stefan Siebert, Annette Eicker, Matthew Rodell, Gil Strassberg, and B. R. Scanlon (2012). "Impact of water withdrawals from groundwater and surface water on continental water storage variations." *J. Geodynamics* 59 143-156.

Doorenbos, J. and Kassam, A. H (1979). Yield response to water. FAO Irrigation and Drainage Paper No. 33, Food and Agricultural Organization, Rome, Italy.

Doorenbos, J. and Pruitt, W. O (1977). Crop water requirements. FAO Irrigation and Drainage Paper No.24, Food and Agricultural Organization, Rome, Italy.

DPR - Detailed project report of Malaprabha reservoir, revised version in 2008, collected manually from MRBC, Division II, office at Navilutheertha, Belgaum district.

Elsner, J. B., and Tsonis, A. A. (1996). “Singular spectrum analysis—A new tool in time series analysis”, Plenum, New York, 1–160.

FAO-UN, AQUASTAT 2016: http://www.fao.org/aquastat/statistics/query/index.html (Jan., 2017)

Gangwar, A., Nayak, T., Singh, R. M. and Singh, A (2017). “Estimation of crop water requirement using CROPWAT 8.0 model for Bina Command, Madhya Pradesh”. *Indian J. Ecol.,* 44, 71–76.

Ghil M, Allen M.R, Dettinger M.D, Ide K, Kondrashov D, Mann M.E, Robertson A.W, Saunders A, Tian Y, Varadi F. and Yiou P. (2002). “Advanced spectral methods for climatic time series”. *Rev. Geophys.,* 40 (1), 1003. 1–41.

Ghill, M., and Vautard, R. (1991). “Interdecadal ocillations and the warming in the global temperature time series”. *Nature.,* 350, 324-327.

Golyandina, N. and Zhigljavsky, A. (2013). “Singular spectrum analysis for time series”, Springer Heidelberg New York Dordrecht London, 1–118.

Haddeland I, Lettenmaier DP, Skaugen T (2006). “Effects of irrigation on the water and energy balances of the Colorado and Mekong river basins”. *J Hydrol*. 324(1-4):210-223.

Han J., G. Huang H. Zhang Z. Li, and Y. Li. (2014). “Heterogeneous precipitation and streamflow trends in the Xiangxi River watershed, 1961–2010.” *J. Hydrol. Eng.* 19 (6): 1247–1258. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000898

Hargreaves G. H, and Samani Z.A (1985). “Reference crop evapotranspiration from temperature”. *Transactions of ASAE.* 1(2): 96-99.

Huang, F., Chen, Q., Li, F., Zhang, X., Chen, Y. and Qiu, L. (2015). “Reservoir-Induced Changes in Flow Fluctuations at Monthly and Hourly Scales: Case Study of the Qingyi River, China.” *J. Hydrol. Eng.,* 20(12), 1–7.

Huang, F., Xia, Z., Li, F., and Guo, L. (2012). “Hydrological Changes of the Irtysh River and the Possible Causes”, *Water Resour Manage* 26:3195–3208.

Huang, F., Xia, Z., Zhang, N., Zhang, Y., and Li, J. (2011). “Flow-Complexity Analysis of the Upper Reaches of the Yangtze River, China”, *American Society of Civil Engineers 16*, (November), 914–919.

Jain, S. K., Kumar, V. and Saharia, M., (2013). “Analysis of rainfall and temperature trends in northeast India”. *Int. J. Climatol.,* 33, 968–978.

Jain, S., Salunke, P., Mishra, S. K., Sahany, S. and Choudhary, N (2019). “Advantage of NEX-GDDP over CMIP5 and CORDEX data: Indian Summer”. *Atmos. Res.,* 228, 152–160.

Jain, S.K. and Kumar, V. (2012) “Trend analysis of rainfall and temperature data for India”, *Current Science*, 102,37 – 49.

Joos A. (1969). “Recent Rainfall Patterns in the Great Plains,” *Paper at AMS Symposium*, Madison, WI, October 21.

Kadam U. S (2015). “Performance assessment of heterogeneous irrigation schemes in India”. Doctoral Thesis, Loughborough University, https://hdl.handle.net/2134/18589.

Kahya E. and Kalayci S. (2004). “Trend analysis of streamflow in Turkey.” *J. Hydrol.,* 289(1–4), 128–144.

Kandlikar, M. (2007). “Air pollution at a hotspot location in Delhi: Detecting trends, seasonal cycles and oscillations”. *Atmos. Environ., 41*(28), 5934–5947.

