STUDY OF STREAMFLOW RESPONSE TO LAND USE LAND COVER CHANGE IN THE NETHRAVATHI RIVER BASIN, INDIA

Thesis

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

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D E C L A R A T I O N

I hereby *declare* that the Research Thesis entitled **Study of Streamflow Response to Land use Land cover Change in the Nethravathi River Basin, India** Which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfilment of the requirements for the award of the Degree of **Doctor of Philosophy** in the Dept. 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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This is to *certify* that the Research Thesis entitled **Study of Streamflow Response to Land use Land cover Change in the Nethravathi river Basin, India** submitted by BABAR SANTOSH FULAJI (Register Number: AM10F02) as the record of the research work carried out by him, is *accepted as the Research Thesis submission* in partial fulfilment of the requirements for the award of degree of **Doctor of Philosophy**.

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Dedicated to

MY FAMILY

AND

BELOVED TEACHERS

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ABSTRACT

The rainfall over Indian sub-continent is erratic and non-uniform in both South-west monsoon and North-east monsoon, which leads to high floods and severe drought in many places. However, India gets three-fourth of its annual rainfall during south-west monsoon season (June to September). The study of extreme events are significant in stochastic behaviour of rainfall pattern. In this study, frequency distribution method, GEV (Generalized Extreme Value) distribution, Mann-Kendall and Sen's slope estimator are used for rainfall trend analysis over the Nethravathi basin, located in Western Ghats of Karnataka state, India. The rainfall data during the monsoon months (June to September) were analysed for a period of 1971 to 2010. The results from these methods have revealed that there is an increasing trend of frequency in class-1 and decreasing trend in class-2 and class-3 respectively. The interpretation of results was carried by the GEV distribution and nonparametric trend analysis (Mann-Kendall and Sen's slope estimator test). The statistical techniques- Block Maxima (GEV) distribution, Mann-Kendall and Sen's slope estimator test have demonstrated better results compared to frequency based method.

Rainfall and land use land cover are considered to be the driving parameters of streamflow characteristics and cause considerable impacts on hydrologic regime of the watershed level. Therefore, an impact of LULC change on streamflow of Nethravathi river has been studied. Soil and Water Assessment Tool (SWAT) was used to construct the hydrologic model to study land use land cover change on streamflow in the Nethravathi basin. The sensitivity analysis was carried out based on Latin hypercube one factor-At-a-Time (LH-OAT) method using SWAT. The parameters Alpha-Bf, Canmax, Ch_K2, Ch_N2, Cn2, ESCO, Gwqmn, Revapmn, Gw_Dalay, Sol_K and Surlag are found to be most sensitive parameters for the Nethravathi river basin. Since SWAT require more number of input data to run, few to meteorological data are being monitored at the basin level or sub-basin level, it is not possible to use SWAT. Hence, an attempt has been made to propose a newly developed flow routing model called runoff coefficient routing model (RCRM), which is simple and require limited data such as precipitation, LULC and streamflow as compared to other models which require too many input data.

The results of the newly developed RCRM model show better agreement with SWAT model in both calibration and validation period with R^2 and NSE greater than 0.70. Therefore, it is concluded that the RCRM model is capable of predicting the streamflow at par with SWAT model. Hence, newly developed RCRM can be used to simulate and predict the streamflow in the data scarce region or basin. This study investigated the impacts of LULC changes on ET, streamflow and groundwater in the Nethravathi river basin using calibrated SWAT model. The impact results revealed that decrease in forest cover and increase agriculture& urban land, led to an increase in streamflow. It has also led to decreased ET and increased groundwater storage. This study provides useful information about impact of LULC change on streamflow, which may further helpful for flood mitigation and efficient water resources planning and management in the region.

Further, the temporal variation in extreme precipitation events have been analysed for two decades (1991 - 2010). The analysis has shown extreme rainfall events have been reduced in the decade-2 (2001 - 2010) compared to decade-1 (1991 - 2000). Further, this study also analysed the impact of extreme precipitation on streamflow using SWAT model. Three hypothetical LULC scenarios have been developed based on the observed LULC change between 2003 and 2013 by satellite images along with field information. The three scenarios are Conversion to Agriculture (CA), Conversion to Built-up/Urban (CB) and Conversion to Wasteland (CW).The scenario-CB is found to be more sensitive as revealed by the result compared to scenarios-CA and scenario-CW.

An attempt has been made to study the impact of vented dams and runoff-river type hydropower dams (without water storage) on streamflow. The model has shown the negative impact for vented dams as some portion of the streamflow is being used for agriculture or diverted or stored. Nevertheless no change was observed in the streamflow for runoff-river type hydropower dams as there is no storage or diversion of water being made.

The present study results would benefit water managers, decision makes and developmental activities of the Nethravathi basin to implement protective measures for sustainable water resources in basin.

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Notations

Abbreviation	Description
AGRR	Agriculture Land
AGWA	Automated Geospatial Watershed Assessment
a_i	Area of the i^{th} LULC in the sub-basin
Alpha_Bf	Base flow alpha factor
ArcSWAT	SWAT analysis on ArcGIS platform
ASTER	Advanced Spaceborn Thermal Emission and Reflection Radiometer
BM	Block Maxima
$C_{1....n}$	Weighted runoff coefficient at subbasib1-n
CA	Conversion to Agriculture
Canmx	Maximum canopy storage index
CB	Conversion to Build up
Ch_K2	Effective hydraulic conductivity in main channel alluvium
C_i	Weighted runoff coefficient for i^{th} sub-basin
CN	Curve Number
Cn_N2	Manning’s n for the main channels
Cn2	SCS runoff curve number for moisture condition II
CO_2	Carbon dioxide
CW	Conversion to Wasteland
CWC	Central Water Commission
DEM	Digital Elevation Model
ENSO	El Nino-Southern Oscillation
E_o	Potential evapotranspiration
Esco	Soil evaporation compensation factor
ET	Evapotranspiration
ETa	Actual Evapotranspiration

EV2	Extreme Value Type II
FDC	Flow Duration Curves
FRSE	Forest Land
GCP	Global Climate Pattern
GEV	Generalized Extreme Value
GIS	Geographical Information System
GIS	Geographical Information System
GNO	Generalised Normal
GPD	Generalized Pareto Distribution
GPS	Global Positioning System
GW_Delay	Ground Water Delay
Gwqmn	Threshold depth of water in the shallow aquifer required for return flow to occur
H_o	Extraterrestrial radiation
HRU	Hydrologic Response Unit
HRU	Hydrological Response Unit
HYLUC	Hydrological Land Use Change
I_a	Initial abstraction
IDF	Intensity Duration Frequency
IMD	India Meteorological Department
IMS	Integrated Modeling System
INDN	Grass/Waste land
IRL	Indian River Lagoon
IRS	Indian Remote Satellite
ISM	Indian Summer Monsoon
k_i	Runoff coefficient of i^{th} LULC in the sub-basin
KINROS	Kinematic Runoff and Erosion
LH-OAT	Latin hypercube One factor-At-a-Time
LISS	Linear Imagining self scanning
LULC	Land Use Land Cover

MAP	Mean Annual Precipitation
MK	Mann-Kendall
NASA	National Aeronautical Space Agency
NBSS & LUP	National Bureau of Soli Survey and Land Use Planning
NPS	Nonpoint Source Pollution
NRCS	Natural Resources Conservations Service
NRCS-CN	Natural Resources Conservation Service Curve Number
NSE	Nash-Sutcliffe model Efficiency coefficient
OACP	Oceanic-Atmospheric Circulation Pattern
PDO	Pacific Decadal Oscillation
POT	Peak Over Threshold
Q_{gw}	Return Flow
$q_{in,1}$	Inflow rate at the beginning of the time step
$q_{in,2}$	Inflow rate at the end of the time step
$q_{in,ave}$	Average inflow rate during the time step
$q_{out,1}$	Outflow rate at the beginning of the time step
$q_{out,2}$	Outflow rate at the end of the time step
Q_{surf}	Surface Runoff
$R_{1\ldots n}$	Runoff at sub-basin1-n
RCM	Regional Climatic Models
RCRM	Runoff Coefficient Routing Model
R_{day}	Rainfall
Revapmn	Threshold depth of water in the shallow aquifer required for revap to occur
RFA	Regional Frequency Analysis
RHMS	Regional Hydrological Modeling System
RMSE	Root mean square error
RS	Remote Sensing
R_T	Total runoff at the Outlet
S	Potential maximum watershed retention

SCS	Soil Conservation Service
Sol_K	Soil hydraulic conductivity
SPAI	Standardized Precipitation Anomaly Index
SSQ	Sum of Squared Residuals
SST	Sea Surface Temperature
Surlag	Surface runoff lag time
SW_0	The water content available for plant uptake, defined as the initial soil water content minus the permanent wilting point water content
SWAT	Soil and Water Assessment Tool
SW_t	The final soil water content
t	Time in days
T_{av}	Mean air temperature for given day
T_{mn}	Minimum air temperature for given day
T_{mx}	Maximum air temperature for given day
T_t	Travel time
URMD	Urban Land
USDA-ARS	United States Department of Agriculture–Agricultural Research Service
V_{in}	Volume of inflow during the time step
V_{out}	Volume of outflow during the time step
$V_{stored,1}$	Storage volume at the beginning of the time step
$V_{stored,2}$	Storage volume at the end of the time step
WAK	Wakeby
WATR	Water body
W_{seep}	Percolation
λ	Latent heat of vaporization
ΔV_{stored}	Change in volume of storage during the time step

CHAPTER 1

INTRODUCTION

1.1 General

The quote by Fitter (2000) "Water is the elixir of life, without it life is not possible" emphasises the importance of water. Water is the most widespread substance found in the natural environment, which plays an important role in all natural and human activities. In the space of all natural and human environments, hydrological cycle acquires great significance and the hydrological cycle integrates land, air and water. It is also responsible for the transport of water throughout the earth's environment. The transport of the water is an important factor for supply of water to mankind.

In the 20th century, the climate system of earth has been altered significantly. Although other climatic changes have occurred naturally, more and more evidence suggest that the recent warming of the atmosphere is related to the human intervention in the earth's climate. Human activities commonly affect the distribution, quantity, and quality of water resources. The human activities affect the interaction of groundwater and surface water is considerably high. The human activity directly and indirectly has the potential to affect both water quantity, quality and the natural flow regime of a river system. Another reason for causing the change in hydrological regime is the land use change. Landuse changes can cause an indirect impact on the hydrological cycle, while direct impacts can result from withdrawals of water and discharges of water, water diversions and formation of dams (flow regulation and water storage).

Hydrological model is the mathematical model, which describes the physical process of water cycle in a river basin or any representative elements. The hydrological models can be applied on different scales, ranging from local to global scale. At the catchment scale, the hydrological cycle conceptually describes water balance associated with the processes taking place in the stream channels. Modelling of regional water fluxes and water balance studies requires different data sets like, climate parameters, landscape structure, LULC and land management practices, etc. Understanding the consequences of land use change for hydrological processes, and integrating this into the hydrological model is a challenging task and it is necessary for better planning of water resources.

In addition to land use and land cover (LULC) change, the hydrological cycle is also affected by climate change. Rainfall and temperature are the two important climate parameters, which plays a key role in hydrological cycle. Changes in rainfall due to global warming influence the rainfall pattern, which in turn affect the hydrologic regime. Hence, a review of hydrologic design and management practices (Jain and Kumar, 2012) are necessary to account the impacts caused by LULC. In recent years, uneven rainfall patterns (extreme rainfall) have been observed worldwide (Rajeevan et al. 2008; Rahamani et al. 2013). A large amount of the variability of rainfall is related to the occurrence of extreme rainfall events and their intensities. Therefore, there is a need to study the extreme rainfall events to mitigate flood damages and proper design of hydraulic structures.

1.2 Extreme Rainfall Analysis

The studies of extreme events are one of the interesting fields in natural science. The aim of extreme value analysis is to quantify the stochastic behaviour of a process at unusually high or low levels. The stochastic behaviour of extreme events can be analysed by their probability distribution function. The statistical frequency analysis of extreme rainfall can be seen as normalization procedure allowing site-to-site comparison. In the past few years, extreme rainfall events have caused major damage to life, properties, public infrastructure, agriculture and tourism in India and other part of the world. Therefore, several activities rely on rainfall frequencies, such as the design of structures (bridge, barrages, dam) or climate studies and specially variable trends to climate change (Zwiers and Kharin, 1998; Kharin and Zwiers, 2005). The frequency analysis methods are widely used to relate the magnitude of extreme events (e.g. heavy rainfall, floods) to a probability of occurrence (Stedinger et al. 1993) in the context of climate change

1.3 Impacts of Land Use Change on Hydrological Modelling

Human factors are increasingly being recognized as the driving force behind the rates and trajectory of change upon the earth's surface (Turner and Meyer, 1994). Land use planning and management are closely related to the sustainability of water resources as changes in land use are linked with amount of water passing through relevant hydrological processes (Guo et al. 2008). For sustainable management of water resources, effective methods and mechanisms should be used. Therefore, the interaction between LULC and hydrological cycle should be understood thoroughly. Land use changes take place due to human intervention such as deforestation, aforestation, agricultural development and urban development within a river basin. Such LULC changes can affect the hydrological cycle. In addition to these human activities, the construction of large reservoirs, inter basin water diversions and water withdrawal for urban, industrial and agricultural needs, will also affect hydrological regime particularly streamflow (response of surface runoff) over space and time.

In the model performance, a simulated flow is compared with the observed values and same is used to assess the accuracy of the model. The mathematical model can be developed and used in the future for numerous practical applications like flood forecasting, water utilization, constructions of dam/reservoirs etc. This require a combination of modelling capabilities, including rainfall forecasting and forecasted land use for runoff generation mechanisms and hydraulic flood wave propagation based on the runoff predictions. Hence, it is important to understand the hydrological responses due to land use changes in order to develop a sustainable catchment management strategy.

1.4 Role of Remote Sensing (RS) and Geographical Information System (GIS) in Hydrological Modelling

Remote sensing aids acquiring information about a phenomenon/object or surface while at a distance from it. Remote sensing technology collects the data of the earth's surface at spatial, spectral and temporal scales. The spatial data includes land use, vegetation cover, soil, topography, etc. In most of the cases, remote sensing data is directly used for hydrological modelling by extracting input variables such as LULC, soil moisture, rainfall, evapotranspiration (ET), etc. through digital image processing. A geographic information system (GIS) is a tool, which helps to manage, integrate, analyse and manipulate the spatial information including remote sensing data according to the user needs.

Nowadays, GIS platforms have become increasingly dynamic, narrowing the gap between historical data and recent hydrologic reality. GIS has become a useful and essential tool in hydrology for scientific study and management of water resources. Remote sensing and GIS technologies are established tools and are widely used in applied hydrology, forestry, land use dynamics analyses, etc. (Singh, 1989; Coppin and Bauer, 1996; Petit and Lambin 2002). Remote sensing and GIS provides observation of changes in hydrological states, which vary over both time and space that can be used to monitor hydrological conditions and changes.

1.5 Scope of the Present Study

There is an increasing attention given in extreme weather and climate phenomena, such as extreme temperature, storm and extreme rainfall events, due to their potential to cause severe societal, economic and environmental impact (Solomon 2007; Diaz and Murnane, 2008). Since there have been a number of recent extreme rainfall events that have caused loss of lives and serious economic damages to property and infrastructure. In particular, there is an increasing interest in learning more about the frequency and intensity of extreme rainfall events that occur as a result of climate change. Extreme rainfall events and increased climate variability are believed to have a greater impact than long-term changes in the mean of climatic variables (Katz and

Brown, 1992; Fischer and Schar, 2009). Hence, the present study aims to study extreme rainfall events and its impact on streamflow.

"Change" can be interpreted in several ways for a given catchments. A catchment that shows a systematic deviation in land cover or climate conditions outside the range of the historic record can be considered as changing catchment (Thirel et al. 2014). In addition to change in climate conditions, the land use change also plays an important role to study the hydrological system. For better understanding of, how hydrological system respond to changing conditions is an important issue studied by various researchers. This study helps to improve the prediction of the impacts of various future environmental changes (Peel and Bloschl, 2011). Hence, the present study has been carried out to study the impact of land use change on streamflow in the Nethravathi river basin. The outcome of the present work would contribute in sustainable development of water resources and management.

1.6 Objectives of the Study

The objectives of this study are:

1. To study the extreme rainfall variability over the Nethravathi basin.
2. To study the streamflow for extreme rainfall variability over the Nethravathi river basin.
3. To develop a hydrological model to predict the streamflow.
4. To study the effect of land use land cover change on streamflow of the Nethravathi river.
5. To study effect of hydropower and vented dams on streamflow.

The study employs a newly proposed Runoff Coefficient Routing Model (RCRM) and Soil and Water Assessment Tool (SWAT) to assess the impacts of LULC change on streamflow of the Nethravathi river basin using remote sensing and GIS techniques over a period of 10 years (2001-2010).

1.7 Organisation of Thesis

The thesis is divided into seven chapters followed by list of references and publications.

Chapter 1 Introduction; it provides an overview of key issues and rationale of this research and objectives, those form the basis of the study.

Chapter 2 Literature review; this chapter outlines the state of the art, various hydrological models, case studies and an overview of research methodology. A research gap, which has been presented in the concluding remarks at the end of this chapters.

Chapter 3 Physiographic description of study area; this chapter describes physiographical features of the study area, location, soil, elevation, LULC and climate parameters such as rainfall, temperature, humidity etc.

Chapter 4 Extreme rainfall analysis; this chapter elucidates the method and analysis of extreme rainfall. There are three methods used in the study. They are frequency based method, GEV (Generalized Extreme Value) distribution (Block Maxima method) and Mann-Kendall with Sen's slope estimator test. The results and discusions of extreme rainfall studies are presented at the end of this chapter.

Chapter 5 Development of hydrological models; this chapter, describes the model development, detailed descriptions about the model selection and model setup. Further, it describes the newly proposed RCRM as an alternate method over SWAT model to estimate runoff. This chapter further estimates the model performance of SWAT model and the proposed RCRM results. The study of LULC change analysis from satellite data is also presented. The calibration and validation results of SWAT and RCRM are presented and discussed at the end of this chapter.

Chapter 6 Impact studies; this chapter, deals with the study of LULC change impacts on streamflow using SWAT model. This chapter also includes the streamflow response of the river due to LULC change for an extreme rainfall event. Further, the chapter is focused on estimation of hydropower potential based on the information available from hydropower projects in the river basin. The study has been carried out related to impact of vented dams on streamflow.The results and discusions of impact studies are presented at the end of this chapter.

Chapter 7 Summary; this chapter represents an overview of results, discussions and conclusions based on chapter 4, chapter 5 and chapter 6. This chapter also discusses scope for future studies that can be taken up.

Figure 1.1 represents the structure of this thesis.

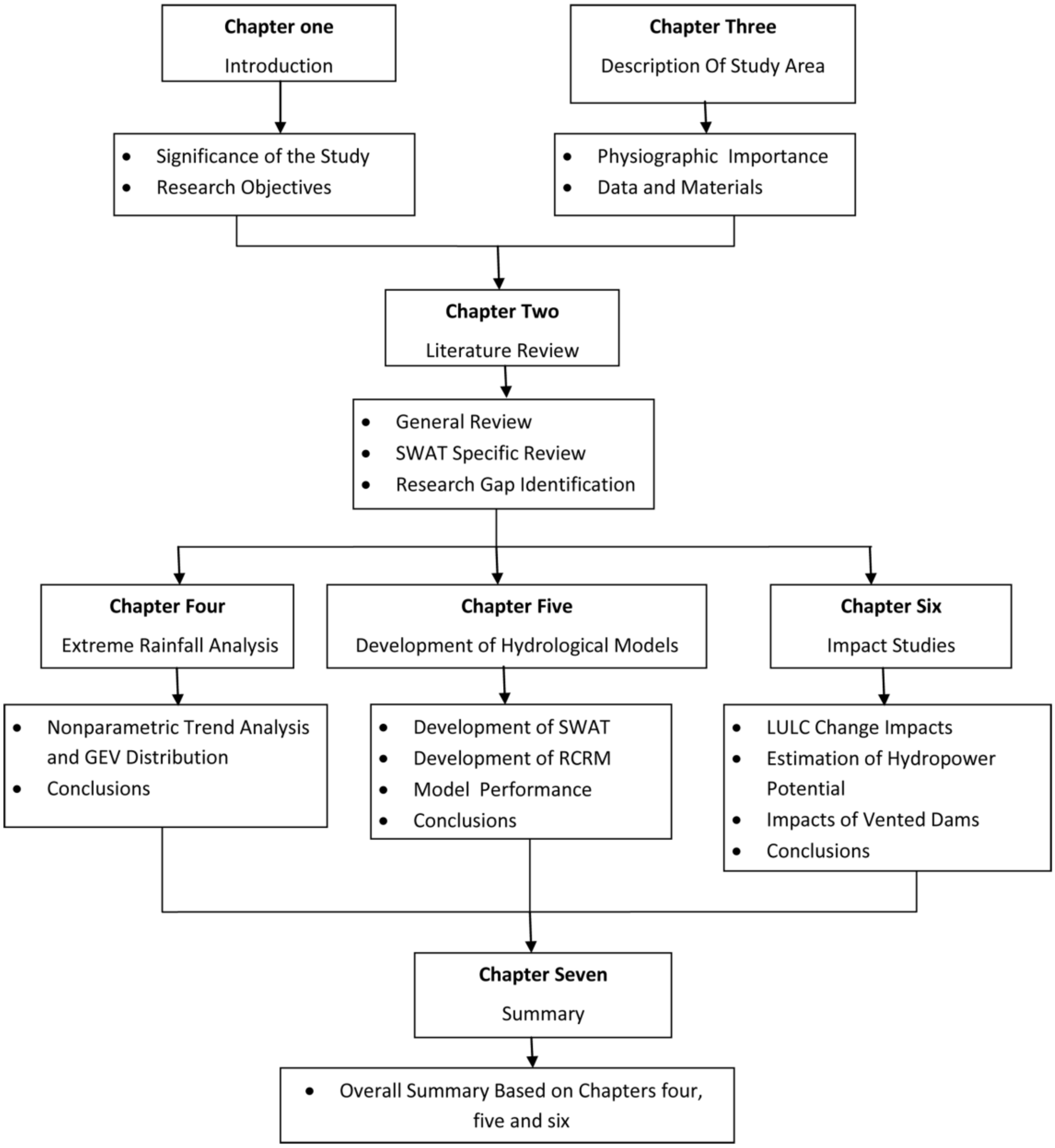


Figure 1.1: Thesis structure

CHAPTER 2

LITERATURE REVIEW

2.1 General

Anthropogenic environmental changes, such as LULC change driven by rapid human population growth and increasing demand for agriculture are causing serious impact on the terrestrial hydrologic cycle. LULC change affects different hydrological processes like evapotranspiration, runoff generation and groundwater. In this regard, it is necessary to study the impacts of LULC changes on hydrological regime. Several attempts have been made in recent times to analyse the impacts of LULC change on various hydrological parameters.

LULC change also leads to increased carbon emissions (due to rapid industrialization and urbanization) has a major impact on the water cycle and the climate (Praskievicz and Chang, 2011). Carbon dioxide and other ‘greenhouse gases’ affect the energy balance, ultimately leading to weather changes. Studies indicate that extreme weather events such extreme rainfall events have become more frequent and more intense with human-induced climate change. Therefore, the extreme rainfall events and change in LULC are becoming a serious issue nowadays and need scientific research to understand inter-relationships.

This chapter presents a review of available literature pertaining to the study of extreme rainfall events, LULC changes and water storage structures such as vented and hydropower dams on hydrological regime.

2.2 Extreme Rainfall Analysis

In recent years, extreme rainfall events have caused several damaging floods (e.g., Mumbai in 2005 and Uttarakhand in 2013). Studying these extreme rainfall events is very important as it affects the design, implementation and operation for effective flood mitigation. Therefore, it is vital to evaluate such extreme events for knowledge discovery so that better flood mitigation policies can be developed. Several attempts have been made to analyse the extreme rainfall events around the world and most of the results indicated that extreme rainfall analysis helps to improve water resources planning and management.

Naghavi and Yu (1995) made an attempt to formulate a practical procedure for regional rainfall frequency analysis. The study suggested use of the generalized extreme value distribution along with the indexed regional probability weighted moments for analyzing extreme rainfall data at Louisiana. **Crisci et al. (2002)** analysed the extreme rainfall in Tuscany, Italy, with an aim of understanding and quantifying the uncertainties linked to the estimation of design storms. Pearson correlation coefficient and Mann–Kendall test were used to analyse the extreme rainfall events. Generalized extreme value distribution was employed to compute design storms with a 30-year return period. The results obtained by Pearson correlation coefficient and Mann–Kendall tests indicated the change in rainfall behaviour from early 1970s. The spatial distribution of the design storms estimated by the GEV distribution was used for detection of the areas affected by the heavy rainfall events.

Tao et al. (2002) compared the performance of different probability distributions in order to identify an appropriate model to provide the most accurate extreme rainfall estimates at a particular site. Based on graphical and numerical comparisons, it was found that the Generalized Normal (GNO), Wakeby (WAK) and GEV could provide the most accurate extreme rainfall estimates. **Fowler and Kilsby (2003)** estimated the long return-period rainfall events when individual records were too short for allowing reliable estimation. Daily rainfall records from 204 sites across the United Kingdom from 1961–2000 were used to develop rainfall growth curves for 1, 2, 5 and 10 day. In this study, the rainfall frequency analysis based on L-moments (Hosking and Wallis, 1997) was used to produce rainfall growth curves with an extreme value distribution. From the results, a little change was observed at 1 and 2 days duration, but significant decadal-level changes were found in 5 and 10-day events in many regions.

Koutsoyiannis (2004) investigated the extreme value distribution of rainfall based on theoretical analysis. The analysis was performed using a collection of 169 stations, each having 100 – 154 years daily rainfall data. The results showed that the shape parameter of the extreme value type II (EV2) distribution was constant for all examined geographical zones of Europe and North America, with a value of $\kappa = 0.15$. This simplifies the general mathematical modeling of the distribution. The two-parameter special cases of the GEV distribution, i.e., the Gumbel and Frechet distributions are considered appropriate for modeling annual maximum rainfall series.