Keiser J, Utzinger J, Tanner M. (2005). “The Effect of Irrigation and Large Dams on the Burden of Malaria.” *The American Society of Tropical Medicine and Hygiene.* 72(4)., 392-406.

Kendall, M. G. (1975). “Rank correlation methods”. Charles Griffin. London.

Kienzle S W. and Schmidt J (2008). “Hydrological impacts of irrigated agriculture in the Manuherikia catchment, Otago, New Zealand”. *J Hydrol New Zeal*. 47(2):67-84.

Kirby M. Ahmad MD. Mainuddin M, Palash W, Qadir ME, and Shah-Newaz SM.(2015). “The impact of irrigation development on regional groundwater resources in Bangladesh”. *Agric. Water Manage.* 159.,264–276. *https://doi.org/10.1016/j.agwat.2015.05.026*

Kiros, G., Shetty, A., and Nandagiri, L. (2017). “Extreme rainfall signatures under changing climate in semi-arid northern highlands of Ethiopia”. *Cogent Geoscience,* 3(1), 1–20.

Krishnan R, Chanrakar A, Bhaskar R. N and Khare. D. (2017). “Analysis of Rainfall Trend before and after Implementation of Eastern Ganga Canal Command.” *World Environmental and Water Resources Congress 2017 – ASCE*., 600-617.

Kueppers, L.M., M. A. Snyder, and L. C. Sloan (2007), “Irrigation cooling effect: Regional climate forcing by land-use change”, *Geophys. Res. Lett.,* 34, L03703.

Kumar raju B C, (2016), “Assessment of variable source area hydrological models in the upper cauvery basin, Karnataka, India”. Ph.D thesis, *National Institute of Technology Karnataka,* Surathkal, Mangalore, India. 198p. https://idr.nitk.ac.in/jspui/handle/123456789/14240

Kumar Raju B.C., and Nandagiri L., (2017). “Analysis of Historical Trends in Hydrometeorological Variables in the Upper Cauvery Basin, Karnataka, India.” *Curr.Sci.,*112(3), 577-587.

Kumar, P., Kumar, S., Barat, A., Parth Sarthi, P. and Sinha, A. K (2020). “Evaluation of NASA’s NEX-GDDP-simulated summer monsoon rainfall over homogeneous monsoon regions of India”. *Theor. Appl. Climatol.,* 141, 525–536.

Kumar, V., Jain, S. K., and Singh, Y. (2010). “Analysis of long-term rainfall trends in India”. *Hydrolog. Sci. J.*, *55*(4), 484–496.

Kustu, M. D., Fan, Y., and Robock, A. (2010). “Large-scale water cycle perturbation due to irrigation pumping in the US High Plains: A synthesis of observed streamflow changes”. *J. Hydrol.*, *390*(3–4), 222–244.

Lehmann, E. L. (1975). “Nonparametrics, Statistical Methods Based on Ranks”. Holden-Day, San Francisco, California, USA.

Leng G, Huang M, Tang Q, Sacks WJ, Lei H, and Leung L R (2013). “Modeling the effects of irrigation on land surface fluxes and states over the conterminous United States: Sensitivity to input data and model parameters”. *J. Geophys. Res. Atmos.*118 (17):9789-9803.

Li Z, G. H. Huang, Y. R. Fan, and J. and L. Xu. (2015). “Hydrologic risk analysis for nonstationary streamflow records under uncertainty.” *J. Environ. Inf.* 26: 41–51

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges (1994), “A simple hydrologically based model of land surface water and energy fluxes for general circulation models”. *J. Geophys. Res.*, **99**(D7), 14415–14428, doi:10.1029/94JD00483.

Lobell D., Bala G., et.al, (2008).“Regional Differences in the Influence of Irrigation on Climate,” *J. Climate.*, Vol.22 pp. 2248–2255.

Lohar and Pal, (1995). “The effect of Irrigation on Pre monsoon Season Precipitation over South West Bengal, India” *J. Appl. Meteorol.*, vol. 8, p.2567-2570.

Madar Y.M (1993). “Regional disparities in the agricultural development in Malaprabha command area”. Published thesis, Department of Geography, Karnataka University. http://hdl.handle.net/10603/107950.

Magilligan, F. J., and Nislow, K. H. (2005). “Changes in hydrologic regime by dams”, *Geomorphology 71*, 61–78.