Baldassarre et al. (2006) investigated the relationships between statistical properties of rainfall extremes and the mean annual precipitation (MAP). Based on the relationships, a regional model was developed for estimating the rainfall depth for a given storm duration and recurrence interval in any location of the administrative regions of Emilia-Romagna and Marche, in northern central Italy. The applicability of the regional model was assessed through Monte Carlo simulations. The spatial interpolation of rainfall extremes or MAP was adopted. The results were able to provide an overly simplified representation of differences between the existing leeward and windward sides of the same mountain. **Jiang et al. (2007)** carried out a study on trend identification of precipitation extreme events. The author found better results by Mann-Kendall test. The results were also shown a significant positive trend in the number of rainstorm days (daily rainfall >50mm). The increased number of rainstorm frequency, rather than intensity, on the middle and lower reaches was contributed to the positive trend in summer precipitation in the Yangtze, China.

Deshpande et al. (2008) estimated point probable maximum precipitation (PMP) and maximum rainfall of different return periods. In this study, data of 210 stations in the Indus basin were used to carry out the extreme rainfall analysis by statistical methods. The results highlighted the importance of extreme rainfall analysis in planning, designing and management of different types of hydraulic structures for optimum utilization of water resources in the basin. **Rajeevan et al. (2008)** studied the trends of extreme rainfall events over India using 104 years (1901- 2004) gridded daily rainfall data. The study showed significant inter-annual and inter-decadal variations in frequency of extreme rainfall events. Detailed analysis showed that inter-annual, inter-decadal trends of extreme rainfall events were modulated by sea surface temperature (SST) variations over the tropical Indian Ocean.

Toffol et al. (2008) analysed different intensities of rainfall events relevant for the urban drainage. The author also investigated the trend analysis using Mann-Kendall test from the Alpine region, Tyrol. The results showed that there is an increase in the number of extreme rainfall events for short durations. It was also found that the short duration intensities were the result of cyclic changes in the rainfall pattern. **Douglas and Fairbank (2011)** have undertaken a study to investigate the presence of trends in extreme precipitation using linear regression and the Mann-Kendall trend test. The results showed Mann-Kendall trend test performed better in detecting trends when compared to linear regression.

Guhathakurta et al. (2011) analysed some of the extreme rainfall indices using reliable, consistent and sufficient amount of rain gauge station data. The study used Mann-Kendall test to identify the changes in the frequency of rainy days as well as heavy rainfall days. **Malik et al. (2012)** analysed the summer monsoon (March to April) rainfall over Indian region using nonlinear spatial correlations. This study conveyed several critical insights into the underlying atmospheric processes responsible for the evolution of Indian summer monsoon (ISM) and related extreme rainfall events. The results indicated the presented method not only helped in visualising the structure of extreme event rainfall fields, but also identified the water vapour pathways and decadal-scale moisture sinks over the region.

Jain and Kumar (2012) reviewed studies related to rainfall trends, rainy days and temperature over India. The study used Mann-Kendall and Sen's slope estimator test to estimate the magnitude of rainfall trend. **Devi and Choudhury (2013)** carried out extreme rainfall frequency analysis for Meteorological Sub-Division 4 of India using L-moments approach. The Serial correlation and Mann-Kendall tests were used for checking autocorrelation and stationarity of the observations. The autocorrelation test indicated that data were serially independent. The return periods for the field data in the sub-division were almost in the range of 1, 2, 5, 10 and 20 years.

Morga et al. (2013) evaluated the variability of extreme annual, seasonal and daily precipitation events and their relationship to inter-annual and inter-decadal phenomena such as El Nino-southern oscillation (ENSO) and Pacific decadal oscillation (PDO). In this study, Mann-Kendall test was used to identify extreme rainfall trends. **Rahamani et al. (2013)** explored rainfall distribution patterns using extreme rainfall frequencies in Kansas. Results showed that there was a shift in the rainfall distribution patterns in Kansas across both time and space. **Wang et al. (2013)** assessed the changes in rainfall patterns for extreme rainfall intensity and frequency. In this study, outputs from an ensemble of regional climatic models (RCMs) were used. The results showed that the potential temporal shift in extreme rainfall events coupled with increased intensities might exacerbate flood magnitudes and lead to increased sediment and nutrient loadings to the estuary.

Chanda and Maity (2015) established the cause of precipitation extremes from a single or a few preselected coupled oceanic-atmospheric circulation patterns (OACPs). The author explored the global fields of six climatic variables to identify the potential global climate pattern (GCP) for influencing the Indian rainfall. The results showed the extreme events can be identified by standardized precipitation anomaly index (SPAI). The combined information extracted from the GCP proved to be highly efficient in predicting dry and wet events in Indian rainfall. **Liu et al. (2015)** estimated the return period for the February 2007 event in Jakarta. The author also investigated the frequencies and magnitudes of extreme rainfall events in Jakarta region by regional frequency analysis (RFA) based on L-moments approach (Hosking and Wallis, 1997). The results showed that there was a need for cautious use of established intensity duration frequency (IDF) curves for larger than 30-year return period. The study found that IDF curves can be beneficial for the policy makers, stakeholders as well as researchers in the field of water resource management.

2.3 Impact of Land Use Change Studies

Land use change processes occur at the interface between human and environmental systems. LULC change plays a key role in controlling the hydrological response of watersheds leading to changes in peak flow characteristics, total runoff, water quality, and hydrologic regime. There have been many studies examining the hydrological response to land use change around the world and most of the results indicated that the impact was due to land use change on water resources. With the change in LULC, the river basins have been facing serious problems of flood, water quality deterioration, water shortage, etc., which critically threatens the living population on the environment and restricts the sustainable development of the regional economy.

Better understanding of the impact mechanism of LULC change on hydrological processes is crucial for sustainable water resources management. Hence, apparently it is necessary to carry out systematic research studies on the LULC and its probable impact on hydrology and land resource for sustainable development and management. Therefore, some of the significant literature on LULC change and its probable impact on hydrological regime has been collected, reviewed and summarized as follows.

Hernandez et al. (2000) evaluated the effects of land cover change and spatial variability of rainfall on the hydrological response of a watershed. In this study, two hydrologic models, namely Kinematic runoff and erosion (KINROS) and SWAT were applied on a small semi-arid watershed. The simulation results showed that both models were able to characterize the runoff response of the watershed due to land cover changes. The impact of land use on hydrologic response in a forest was assessed by **Wooldridge et al. (2001**) using simple semi-distributed model. The model results revealed qualitative evidence and helped to improve confidence level of investigation in the land use change studies on hydrological processes. **Kim et al. (2002)** studied the effects of land use change on runoff volume in the Indian river lagoon (IRL) watershed, Florida using SWAT model. Results indicated that the land use change has shown a dramatic impact on annual runoff.

Miller et al. (2002) analysed land cover change in the watersheds that contribute to runoff of the upper San Pedro river in Sonora, Mexico, and the southeast Arizona. The results demonstrated that the usefulness of integrating remote sensing data and distributed hydrologic models for assessing hydrologic response in the watershed. **Pikounis et al. (2003)** investigated the hydrological effects of specific land use changes in Pinios river, central Greece catchment using SWAT on a monthly time step. The results of the proposed changes in land use scenarios have shown increase in runoff during wet months and decrease during dry periods. The deforestation scenario was the one that resulted in the greatest modification of total monthly runoff in this study.

Croke et al. (2004) predicted hydrologic response in gauged and ungauged catchments under forest cover change. Results showed as the forest cover decreases, the proportion of streamflow volume in the quick flow component increases. Therefore, the impacts of forest cover change led either increase or decrease in annual wet season discharge and reduce dry season discharge. **Mutie (2006)** studied the hydrological response of land cover change in the Mara river basin, Kenya. The developed hydrological model was run separately with the reclassified LULC datasets of 1973 and 2000. The study has depicted that the water resources are reasonably changing at an alarming rate.

Stackelberg et al. (2007) simulated the hydrologic response of the two catchments and predicted the hydrologic effects of converting the native pasture to pine plantation. The results showed that conversion of the catchments from the baseline pasture condition to grassland resulted in a reduction of average annual water yield. The model also predicted a reduction in mean annual water yield from the catchment. **Choi and Deal (2008)** carried out comparative research on Cellular Automata approach distributed model, dynamic, spatial urban growth model and a semi-distributed continuous hydrological model to predict hydrological variable response. The study recommended that the distributed land use change model and semi-distributed hydrological model are good decision support system for long-term scenario-based assessment.

Li et al. (2009) assessed the impacts of land use change and climate variability on surface hydrology (runoff, soil water content and evapotranspiration) in an agricultural catchment using SWAT model. Results indicated that the SWAT model proved to be a powerful tool to simulate the effect of environmental change on surface hydrology, particularly runoff and soil water. **Savary et al. (2009)** introduced a methodology to assess possible hydrological response of the Chaudiere river watershed, Canada, using integrated modeling system (IMS). The results confirmed that the hydrological regime of the Chaudiere river was highly sensitive to land cover. **Delgado et al. (2010)** carried out a test on hydrological land use change (HYLUC) model to simulate daily flows and water balance of the Cardener river basin (NE Spain). The model simulated the historical daily flows and annual water balances of Cardener river basin. The model also provided good results in dry period rather than wet period.

Sang et al. (2010) implemented the SWAT model in the regions completely affected by human activities using long-term measured climate and hydrologic data of Tianjin. The model showed good result in the water resource and water environment management in the area of strong human activity. **Bharati and Jayakody (2011)**

investigated the effect of water resource development (Farakka Barrage) as well as the influence of land use change on hydrology and water balance of the Gorai river catchment. The results showed that there was a reduction in upstream inflows due to construction of the barrage, which was a major reason for reduced discharges into the delta.

Homdee et al. (2011) investigated potential impacts of LULC on the water budget of the Chi river basin in Thailand using SWAT model. Five plausible scenarios of land use change were evaluated, including a conversion of forested area, expansion of farmland and switching of rice paddy fields to energy crops. The results showed a decrease in Evapotranspiration (ET) by nearly 12% and increase water yield by 5.1% during dry season. The conversion of farmland to a sugarcane plantation for biofuel production showed significant effect on seasonal ET. **Masih et al. (2011)** simulated impacts of increasing water consumption in the upstream rain-fed areas of the Karkheh Basin, Iran using SWAT model. Three scenarios were tested at sub-basin and basin levels: converting rain-fed areas to irrigation agriculture (S1), improving soil water availability through rainwater harvesting (S2), and a combination of both (S3). In this study, it was recommended that only a limited agricultural area could be converted from rain-fed to irrigated agriculture.

Nie et al. (2011) quantified the contributions of changes from individual LULC classes on hydrological process in the upper San Pedro watershed using SWAT model. The results revealed that the urbanization was the strongest contributor to the increased surface runoff and water yield. Further, the study also identified that replacement of desert scrub by mesquite was the strongest contributor to the decreased base flow/percolation, were responsible for increased ET. **Palamuleni et al. (2011)** investigated impacts of land cover change on the degradation of the flow regimes for the Upper Shire river. The simulation results showed that 2002 land cover data produced higher flow peaks and faster travel times compared to the 1989 land cover data. This was mainly due to the LULC changes detected from 2002 and 1989 date.

Dixon and Earls (2012) used SWAT coupled with GIS to examine the land use change (Urbanization) on streamflow. The results indicated that the SWAT model can simulate (e.g., increased urban area) the streamflow due to changes in urban class. **Getachew and Melesse (2012)** identified the impact of land use change on the hydrology of the Angereb watershed and suggested remedial measures using SWAT model. The results revealed that the wet season flow increased for the most recent years, while the dry season flow decreased considerably due to land use change. This was mainly attributed to land degradation (conversion of forest to agriculture). The study recommended that, LULC change can be controlled in the watershed and some measures could be taken for the planning and management of the land cover change.

Hamad et al. (2012) evaluated the effect of land use change on the water budget of the Gaza Strip using automated geospatial watershed assessment (AGWA) and SWAT modeling environment. A unique linear relationship between the relative change in urban areas and the corresponding relative change in surface water has been investigated from the simulation results. Further, the study found that the analysis of different urbanization scenarios led to make decisions for the future development. **Hosseini et al. (2012)** investigated the effects of land use changes on water balance of the Taleghan catchment before and after the dam construction. SWAT model was used to predict water balance in the middle and at the outlet of the catchment. The results indicated a progressive increase in surface runoff and decline in interflow and groundwater flow due to dam construction. Further, the study highlights the need to control of the accelerated degradation of the natural resources that had taken place during the last decade.

Liroang and Jianyun (2012) analysed hydrological response to climate change using SWAT model in the Beijiang river basin, China. The authors used 15 sets of climate scenarios under the same land use situations. The results show that increase in temperature, evapotranspiration and decrease in water yield for the given rainfall. Additionally, ET and water yield increases rainfall when temperature was kept same. **Liu et al. (2012)** used regional hydrological modeling system (RHMS) in Huaihe river basin in East China to study streamflow. The results demonstrated the effectiveness of the applied method (RHMS) to study streamflow modeling which helped real flood forecasting. **Nie et al. (2012)** quantified how mesquite (species of small trees in the genus Prosopis) encroachment influences the major hydrological processes at the basin scale. This study was especially relative to the potential impact of landscape change on water provisioning. The simulation results showed that the annual average ET increases with the removal of grassland, while surface runoff and percolation decreases with mesquite encroachment.

Yang et al. (2012) examined the land developments such as tourist complexes, development of residential properties and construction of impermeable layer (roads) affects the amount of direct runoff in major streams of Jeju Island using the SWAT model. The results showed that impermeable land development led to considerable increase in the runoff. In addition, it was found that the amount of direct runoff increased by 1 to 6%. **Baker and Miller (2013)** used SWAT model to determine hydrological alterations due to land use changes in the Njoro river watershed. The simulation results showed the land use changes have resulted in increased surface runoff and decreased groundwater recharge. The study also found hydrologic regime was significantly affected by spatial and temporal LULC change in the uppermost reaches of the forested highlands. These changes led to negative impacts on the ecological health of the river system (Lake Nakuru).

Du et al. (2013) quantified the hydrological processes in a rapid urbanization region of Qinhuai river basin, China by SWAT model. In terms of long-term water balance and flood event simulations, the results showed that varied parameterization approach has a large improvement over the conventional fixed parameterization approach. The proposed modeling approach provided an essential reference for the study to assess the impact of LULC changes on hydrology of the Qinhuai basin. **Fang et al. (2013)** carried out a case study to investigate the impacts of LULC changes on the catchment-scale hydrological cycle in the Laohahe river catchment using SWAT model. The results have shown improved understanding in modeling of hydrologic responses to LULC changes. These results helped in decisions making for agricultural area in the Laohahe river catchment.

Li et al. (2013) assessed the impacts of land use change on soil water and river health of upper Huaihe river basin, China using SWAT model. The results indicated that the SWAT model proved to be a powerful tool to simulate runoff generation satisfactorily. The authors also proposed different land use change scenarios to study the rainfall-runoff relationship. The changes in land use scenarios alter the rainfall-runoff relationship. The results also showed that for same amount of rainfall, farmland produced the most runoff while woodland produced the least runoff. **Nyeko et al. (2013)** analysed the degree to which water yield in a particular basin can be changed by altering the vegetation cover. The study investigated the impact of changes in spatial afforestation, agroforestry and agricultural land use policies on water resource availability. The results indicated that the afforestation reduced water yield, while agroforestry and agricultural land use increased the water yield in a basin level.

Prasena and Shrestha (2013) assessed the effects of land use change on runoff in the Bedog sub-basin using Soil and Water Assessment Tool-Water Balance (SWAT-WB) model. The results have shown the change in land use that found to be responsible for an increase in annual runoff between 3.42% – 4.67%. This study has shown the dynamics of surface runoff due to LULC change. **Wagner et al. (2013)** assessed land use change impacts on water resources in an area with limited seasonal water availability. The results indicated that an increase in agricultural area leads to changes in water availability and water demand in the dry season due to increased utilization of irrigation water.

Zhou et al. (2013) examined the impacts of land use change on hydrological fluxes in a rapid urbanization in the lower reach of the Yangtze river basin. The results showed the urbanization on hydrological fluxes were different in different seasons. The increase in surface runoff caused by urban expansion was higher in wet years than in dry years. **Krishna et al. (2014)** simulated the impact of change in land use on water yield of the upper Manair catchment of the upper Manair dam using SWAT model. The model simulated water balance components by reducing the area under paddy cultivation through three alternate cropping scenarios. The results revealed that reduction in area under paddy cultivation and allowing the same area to be irrigated with dry crops could lead to a sustainable water resource management policy.

Pereira et al. (2014) evaluated the possible impacts of deforestation on the key water balance components in the Galo creek watershed. Simulations in different scenarios accounted that deforestation could cause decrease in evapotranspiration and an increase in the total runoff. The results concluded that an increase in forest cover can ensure a minimum flow in the dry season and thus normalize the maximum flow in the flood period. **Younghun et al. (2014)** analyzed the spatial and quantitative changes of land use influence on hydrological response of Gapcheon watershed. The results demonstrated that as urban area increased, the daily streamflow also increased. The study concluded that quantitative change in land use had a significant role in the catchment water balance. **Zhu and Li (2014)** analysed the long-term (1984 to 2000) impacts of LULC change on streamflow and nonpoint source pollution (NPS) for the Little river watershed using SWAT. The results revealed a 3% increase in streamflow for the whole watershed from 1984 to 2010.

Can et al. (2015) evaluated the impact of several LULC change scenarios on hydrology and sediment movement in the Fuhe river system using SWAT model. The results of four hypothetical LULC scenarios revealed that for same precipitation, basin slope and soil texture; the paddy fields produced more amount of runoff whereas the groundwater recharge and ET reduced. **Deng et al. (2015)** analysed the impact of land use change on various hydrological factors using different land use scenarios. In this study three land use scenarios (1980, 2000 and simulated land use upto 2020) were established. Then the surface runoff and evapotranspiration for each scenario was simulated using the SWAT model. The results revealed that SWAT could be used as a useful tool for simulating surface runoff and potential evapotranspiration in a watershed.

Eshtawi et al. (2015) quantified the impact of urban area expansion on the surface runoff and coastal aquifer recharge using SWAT model. The SWAT model successfully simulated the water budget components like percolation, surface runoff and evapotranspiration. The study concluded that the SWAT model could effectively simulate the surface runoff, ET and groundwater storage in a complex watershed. **Li et al. (2015)** investigated the changes in the hydrological processes under different land use scenarios based on the degrees of water constraints. Specifically, according to the improvement of the water utilization ratio, three land use scenarios were designed. The results indicated both surface runoff and water yield changed with forest and grassland expansion. The impacts of LULC change on hydrological processes were found to be complex, wherein runoff showed a decreasing trend with an expansion of forest and grassland.

Lu et al. (2015) investigated the impact of LULC changes on the hydrology of the upper Fenhe river watershed by an integrated approach, which used hydrological modeling and remotely sensed digital maps of LULC changes. The study also investigated the contribution of individual LULC changes on the runoff. The results showed the LULC changes in the upper Fenhe river watershed increases PET and water yield. While the expansion of the forest and grassland increased the PET and AET, the study also found that soil and water conservation practices increased the runoff. The results proved to be helpful for the better water resources and land use planning and management.

Ouyang et al. (2015) identified the impact of long-term land use conversion on water cycle dynamics in the freeze and thawing agricultural area using SWAT model. The results from this study showed that multiple data sources for farmland eco-hydrological analysis could be used for an efficient irrigation management. The integrated weather, irrigation, and soil water information can be used for optimal irrigation practices leading to less withdrawals of groundwater. **Quyen et al. (2015)** assessed the impact of land use change on runoff in the Srepok watershed by applying GIS and SWAT model. The results showed that increasing land use scenario resulted less surface flow, whereas the lateral and base flows are increased. Further, the study recommended the best land cover ratio for Srepok watershed.

Rodrigues et al. (2015) evaluated the impact caused by changing land use on water availability in the Para river basin (Minas Gerais) using SWAT model. The study involved replacing original vegetation by pasture. The results showed that conversion of 38% natural vegetation to pasture land caused a 8.36% decrease in mean evapotranspiration over the whole basin. It was also observed that the river flow had increased by 10% due to changes in land use. **Santos et al. (2015)** assessed the impact of the land use changes between the periods 1967−1974 and 1997−2008 on the streamflow of Tapacura catchment (North-eastern Brazil) using the SWAT model. The result has shown a reduction in mean wet monthly flow for 1997−2008 land cover decreased by 12.6% when compared to the land cover in 1967−1974. The study concluded that SWAT model performed satisfactorily for simulating the runoff in the Tapacura watershed.

Schilling et al. (2015) evaluated the role of sub-basins with different dominant land covers on streamflow of Clear Creek, Iowa, USA watershed having 27.5 Km^2 using SWAT model. Hydrologic output from urban sub-basins further showed evidence for increased flashiness, indicated by an increased frequency in high flow; rapid rise and fall rates and short duration of high and low flood pulses. The results indicated the land cover plays a dominant role in controlling hydrologic variability in the sub-basin level within a watershed. **Sukwimolseree and Kosa (2015)** determined the effects of the land use change on surface runoff in the upper Mun river basin by applying SWAT model. The SWAT model was able to evaluate the surface runoff that helps to understand the inter-relationship between hydrological components in the Mun river basin.

Wu et al. (2015) analyzed the effects of afforestation on the water yield using SWAT model. The results concluded that during 1980 – 2010 there was a significant positive relationship between afforestation and water yield in the upstream area of the Heihe river basin. The annual water yield increased by 1.2 mm when the forest cover increased by 1%. The results found to be beneficial in improving the sustainable forest management to evaluate the impacts of different forest management scenarios on hydrology of Heihe river basin.

2.4 Summary of Literature

From a review of the past studies on LULC change on hydrology and water resources found that the river basin studies are most essential for sustainable water resources development and management. The water balance method is widely used to estimate the hydrological components in a river basin. Due to the availability of streamflow data at gauging station, a model can be calibrated and validated with respect to time and space. There are several studies have been carried out across the world based on water balance, numerical and spatial models in a river catchment

The previous studies on the extreme rainfall analysis revealed that the extreme rainfall analysis plays a major role in design, implementation and operation of flood measures. It also focused on important to assess the changes in rainfall patterns for extreme rainfall intensity and frequency. Hence, there is a wide scope to study the characteristics and behaviour of extreme rainfall events. The extreme rainfall analysis can be studied by GEV distribution method as well as nonparametric trend analysis.

The past studies revealed that the use of remote sensing techniques in hydrological models play a major role in accounting realistic LULC. Hence, there is a wide scope to study the characteristics and behaviour of streamflow responses due to change in LULC. The streamflow response can be studied by developing a distributed hydrological model like SWAT. Further, it is found that there are limited studies found on storage structures like dams, barrages, etc. and their probable impacts on streamflow response. Therefore, there is a need to develop a regional hydrologic model integrating such storage structures along with LULC change.

However, several studies have been carried out the study of streamflow response to LULC change using SWAT model. Since the input parameters in the SWAT model is more, some of the data like radiation, humidity, wind speed, etc. are not being monitored at sub-basin level in many watersheds. In such situations, the SWAT model cannot be used. To overcome this difficulty of providing all meteorological data, an attempt has been made to develop a simple runoff model, which can be applied as a distributed model consisting only precipitation, LULC and the hydrologic soil data to estimate runoff. This research has proposed a runoff model called “Runoff Coefficient Routing Model (RCRM)”,works based on runoff and weighted runoff coefficients for each sub-basin.

CHAPTER 3

DESCRIPTION OF STUDY AREA

3.1 Physiographic Description of Study Area

The Western Ghats, locally called ‘Sahyadri Range’ are unbroken relief consisting thick tropical forest to the west coast of the Indian peninsula, for almost 1600 km extending from Tadri in the north to Kanyakumari in the south. All major rivers of south India are originate in this Western Ghat hill range. The Western Ghat regions can be divided into three zones,

1. Northern zone (Surat to Goa)
2. Central zone (Goa to Nilagiri hill)
3. Southern zone (below Phalgat gap)

The annual rainfall in the Western Ghats varies from 1500 mm to 5000 mm and annual average is about 3000 mm. Rainfall in the Western Ghats occurs during three separate seasons, pre-monsoon (March to May), south-west monsoon (June to September), and north-east monsoon (October to December), which contribute about 4%, 90% and 6% of the total annual rainfall respectively.

Nethravathi river basin is selected for the present study. The Nethravathi river basin lies in the central zone of Western Ghats, covering western part of Karnataka state. The Nethravathi river basin experiences a wide variation of climate, LULC and topography. This study has been conducted to study the effects of LULC change on streamflows of the Nethravathi river basin. The Nethravathi river is one of the important west flowing rivers in the state of Karnataka. Some of the popular religious and pilgrimage places are located on the banks of this river. They are Dharmasthala, Kukke Subramanya, Bantwal, Mangalore, Pane Mangalore and Ullal. The geographical location of the Nethravathi river basin lies between 12º29'11" N to 13º11´11"N latitudes and 74º49´08" E to 75º47´53" E longitudes as shown in the Figure 3.1.