Magilligan, F. J., Nislow, K. H., and Graber, B. E. (2003). “Scale-independent assessment of discharge reduction and riparian disconnectivity following flow regulation by dams”. *Geology*, *31*(7), 569–572.

Mahmood R, Foster S.A, Keeling T, Hubbard K.G, Carlson C, and Leeper R, (2006). “Impacts of irrigation on 20th century temperature in the northern Great Plains,” *Glob. Planet. Change*, vol. 54, no. 1–2, pp. 1–18.

Mann, H. B. (1945). “Nonparametric tests against trend.” *Econometrica: J. Econometric Soc.*, 13(3), 245–259.

Marhaento, H., Booij, M.J., Rientjes, T. and Hoekstra, A. Y (2017). "Attribution of changes in the water balance of a tropical catchment to land use change using the SWAT model," *Hydrol. Process.,* vol. 31, pp. 2029–2040.

Marhaento, H., Booij, M.J., Rientjes, T. and Hoekstra, A. Y. (2017). "Attribution of changes in the water balance of a tropical catchment to land use change using the SWAT model," *Hydrol. Process.,* vol. 31, pp. 2029–2040

Massart, D. L. Smeyers-Verbeke, J. Capron, X. and Schlesier, K. (2005). "Visual presentation of data by means of box plots", Lc Gc Europe,18, 215–218.

McDonald, M. G. and A. W. Harbaugh. (1984) "A modular three-dimensional finite-difference ground-water flow model." *Techniques of water-resources investigations* (1984): 83-875.

Mekonnen, D.F., Duan, Z., Rientjes, T. and Disse, M (2018). "Analysis of combined and isolated effects of land-use and land-cover changes and climate change on the upper Blue Nile River basin's stream flow," *Hydrol. Earth Sys. Sci.,* vol. 22, pp. 6187–6207

Michel R, Chanasyk D and Miller J (2013). "Modeling the effect of irrigation on the hydrological output from a small prairie watershed". *Can Water Resour J.* 38(4):280-295.

Moore N, and Rojstaczer S (2001). "Irrigation-induced rainfall and the great plains". *J Appl Meteorol* 40:1297–1309.

Moriasi, D.N., Arnold, J.G., Van Lie, M.W., Bingner, R.L., Harmel, R.D., and Veith, T.L. (2007). "Model evaluation guidelines for systematic quantification of accuracy in watershed simulations." *T. ASABE, 50,885-900.*

Mudbhatkal, A., Raikar, R. V., Venkatesh, B., & Mahesha, A. (2017). "Impacts of Climate Change on Varied River-Flow Regimes of Southern India". *J. Hydrol. Eng.,* 22(9), 05017017.

Narayanamoorthy A. (2006). "Potential for drip and sprinkler irrigation in India". *Draft, IWMI-CPWF Project on Strategic Analysis of India's National River Linking Project.* International Water Management Institute: Colombo, Sri Lanka.

Nash, J.E. and Sutcliffe, J.V. (1970). "River flow forecasting through conceptual models part I- A discussion of principles." *J.of Hydrolo.,* 10, 282-290.

Nilsson, C., Reidy, C. A., Dynesius, M., and Revenga, C. (2005). "Fragmentation and flow regulation of the world's large river systems." *Science,* 308(5720), 405-408.

Ozdogan, M., Rodell, M., Beaudoing,H. K. and David L. Toll. (2010). " Simlating the Effects of over the United States in a Land Surface Model Based on Sattelite-Derived Agricultural Data". *J. Hydrometeorology,* 171–184, https://doi.org/10.1175/2009JHM1116.1

Ozdogan, M., and G. Gutman (2008), A new methodology to map irrigated areas using multi-temporal MODIS and ancillary data: An application example in the continental US, *Remote Sens. Environ*., 112(9), 3520–3537.

Poff, N. L., Olden, J. D., Merritt, D. M., and Pepin, D. M. (2007). "Homogenization of regional river dynamics by dams and global biodiversity implications". *Proceedings of the National Academy of Sciences of the United States of America*, *104*(14), 5732–5737.

Pokhrel Y, Hanasaki N, Koirala S, Cho J, Pat J, Kim H, Kanae S, and Oki T (2012). "Incorporating Anthropogenic Water Regulation Modules into a Land Surface ModeL", *Hydrology in Earth System Science and Society (HESS),* American Meteorological Society. Vol.13. p.255-269.