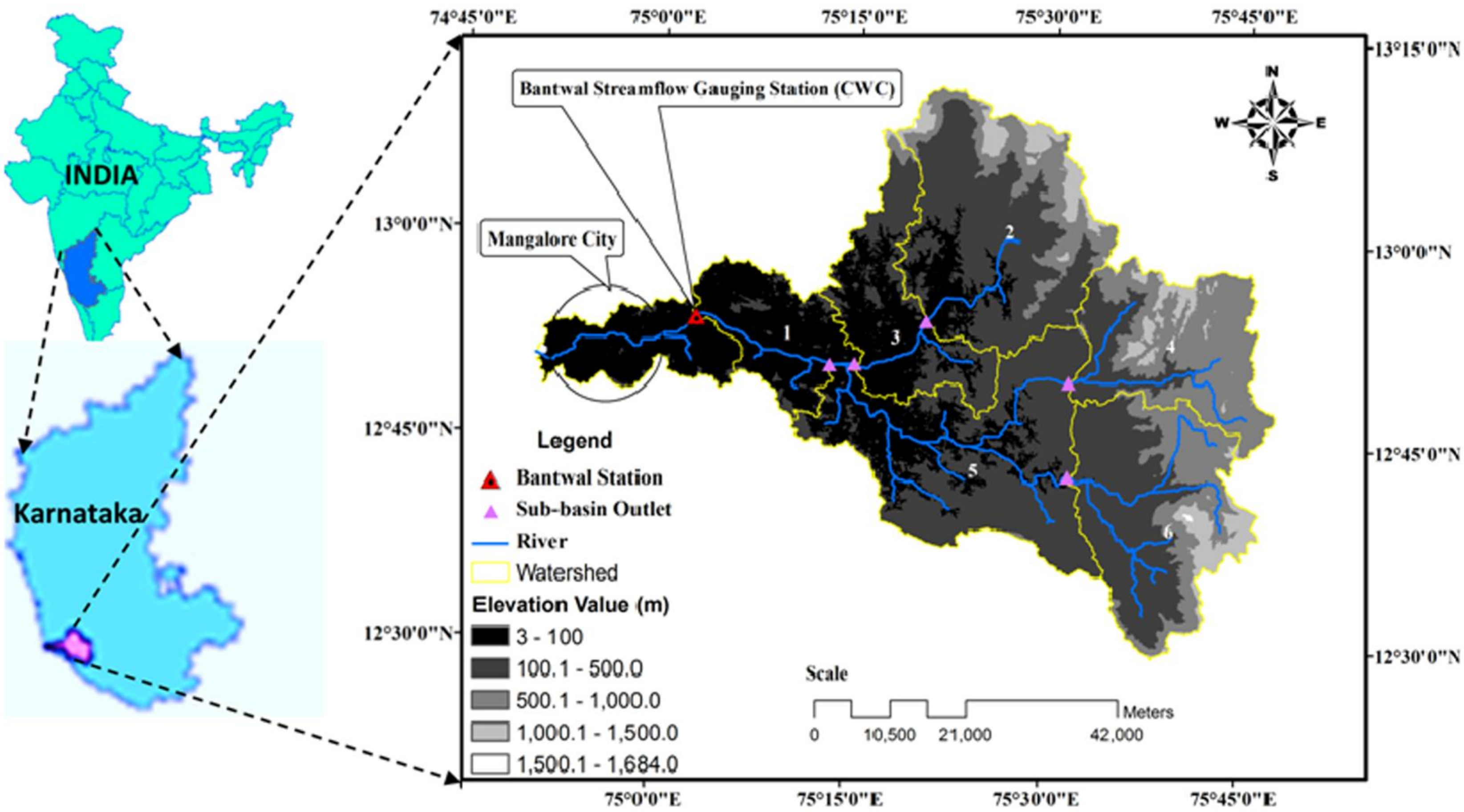


Figure 3.1: DEM showing Nethravathi basin

The Nethravathi river originates in the south of Samse village in the Western Ghats at an elevation 1200 m above mean sea level. The river is joined by MundajaNeriya, ShishlaUppar and Beltangady nallas from either side. Further downstream, Kumaradhara river joins Nethravathi river at Uppinangadi after which it satrts flowing westward in the coastal plains and joins the Arabian sea at Mangalore. The elevation in the Nethravathi river basin varies approximately in the range of 0 to 1200 meters above mean sea level. Total length of the river is about 103 Kilometers, which drains an area of about 3657 km^2 (CWC-2006).

The Nethravathi river water is being used for irrigation, industries and drinking for more than 0.6 million people, petrochemical industries established at the Mangalore city and for religious purposes at places like Dharmasthala and Kukke Subramanya. LULC change that occurs in the basin is due to rapid industrialization and urbanization may change the streamflow pattern. In turn, this change affects the water resources distribution in the river basin.

3.2 Geology and Soils

The basement rocks in the basin are Archean age, which is one of the oldest rocks of peninsular India. Gneiss is the preliminary rock formations of the basin. They are overlaid by laterite. Due to heavy leaching during rainy season, a thin layer of clay is formed at the base of porous laterites. The clay layer is about a meter or two meter in thickness. The thickness of the laterite gradually decreases towards the coast. Thin alluvial sand covers these laterites. Highly porous sandy soils, coastal alluvial and red loam are the three types of soils found in the basin (Putty et al.2000).

3.3 Climate

Average annual rainfall over the Nethravathi river basin is about 3930 mm. The weather is highly humid throughout the year and particularly, during the south-west monsoon when mean humidity exceeds 85%. The mean daily temperature during the months of March to May exceeds 35^0 C. The south-west monsoon period is the coolest parts of the year with the mean daily temperature below 200 C. Winds are strong and mainly south westerly during south west monsoon period.

3.4 Vegetation and Land Use

The heavy rainfall in the area favours luxurious growth of vegetation. The upper portion of the basin lies in the Western Ghats region, which is covered with dense timber forests. Forest of different types, in varying stages from evergreen scrub to fully-grown forest can be seen in the basin. Having a humid and tropical climate, this study area falls in the tropical region and is highly suitable for horticultural crops. Arecanut, Coconut, Cashew, Rubber, Okra and Tapioca these are the some of the important horticultural crops. As per the 2003 LULC statistics over Nethravathi river basin was analyzed by processing IRS 1 D-LISS-3 satellite image acquired on March 2003, shows LULC class as forest, agriculture, wasteland, water and urban categories covers area in percentage as 47.31, 48.70, 2.14, 1.61 and 0.23 respectively.

3.5 Data and Materials Used

A range of spatially distributed data such as topographic features, hydrologic soil types, land use land cover and the stream network are needed to study hydrological regime. In addition to this, meteorological data such as temperature and hydrological data such as precipitation and streamflows are also necessary. Table 3.1 summarizes the input data used in the present study.

Table 3.1: Input data and their sources for the Nethravathi river basin

Data Type	Scale/Resolution	Data Descriptions/Source
DEM	30m×30m	Elevation data from ASTER DEM
Soil	1 km×1 km	Soil texture data from National Bureau of Soil Survey & Land Use Planning, ICAR, Bangalore, India
Land use:	IRS 1D LISS-3 23.5m×23.5m	Land classification and their

	acquired on March 2003 Landsat 30m×30m acquired on January 2013	attributes from Indian remote sensing satellite image and Landsat image
Meteorological data	From 1971- 2010	Daily rainfall and temperature data from Indian Meteorological Department (IMD), India, Karnataka State Irrigation Dept. and Drought Monitoring Center, Bangalore.
Streamflow data	From 2000 to 2009	Daily streamflows from Central Water Commission, India

3.5.1 Digital Elevation Model Data

In the present study, land surface topography is determined using 30-meter ASTER Digital Elevation Model (DEM) available on NASA website (http://www.jspacesystems.or.jp/ersdac/GDEM/E/4.html) has been used. DEM data has been used to delineate the watershed and drainage patterns of the surface area. Sub-basin parameters such as slope length of the terrain, slope gradient, and the stream network characteristics like channel length, width and slope are also derived from DEM. Figure 3.1 represents the elevation information of the study area. The west portion of the basin has gentle slope variation and eastern portion of the basin has steep slope.

3.5.2 Land Use and Soil Types

The land use of the study area is classified into five classes viz. Forest, Agriculture, Water, Wasteland and Urban (first level classification) using the IRS 1D- LISS 3 satellite image obtained during March 2003 (Figure 3.2) and Landsat image during January 2013. The soils are generally classified into hydrological classes, viz. A, B, C and D. The soil data from NBSS & LUP is reclassified into hydrological soil groups A, B, C, and D based on soil properties such as infiltration, grain size and texture. The same has been used in this study. The Figure 3.3 represents soil class in the Nethravathi river basin up to Bantwal gauging stations.

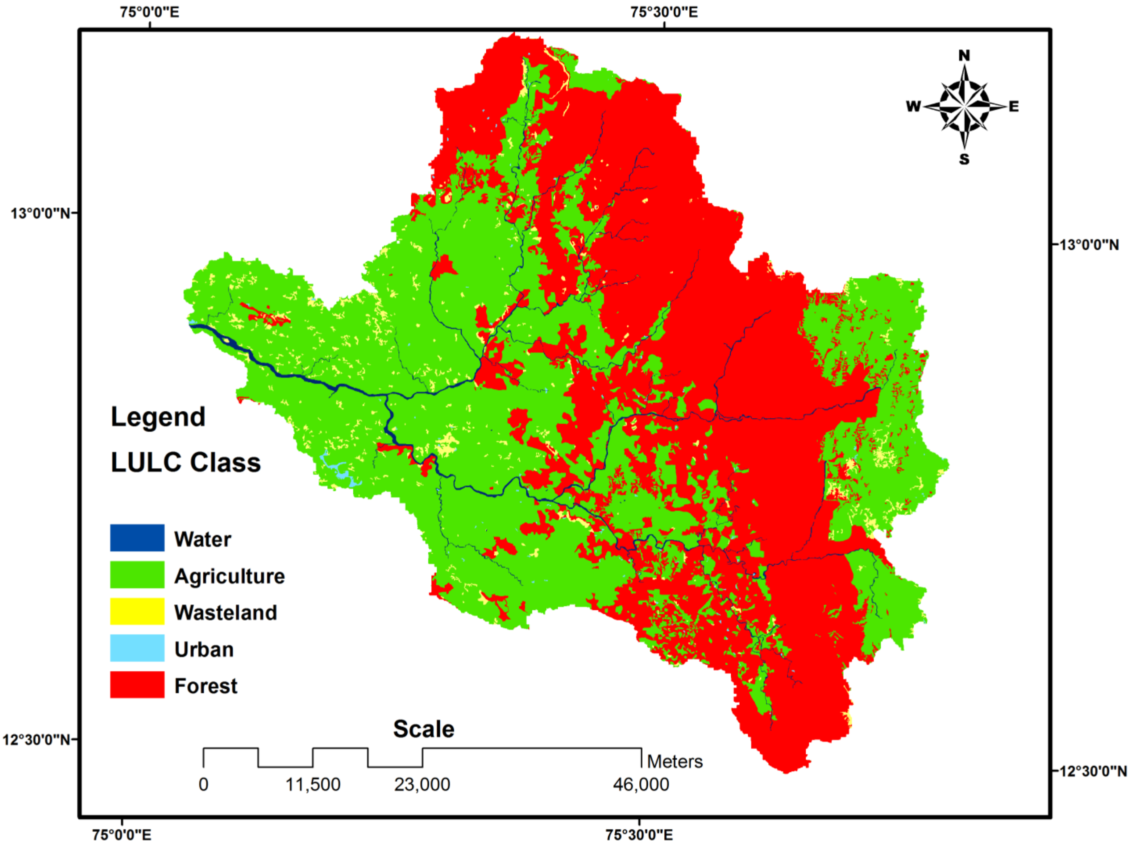


Figure 3.2 Land use map of study area

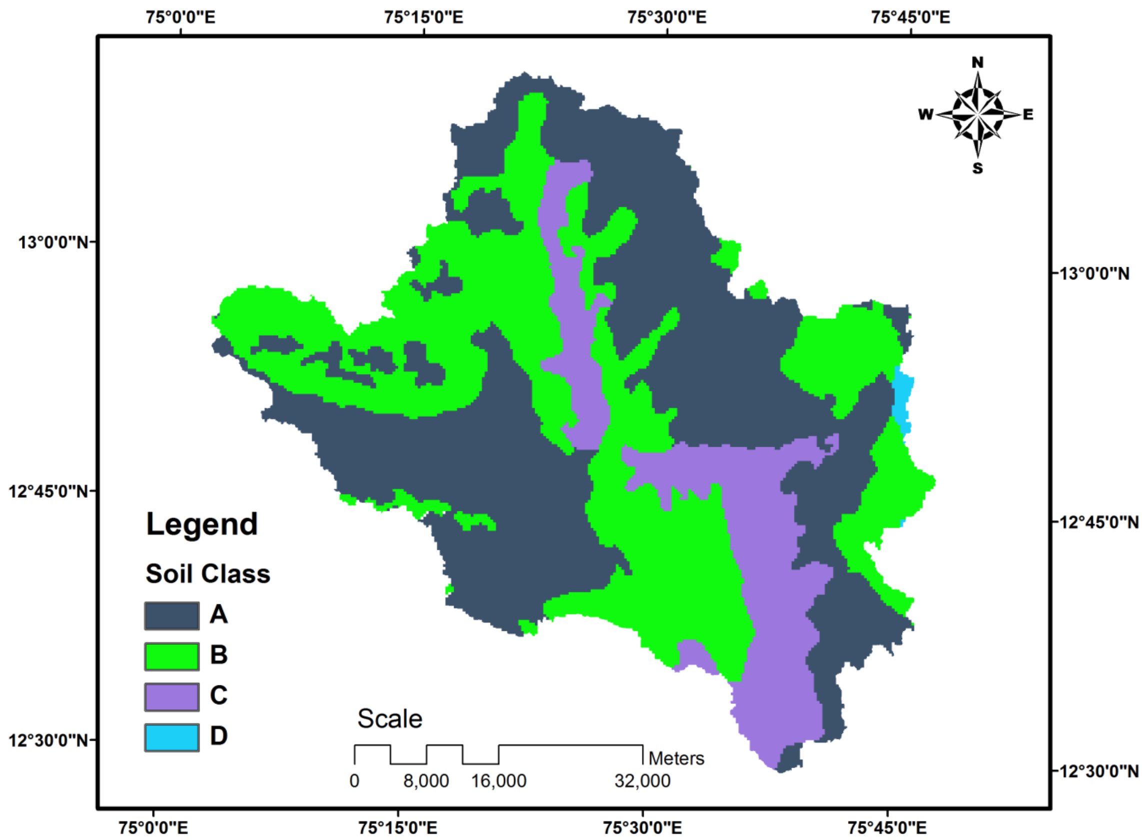


Figure 3.3 Soil map of study area

3.5.3 Meteorological Data

The current study uses daily meteorological data collected from the year 2001 to 2010, and it is procured from India Meteorological Department (IMD). Data from twelve rain gauge stations and four 0.5 deg gridded stations are used in the present study. Figure 3.4 shows the distribution of rain gauge stations and IMD stations over the Nethravathi basin. The data obtained has been pre-processed for consistency. The average percentage of missing data in the observed data sets has been found to be less than 5% and 0% of precipitation and temperature, respectively.

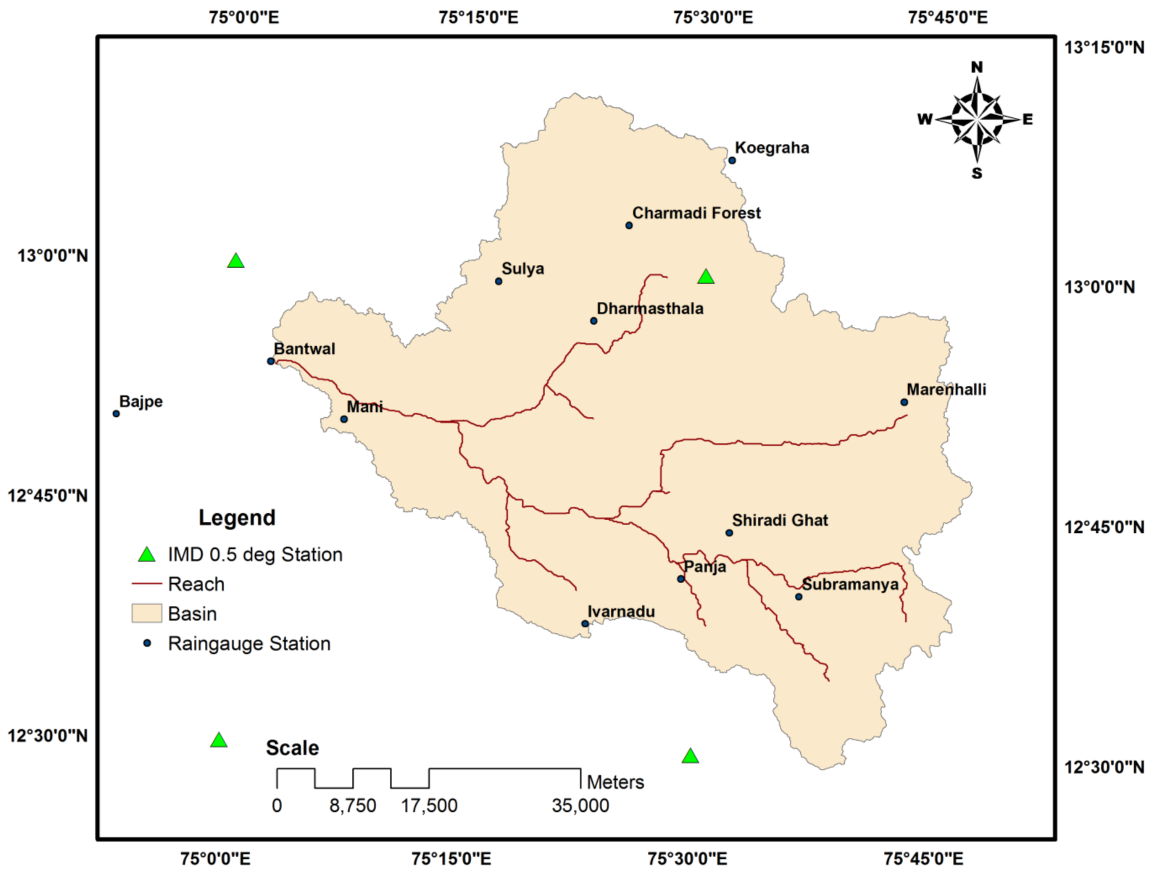


Figure 3.4 Raingauge stations in study area

3.5.4 River Discharge

The Nethravathi river is being gauged at Bantwal location by CWC (Central Water Commission, Ministry of Water Resources of India) as shown in the Figure 3.4. The daily stream discharge data has been collected from 2000 to 2009. The streamflow data also has been checked for consistency before being used in the further analysis.

3.6 Software Used

ERDAS Imagine 9.3: This software is used to process the satellite images. The pre-processing of satellite images such as noise removal, geometric correction etc. are carried out with the ERDAS Imagine (Leica Geosystems, 2008). The LULC map has been prepared by maximum likelihood classifier of supervised classification. Finally, change detection is carried out by image differencing between 2003 and 2013 classified images in the ERDAS Imagine 9.3 Software.

ArcGIS 9.3: This software is used as platform to develop the hydrological models as (SWAT) for Nethravathi river basin. ArcSWAT 2009 is installed on ArcGIS 9.3, ESRI platform (Sheshukov et al. 2012). Further, this software is used to process and develop the different LULC scenarios such as, CA (Conversion to Agriculture), CB (Conversion to Built-up) and CW (Conversion to Wasteland) have been developed using ArcGIS 9.3 software (Diek et al. 2012). Further, the developed model is used to study the LULC change impact on streamflow.

Microsoft Office 2007: Microsoft word 2007 is used for writing the research paper and reports. Microsoft excel is used as recording and plotting of data. Power point is used for PPT preparation. XLSTAT is installed in excel 2007 platform. Further, it has been used to study the extreme rainfall trend analysis.

CHAPTER 4

EXTREME RAINFALL ANALYSIS

4.1 Introduction

The extreme events are playing an important role across the disciplines like finance, insurances, hydrology and climate (Reiss and Thomas, 2007; Min et al. 2011). The studies of extreme events are one of the interesting fields in natural science. The aim of extreme value analysis is to quantify the stochastic behaviour of a process at unusually high or low levels. The probability distribution function can be used to study the stochastic behaviour of extreme events. The statistical frequency analysis of extreme rainfall can be seen as normalization procedure allowing site-to-site comparison. Therefore, a number of applications such as design of civil engineering structures (bridge and dam), climate studies (variable trends of climate parameters) are dependent on study of rainfall frequencies (Zwiers and Kharin, 1998; Kharin and Zwiers, 2005).

Global warming induced changes in rainfall has a considerable effect on the hydrological cycle and the pattern of streamflow, requiring a review of hydrologic design and management practices (Jain and Kumar, 2012). Rainfall patterns are expected to change significantly as a result of climate change (Kyoung et al. 2011). The frequency analysis methods are widely used to relate the magnitude of extreme events (e.g., heavy rainfall, floods) to a probability of occurrence (Stedinger et al. 1993) in the context of climate change.

The existing literature on statistical analysis of extreme rainfall trend is focused significantly on extreme value theory. Several researchers have found out the extreme trends in environmental and meteorological fields are best addressed by using probability models. The probability distributions of extreme events are performed by block maxima (BM) method or peak over threshold (POT). Generalized Extreme Value (GEV) distribution block maxima (BM) methods are used in the present study.

4.2 Methodology

The daily rainfall data were collected for 12 stations which are uniformly distributed over Nethravathi river basin from National Data Centre, IMD, Pune, Drought Monitoring Cell, Bangalore and Karnataka State Irrigation department for a period of 1971 to 2010. In the present study, extreme rainfall event trend analysis has been carried out using following methods.

1. Frequency Distribution Method
2. GEV Distribution (Block Maxima)
3. Nonparametric Trend Analysis (Mann-Kendall and Sen's slope estimator test)

4.2.1 Frequency Distribution Method

A large amount of variability of rainfall is related to the occurrence of extreme rainfall events. Based on the amount of rainfall collected in a day, frequency distribution method for extreme rainfall events is carried out. However, for extreme event studies (Attri and Tyagi 2010), rainfall has been regrouped into three broad classes viz.

1. Class-1 - Light to rather heavy rainfall ($0 < R \leq 64.4$ mm),
2. Class-2 - Heavy rainfall ($64.4 < R \leq 124.4$ mm) and
3. Class-3 - Very heavy to exceptionally heavy rainfall ($R > 124.4$ mm).

Where R is the rainfall event,

The rainfall greater than 124.4 mm is considered as extreme rainfall events in the present study as suggested by Pattanaik and Rajeevan (2010) in one of his studies.

4.2.2 Generalized Extreme Value

Generalized extreme value distribution fitted to block maxima (BM) or blocks of time windows like an annual maxima time series. For most practical applications of climate and rainfall, BM-GEV methods are used widely to get the precise information from the historical data (i.e., annual maxima). There are three types of standard distributions, which can parameterize within the location and scale families. The three types of GEV distributions (Figure 3.1) depending on shape parameter (k), that three types of distributions have different support and tail behaviour. The three GEV distribution are Gumbel distribution (eq. 4.1), Frechet distribution (eq. 4.2) and Weibull distribution eq. (4.3).

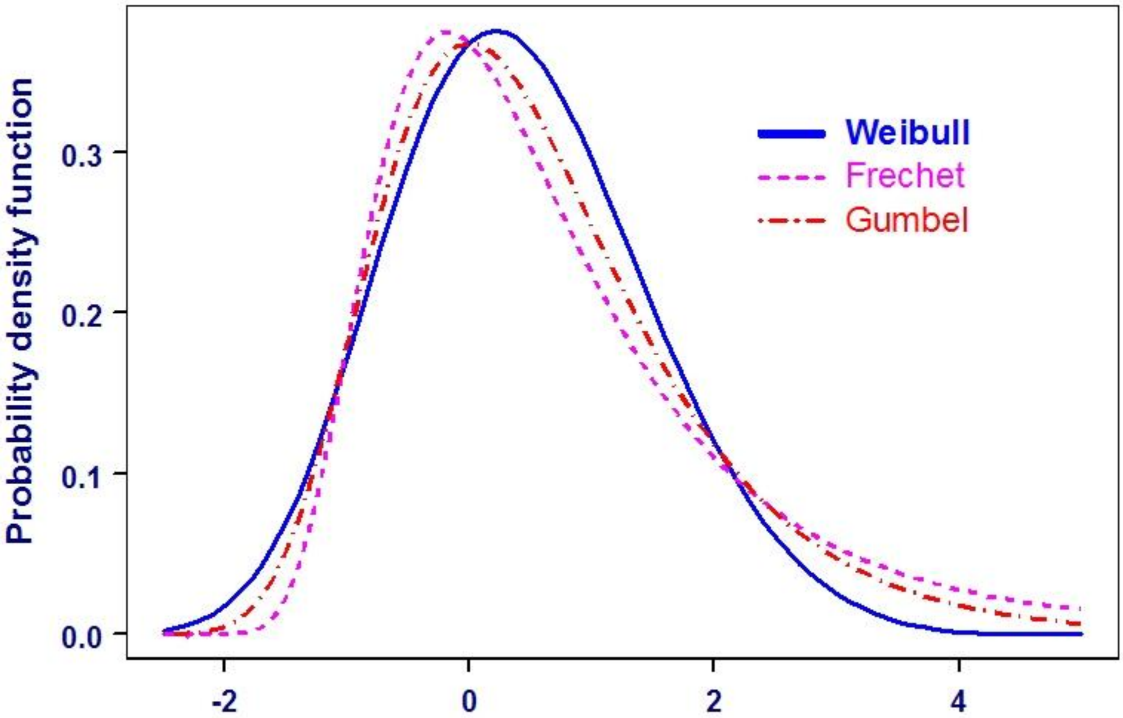


Figure.4.1: Generalized extreme distributions (Richard Katz, 2011)

1. Gumbel distribution

$$\wedge(x) = exp\left\{-exp\left[-\frac{x-d}{c}\right]\right\}, x \in X \tag{4.1}$$

2. Frechet distribution

$$\Phi_{\alpha}(x) = \begin{cases} 0, & if\ x \leq d \\ exp\left\{-\left(\frac{x-d}{c}\right)^{-\alpha}\right\}, & if\ x > d \end{cases} \tag{4.2}$$

3. Weibull distribution

$$\Psi_{\propto}(x) = \begin{cases} exp\left\{-\left(\frac{x-d}{c}\right)^{-\propto}\right\}, & if\ x > d\,, \\ 0\,, & if\ x\ \leq d \end{cases} \tag{4.3}$$

Where$x \in X$,$\wedge(x)$ =Gumbel distribution,$\Phi_{\alpha}(x)$= Frechet distribution,

$\Psi_{\propto}(x)$ = Weibull distribution,$d = \mu$ = location parameter,

c = σ = scale parameter and $\propto = k$ = shape parameter

It is advantageous to reformulate these three types into one family of distribution. The generalized Gumbel, Frechet and Weibull families can be combined into a single family of distribution as given by eq. (4.4).

$$G(x) = exp\left\{\left[1 + k\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/k}\right\} \quad where\ 1 + k\left(\frac{x-\mu}{\sigma}\right) > 0 \tag{4.4}$$

The model has three parameters: a location parameter$\mu \in \mathbb{R}$, a scale parameter$\sigma > 0$ and a shape parameter $k \in \mathbb{R}$. The generalized Frechet and Weibull distribution corresponds to the cases $k > 0$ and $k < 0$ respectively. The generalized extreme value distribution describes the probability of block maxima is the fit of the distribution to the annual series of maxima.