Rani, S. Y. R., Venkateswarao, B. and Sreekanth, S (2011). "Modernization of an existing irrigation project by performance evaluation using performance indicators". *Int. J. Math. Eng.*, 141, 1273– 1292.

Reshmi, T.V. (CISED), Anne Bjørkenes Christiansen (NIVA), Shrinivas Badiger (CISED), and David N. Barton (NIVA) -(2008), "Hydrology and Water Allocation in Malaprabha -Comprehensive database and integrated hydro economic model for selected water services in the Malaprabha river basin". REPORT SNO 5695-2008.

Reshmidevi T V., Nagesh Kumar D (2014). "Modeling the impact of extensive irrigation on the groundwater resources". *Hydrol Process*. 28(3):628-639.

Rodell, M., Velicogna, I., and Famiglietti, J. S. (2009). "Satellite-based estimates of groundwater depletion in India." *Nature. 460*(7258), 999–1002.

Roy, P.S., Meiyappan, P., Joshi, P.K., Kale, M.P., Srivastav, V.K., Srivasatava, S.K., Behera, M.D., Roy, A., Sharma, Y., Ramachandran, R.M., Bhavani, P., Jain, A.K. and Krishnamurthy, Y.V.N., (2016). "Decadal Land Use and Land Cover Classifications across India, 1985, 1995, 2005," ORNL DAAC, Oak Ridge, Tennessee, USA.

Sacks W.J, Cook B.I, Buenning N, Levis S, and Helkowski J.H, (2009). "Effects of global irrigation on the near-surface climate," *Clim. Dyn.*, vol. 33, no. 2–3, pp. 159–175.

Sang Y. F, Wang Z, and Liu C. (2014). “Comparison of the MK test and EMD method for trend identification in hydrological time series”. *J. Hydrol.*, 510, 293–298.

Santhi, A., Arnold, J.G., Williams, J.R., Dugas, W. A., R. Srinivasan and Hauck, L.M. (2001). “Validation of the SWAT model on a large river basin with point and nonpoint sorces.” *J American water resources Association* 37(5): 1169-1188.

Schickedanz, P. T. (1976). “The effect of irrigation on precipitation in the Great Plains” p. 111.

Schreider, S. Y., Jakeman, A. J., Letcher, R. A., Nathan, R. J., Neal, B. P., and Beavis, S. G. (2002). “Detecting changes in streamflow response to changes in non-climatic catchment conditions: Farm dam development in the Murray-Darling basin, Australia’. *J. Hydro.* 262(1–4), 84–98.

Seckler D, Amarasinghe U, Molden D, De Silva R, Barker R.(1998). World Water Demand and Supply, 1990 to 2025: *Scenarios and Issues*. 19., 1-50.

Segal M, Z. Pan, R. W. Turner, and E. S. Takle, (1998). “On the Potential Impact of Irrigated Areas in North America on Summer Rainfall Caused by Large-Scale Systems,” *J. Appl. Meteorol.*, vol. 37, p. 325–331.

Sen, P. K. (1968). “Estimates of the regression coefficient based on Kendall’s tau.” *J. Am. Stat. Assoc.,* 63(324), 1379–1389.

Shanan L. (1987). ‘*The Impact of Irrigation*’ Land Transformation in Agriculture, John Wiley & Sons Ltd., 115-131.

Shiklomanov I a. (1998). “World Water Resources. A new appraisal and assessment for the 21st century”. *United Nations Educ Sci Cult Organ.* 40p.

Siebert, S., Doll, P., Hoogeveen, J., Faures, J.M., Frenken, K., and Feick, S. (2005). "Development and validation of the global map of irrigated areas”. *Hydrol. Earth Syst. Sci.,* 9, 535-547.

Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Döll, P., and Portmann, F. T. (2010).” Groundwater use for irrigation - A global inventory”. *Hydrology and Earth System Sciences*, *14*(10), 1863–1880.

Singh V. Jain S.K. and Shukla, S. (2010) “Response of hydrological factors and relationships between runoff and sediment yield in the subbasin of Satluj River, Western Himalaya, India”, *Int. J. of Civil and Structural Engineering,* 2, 205 – 221.

Singh, H. P., Sharma, M. R., Hassan, Q. and Ahsan, N (2013). “Performance evaluation of irrigation projects – a case study of lift irrigation scheme Sirsa

Manjholi in Solan area of Shivalik Himalayas". *Asian J. Adv. Basic Sci.*,1(1), 79–86.

Sneyers, R. (1990). "On the Statistical Analysis of Series of Observations". Technical Note no. 143, WMO-no. 415, World Meteorological Organization, Geneva, Switzerland.

Solow, A. R., and Patwardhan, A. (1996). "Extracting a smooth trend from a time series: A modification of singular spectrum analysis". *J. Clim.*, 9(9), 2163–2166.

Sorooshian S, Aghakouchak A, and J. Li (2014). "Influence of irrigation on land hydrological processes over California". *J.Geophysical Research : Atmospheres.* 119: p.1-16.

Srinivasulu A (2003). "Crop water requirements in comparison to actual water applied in some canal commands of Krishna Western Delta". *J. Agric. Eng.,* 40(4), 43–50.

Stidd, C.K. (1967). "Local Moisture and Precipitation". Preprint series No.45, Desert Research Institute, University of Nevada, Reno, p. 34.

Stockle CO. (2001). "*Environmental impact of irrigation: a review."* Washington Water News Briefs., p.15

Subash, N., Singh, S. S., and Priya, N. (2011). "Variability of rainfall and effective onset and length of the monsoon season over a sub-humid climatic environment". *Atmos. Res.*, *99*(3–4), 479–487.

Sun, T., and Feng, M. L. (2013). "Multistage analysis of hydrologic alterations in the yellow river", *River Res. Applic*. 29: 991–1003.

Surendran, U., Sushanth, C. M., George, Mammen and Joseph, E. J (2017). "FAO-CROPWAT model-based estimation of crop water need and appraisal of water resources for sustainable water resource management: pilot study for Kollam district – humid tropical region of Kerala, India". *Curr. Sci.,* 112, 76–86.

Syvitski, J. P. M., Vörösmarty, C. J., Kettner, A. J., and Green, P. (2005). "Impact of Humans on the Flux of Terrestrial Sediment to the Global Coastal Ocean". *Science*, *308*(5720), 376–380.

Tang Q, Oki T, Kanae S, and Hu H (2007). "The influence of precipitation variability and partial irrigation within grid cells on a hydrological simulation". *J. Hydrometeorol.* 8(3):499-512.

Tatsumi K, and Yamashiki Y (2015). "Effect of irrigation water withdrawals on water and energy balance in the Mekong River Basin using an improved VIC land surface model with fewer calibration parameters". *Agric Water Manag*. 159(July):92-106.

Tebakari, T., Yoshitani, J., & Suvanpimol, P. (2012). "Impact of large-scale reservoir operation on flow regime in the Chao Phraya River basin, Thailand." *Hydrol. Process.* 26, 2411–2420.

Thilakarathne M and Sridhar V (2017). "Characterization of future drought conditions in the Lower Mekong River Basin".*Weather and Climate Extremes*,Volume 17,Pages 47-58,ISSN 2212-0947,https://doi.org/10.1016/j.wace.2017.07.004.

Thiruvengadachari, S. and Sakthivadivel, R. (1997), "Satellite remote sensing for assessment of irrigation system performance: a case study in India". *IWMI Research Report 009,* https://doi.org/ 10.3910/2009.017.

Thrasher, B., Xiong, J., Wang, W., Melton, F., Michaelis, A. and Nemani, R.(2013). "Downscaled climate projections suitable for resource management. Eos Trans," *American Geophysical Union*, vol. 94, pp. 321–323.

Trivedi, A., Pyasi, S. K. and Galkate, R. V (2018). "Estimation of evapotranspiration using CROPWAT 8.0 model for Shipra River Basin in Madhya Pradesh, India". *Int. J. Curr. Microbiol. Appl. Sci.*, 7(5), 1248–1259.

Tukey, J. W. (1977). "Exploratory Data Analysis". Reading, MA: Addison Wesley.

Tzagkarakis, G., Papadopouli, M., and Tsakalides, P. (2009). "Trend forecasting based on Singular Spectrum Analysis of traffic workload in a large-scale wireless LAN". *Performance Evaluation*, *66*(3–5), 173–190.

Unnikrishnan, P., and Jothiprakash, V. (2015). "Extraction of Nonlinear Rainfall Trends Using Singular Spectrum Analysis". *J. Hydrol. Eng.*, 5015007(15), 1–15.

Utah State University Foundation, 1969. FAO: http://www.fao.org/3/V8350E/v8350e09.htm (Jan., 2017)

Valdés-Pineda, R., Cañón, J. and Valdés, J. B. (2018). "Multi-decadal 40- to 60-year cycles of precipitation variability in Chile (South America) and their relationship to the AMO and PDO signals". *J. Hydrol.*, *556*, 1153–1170.