4.2.3 Nonparametric Trend Analysis

A nonparametric test is taken into consideration over the parametric one since it can avoid the problem raised by data skew (Smith, 2000).Recent studies show that the most extensively used method for detecting the trend is the nonparametric Mann-Kendall trend test. Mann (1945) originally derived the test and Kendall (1975) subsequently derived the test statistic commonly known as the Kendall’s tau statistic. It was found to be an excellent tool for trend detection in different applications (Lettenmaier et al., 1994) such as rainfall, flood, etc.

4.2.3.1 Mann-Kendall Test

The Mann-Kendall statistic S is given by the following eq. (4.5)

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{4.5}$$

The application of trend test is applied to a time series x_i that is ranked from i = 1,2,………n-1 and x_j, which is ranked from j = i+1,2,……….n. Each of the data point x_i is taken as reference point, which is compared with the rest of the data point's x_j so that eq. (4.5) yields the following eq. (4.6).

$$\operatorname{Sgn}(x_j - x_i) = \begin{cases} +1, > (x_j - x_i) \\ 0, = (x_j - x_i) \\ -1, > (x_j - x_i) \end{cases} \tag{4.6}$$

It has been documented that when n ≥ 8, the statistic S is approximately normally distributed with the mean. Where n = the total number data points.

The variance Mann-Kendall statistic S is given by eq. (4.7) as follows

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(i)(i-1)(2i+5)}{18} \tag{4.7}$$

Where t_i is the number of ties up to sample i. Then the test statistic Z_c is computed by eq. (4.8)

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\operatorname{Var}(s)}}, S > 0 \\ 0 \quad\quad , S = 0 \\ \frac{S-1}{\sqrt{\operatorname{Var}(S)}}, S < 0 \end{cases} \tag{4.8}$$

The statistic Z_c follows a standard normal distribution. A positive value of Z_c signifies an upward trend and a negative value of Z_c signifies downward trend. A significance level α is also utilised for testing either an upward or downward monotone trend (a two-tailed test). If Z_c appears greater than Zα/2, then the trend is considered as significant, otherwise no significant. Where, α depicts the significance level.

4.2.3.2 Modified Mann–Kendall (MK) Test

'Pre-whitening' is the procedure that removes the red noise component from the time series. Pre-whitening is being used for detecting a trend in a time series in the presence of autocorrelation (Mondal et al. 2012). Pre-whitening is stated to reduce the rate of detection of significant trend in the MK test. Thus, the modified MK test has been used for trend detection of an auto-correlated series. In the present study, the autocorrelation between ranks of the observations (ρ_k).The rank of observation has been estimated after subtracting an estimate of a nonparametric trend such as Sen's median slope from the data.

Significant values of ρ_k have been used for calculating the variance correction factor $\frac{n}{n_s^*}$ shown in eq. (4.9) as the variance of S is underestimated for the positively auto-correlated data.

$$\frac{n}{n_s^*} = 1 + \frac{2}{n(n-1)(n-2)} X \sum_{k=1}^{n-1} (n-k)(n-k-1)(n-k-2)\rho_k \quad (4.9)$$

Where 'n' represents the actual number of observations, n_s^* is represented as an effective number of observations to account for the autocorrelation in the data and $\rho_k$is considered to be the autocorrelation function for the ranks of the observations (Mondal et al. 2012).

The corrected variance $V^*(S)$ is then calculated by eq. (4.10)

$$V^*(S) = V(S) \times \frac{n}{n_s^*} \quad (4.10)$$

where V (S) is from eq. (4.7). The rest is same as in the MK test.

4.2.3.3 Sen's Slope Estimator Test

The magnitude of trend is predicted by the Sen's slope estimator. Here, the slope (T_i) of all data pairs (Sen, 1968) is computed by eq. (4.11)

$$T_i = \frac{x_j - x_k}{j - k} \quad (4.11)$$

Where x_j and x_k are the data values at time j and k (j>k). The median of these N values of T_i is represented as Sen's estimator of slope, which is given by eq. (4.12)

$$Qi = \begin{cases} T_{\frac{N+1}{2}} & \text{if N is odd} \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right) & \text{if N is even} \end{cases} \tag{4.12}$$

Sen's estimator is computed as Q_{med}=T(N+1)/2, if N appears odd and it is considered as Q_{med}=[TN/2+T(N+2)/2]/2, if N appears even. At the end, Q_{med} is computed by a two sided test at 100 (1-α)% confidence interval and then a true slope can be obtained by nonparametric test. Positive value of Qi indicates an upward or increasing trend and a negative value of Qi represents downward or decreasing trend in the time series.

4.3 Results and Discussions

4.3.1 Frequency Based Extreme Rainfall Events

During southwest monsoon season from June to September (June, July, Aug, Sept.), the frequency of Light to rather heavy rainfall ($0 < R \leq 64.4$ mm) is classified as class-1,which shows slightly increasing trend over Nethravathi river basin as indicated in Figure 4.2.

The frequency of heavy rainfall ($64.4 < R \leq 124.4$ mm) is classified as class-2, which shows overall decreasing trend over the basin but there is a variation between 1995 and 2010. The frequency trend as indicated in Figure 4.3shows decrease in number of rainy days from 1995 to 2001 and the rainy days are increased afterwards.

During southwest monsoon season from June to September (June, July, Aug, Sept.), the frequency of extreme rainfall (Rainfall ≥ 124.4 mm) is classified as class-3,which shows decreasing trend over Nethravathi river basin as indicated in Figure 4.4. However, the overall result show a gradual decrease in extreme rainfall events from 1971 to 2010 as observed in Figure 4.4.

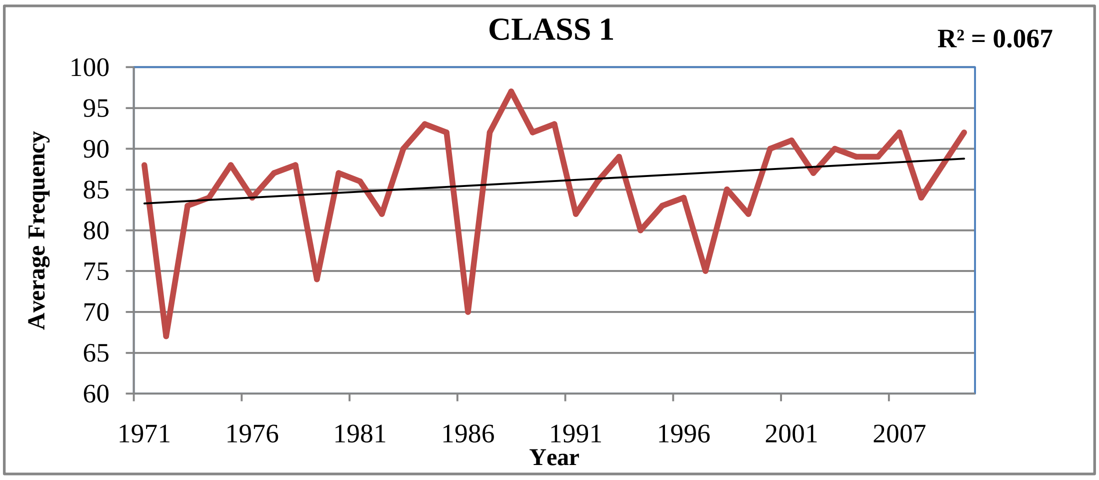


Figure 4.2: Light to rather heavy rainfall (0 < R ≤ 64.4 mm)

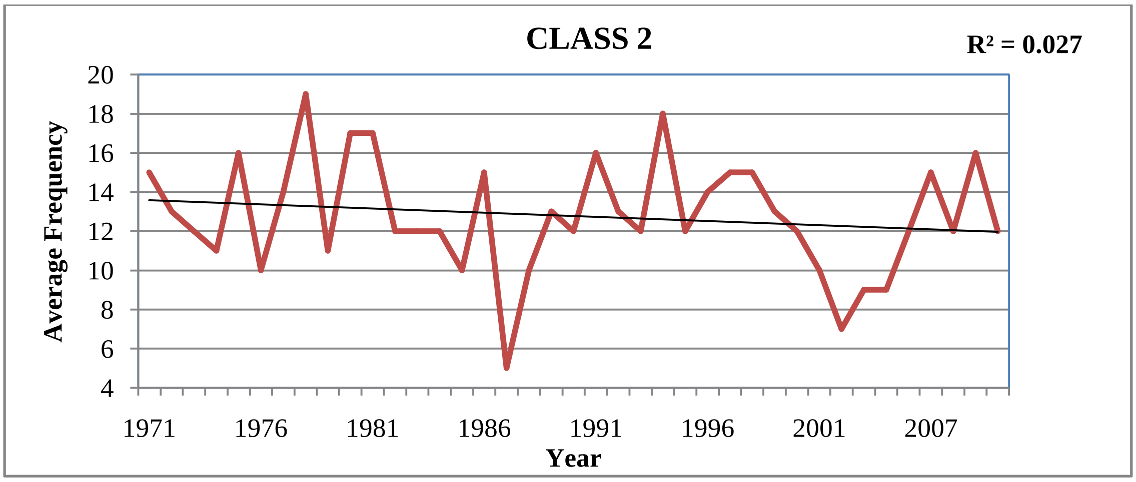


Figure 4.3: Heavy rainfall (64.4 < R ≤ 124.4 mm)

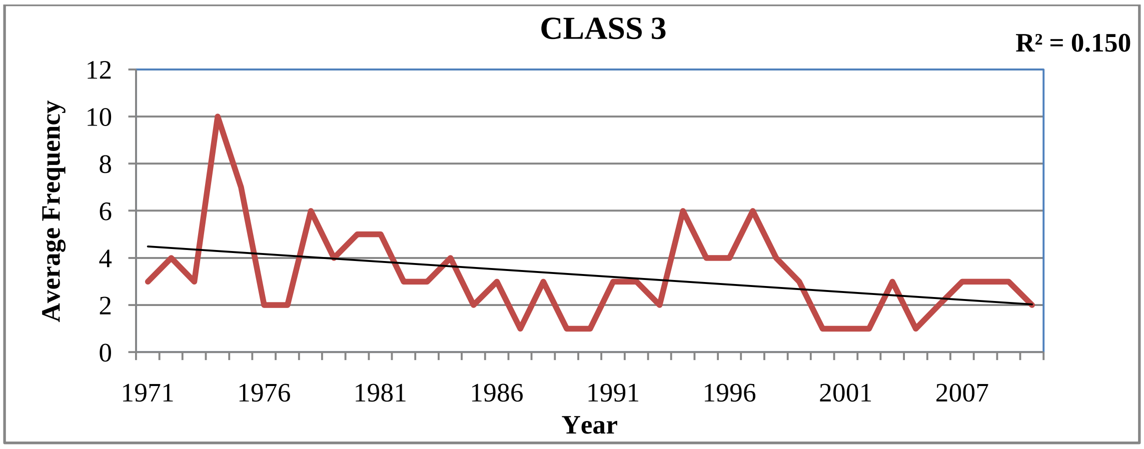
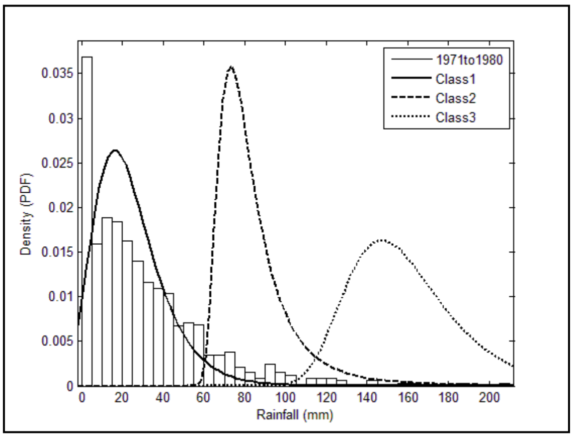


Figure 4.4: Very heavy to exceptionally heavy rainfall (R > 124.4 mm)

4.3.2 GEV (Generalized Extreme Value) Distribution

For Generalized Extreme Value (GEV) distribution, the probability distributions of extreme events are performed by block maxima (BM) method. Figure 4.5 shows density plots using last 40 years of rainfall data, which gives class wise block maxima distribution.