Van Griensven, A., Meixner, T., Grunwald, S., Bishop, T., Diluzio, M., Srinivasan, R. (2006)." A global sensitivity analysis tool for the parameters of multi-variable catchment models." *J. of Hydrol.,* 324 (1-4), 10-23.

Verma, R., Gangwar, A., Kumar, M. and Verma, R. K (2019). "Study on water requirement of rice using CROPWAT model for Lucknow Division of Uttar Pradesh". *J. Agri. Search.*, 6(1), 44–49.

Vogl, A. L., and Lopes, V. L. (2009). “Impacts of water resources development on flow regimes in the Brazos River”. *Environmental Monitoring and Assessment, 157*(1–4), 331–345.

Wada Y, Van Beek LPH, Van Kempen CM, Reckman JWTM, Vasak S, and Bierkens MFP (2010). “Global depletion of groundwater resources”. *Geophys. Res. Lett.* 37(20):1-5.

Wang, H., Sankarasubramanian, A., and Ranjithan, R.S. (2015). “Understanding the low- frequency variability in hydroclimatic attributes over the south eastern US”. *J. Hydrol.* 521, 170–181.

Wang, R., Ma, H.G., Liu, G.Q., and Zuo, D.G. (2015). “Selection of window length for singular spectrum analysis”. *J. Franklin Inst.* 352 (4), 1541–1560.

Yang, T., Zhang, Q., Chen, Y. D., Tao, X., Xu, C., and Chen, X. (2008). “A spatial assessment of hydrologic alteration caused by dam construction in the middle and lower Yellow River , China”, *Hydrol. Process.* 22, 3829–3843.

Yapo, P.O., Gupta, H.V. and Sorooshian, S. (1996). “Automatic calibration of conceptual rainfall-runoff models: sensitivity to calibration data.” *J.of Hydrolo.,*181, 23-48.

Yates David., Sieber Jack., Purkey David., Huber-Lee., Annette and Galbraith, Hector. (2005a). WEAP21 - A Demand, Priority, and Preference-Driven Water Planning Model Part 1: Model Characteristics. Water International - *WATER INT.* 30(4). 487-500. DOI:10.1080/02508060508691893.

Yates D., Purkey, D., Sieber J., Huber-Lee., Galbraith H., 2005b. “WEAP21 – A demand, priority and preference-driven water planning model: Part 2: Aiding freshwater ecosystem service evaluation”. *Water Int*., 30(4)., 501-512.

Young R.A., Onstad C. A., David D Bosch and Anderson W. P. (1989). “AGNPS: A Non-Point-Source Pollution Model for Evaluating Agricultural Watersheds.” *J. Soil Water Conserv.*, 44(2), 168-173.

Zeng, R. and Cai, X. (2014). “Analyzing streamflow changes: Irrigation-enhanced interaction between aquifer and streamflow in the Republican River basin.” *Hydrol. Earth Syst. Sci.*, *18*(2), 493–502.

Zhang, X., Zwiers, F. W., Hegerl, G. C., Lambert, F. H., Gillett, N. P., Solomon, S., Peter, A. S. and Nozawa, T. (2007). “Detection of human influence on twentieth-century precipitation trends”. *Nature,* 448(7152), 461–465.

PUBLICATIONS

Journals

- Usha Aswathaiah and Lakshman Nandagiri (2020). "Extraction of Non-Linear Trends in Time Series of Rainfall using Singular Spectrum Analysis". *Journal of Hydrologic Engineering, ASCE*. Vol.25 (12), 04020053-1 to 16.

- Usha Aswathaiah and Lakshman Nandagiri (2020). "Historical Development of Irrigated Agriculture in the Malaprabha Project, Karnataka State, India". *Current Science*. Vol. 119 (7), 1149 to 1158.

International Conferences

- Usha Aswathaiah and Lakshman Nandagiri (2019). "Reservoir and Land-Use Induced Changes in River Flow Dynamics in a Tropical River Basin in India." *Geophysical Research Abstracts* Vol. 21, EGU2019-1658, Vienna, Austria.

- Usha Aswathaiah and Lakshman Nandagiri (2018). "Identification of Rainfall trends using Singular Spectrum Analysis." *Proc., International Conference on Hydraulics, Water Resources and Coastal Engineering*, 19-21 December 2018, NIT Patna.

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