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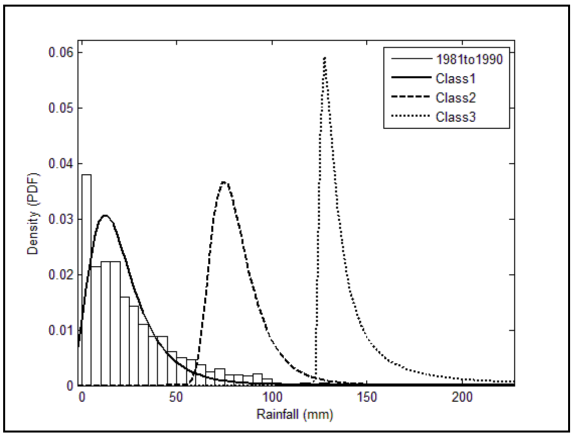

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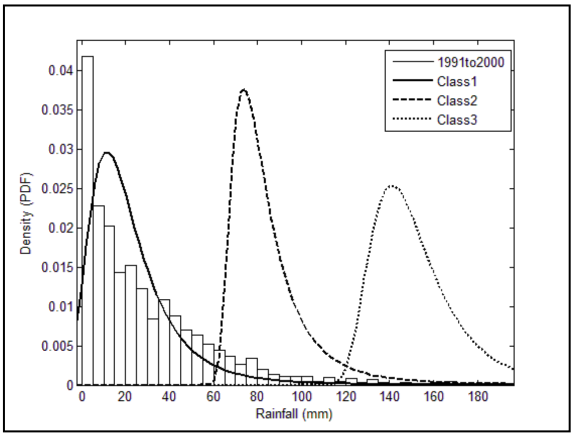

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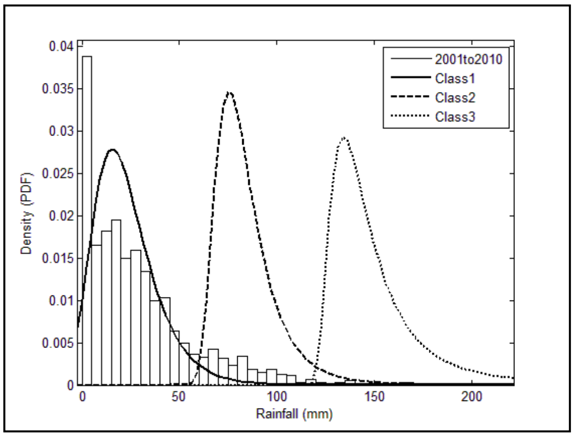


(d)

Figure 4.5: GEV distribution Density (PDF) plot class wise (a) 1971-1980 years, (b) 1981-1990 years, (c) 1991-2000 years and (d) 2001-2010 years.

The GEV distribution is used to estimate the parameters such asμ, σ, and k. The detailed information about parameters corresponds to class-1, class-2 and class-3 are given in the respective table 4.1, table 4.2 and table 4.3. The standard error for each parameter was computed and presented in the above mentioned tables.

At each station, the GEV distribution is fitted to these annual maxima by likelihood function. For each station, three GEV parameters (μ, σ, k) are estimated. The class wise parameter information is given in Table 4.1, 4.2 and 4.3.

Table 4.1: Class-1 parameters obtained from GEV distribution.

Data Years		**1971-1980**	**1981-1990**	**1991-2000**	**2001-2010**
Parameters	k (Shape)	-0.0154	0.0976	0.1556	-0.0185
	Standard Error	0.0378	0.0363	0.0442	0.0363
	σ (Scale)	13.9211	11.9876	12.5467	13.1998
	Standard Error	0.4202	0.3589	0.4199	0.3938
	μ (Location)	16.071	13.4182	13.2881	15.3256
	Standard Error	0.5421	0.4552	0.5137	0.5117

Table4.2: Class-2 parameters obtained from GEV distribution.

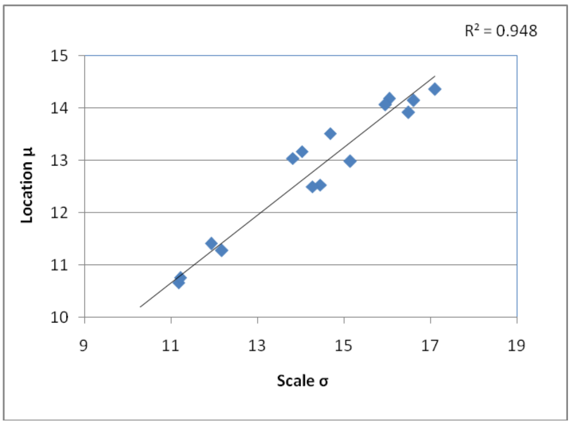
Data Years		**1971-1980**	**1981-1990**	**1991-2000**	**2001-2010**
Parameters	k (Shape)	0.2541	0.0814	0.2757	0.1091
	Standard Error	0.13	0.11	0.12	0.11
	σ (Scale)	10.5500	10.0295	10.0793	10.6699
	Standard Error	1.06	0.96	0.99	0.94
	μ (Location)	75.3445	75.6326	76.1268	76.6344
	Standard Error	1.26	1.22	1.16	1.17

Table 4.3: Class-3 parameters obtained from GEV distribution.

Data Years		**1971-1980**	**1981-1990**	**1991-2000**	**2001-2010**
Parameters	k (Shape)	-0.0267	0.8121	0.0937	0.3402
	Standard Error	0.36	0.40	0.47	0.29
	σ (Scale)	22.5660	8.0624	14.5522	13.2322

	Standard Error	5.48	3.34	4.32	3.66
	μ (Location)	146.6370	131.0870	142.5210	137.9860
	Standard Error	6.67	2.87	5.10	4.22

The GEV location (μ) and scale (σ) parameters are estimated at each station and plotted one against the other with regression line as shown in Figure 4.6. From the analysis, coefficient of determination (R^2) was found to be 0.942, 0.729 and 0.648 respectively for class-1, class-2 and class-3.It seems reasonable to assume a linear relationship of the form μ = a + bσ between these two parameters.



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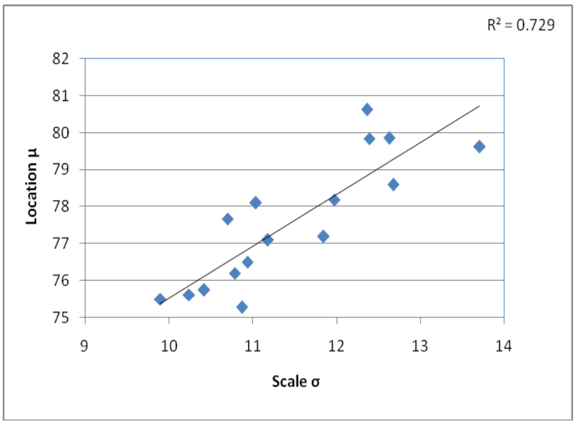

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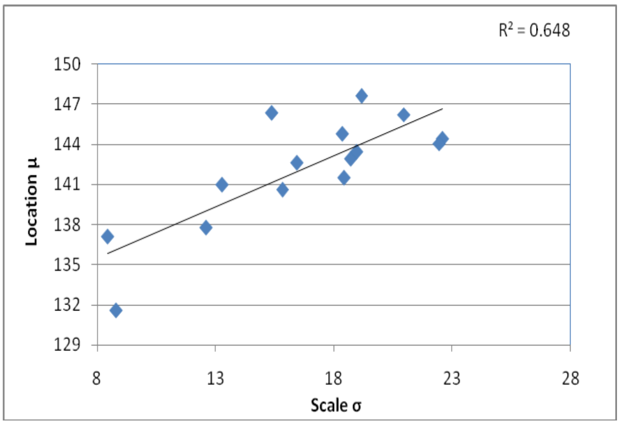
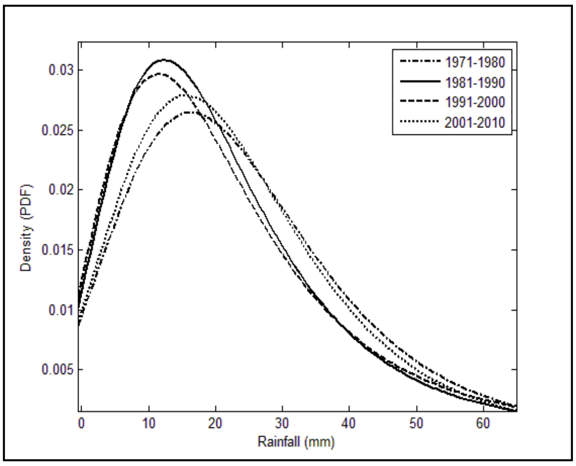


(c)

Figure 4.6: Scatter plots of GEV location parameters (μ) against scale parameters (σ) (a) Class-1, (b) Class-2 and (c) Class-3.

The Figure 4.6 shows a better fit between location and scale parameter for class-1 when compared to class-2 and class-3 plots. However, class-3 shows more variations compare to class-1 and class-2 as R^2 is very less. The GEV distribution results shown that the R^2 values have been improved to 0.948, 0.729 and 0.648 respectively for class-1, class-2 and class-3 as compare to frequency distribution method. Figure 4.7 shows the class wise density plots of the present study by GEV distribution for the period of 1971 to 2010, which indicates variation of block maxima in rainfall events for last four decades within the Nethravathi basin.



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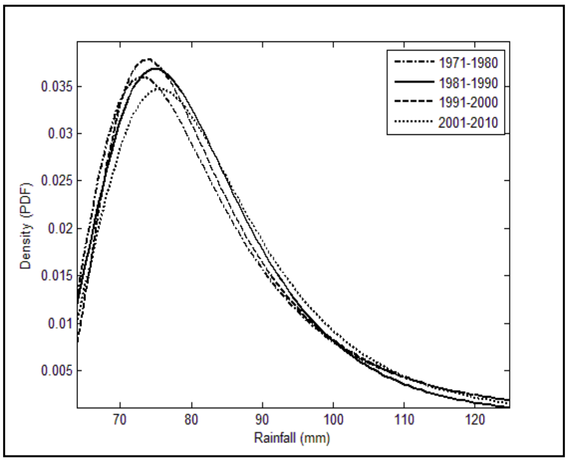

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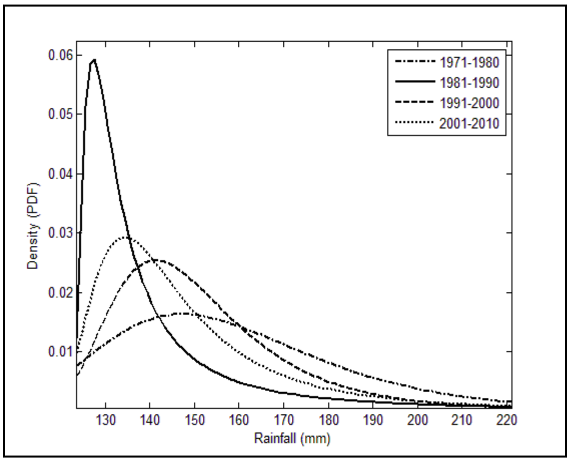


(c)

Figure 4.7: Density plots of GEV distribution using average rainfall with particular class (a) Class-1, (b) Class-2 and (c) Class-3

Class-1 and class-3 shows more variations compare to class-2 as observed from Figure 4.6. Hence, it is concluded that the GEV distribution brings out substantial information about the density variation of rainfall events with different class.

4.3.3 Nonparametric Trend Analysis

Mann-Kendall test was carried out for 40 years monsoon rainfall data (June to September) in this study. From Mann-Kendall test, the Z_c statistic values found to be 1.4693, -0.8844 and -2.2270 for class-1 class-2 and class-3 respectively. A positive trend was observed in class-1 and negative trend was observed for class-2, and class-3 in the Nethravathi river basin as presented in Figure 4.8.

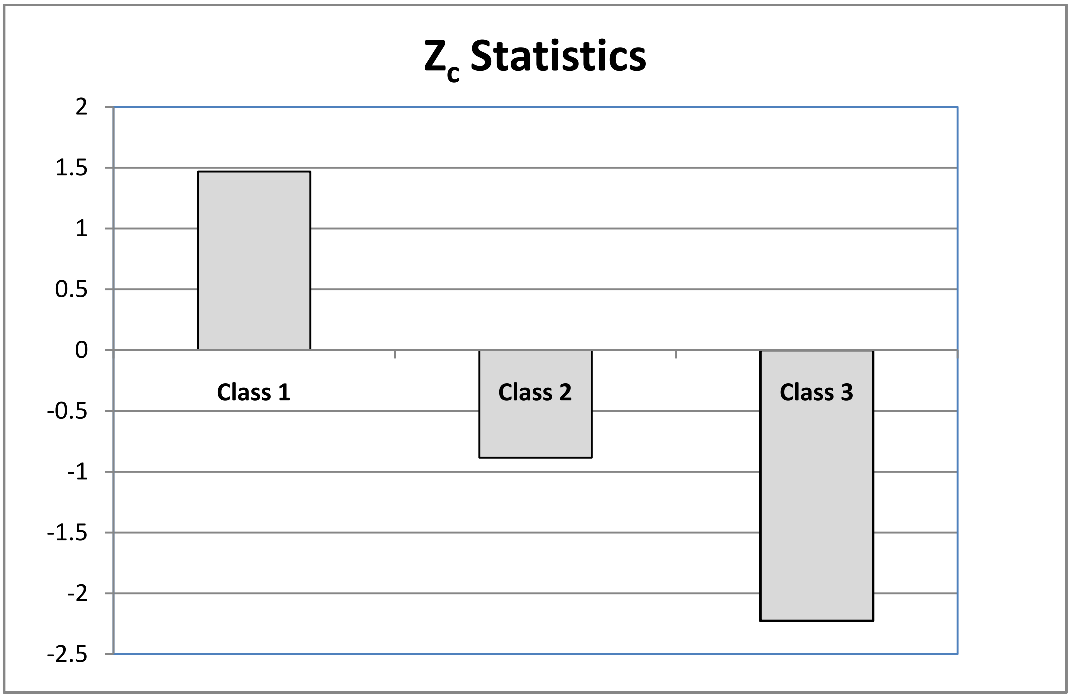


Figure 4.8: Class wise Z_c statistic value for Nethravathi basin

Table 4.4 presents the Sen's slope indicating class wise slope magnitude and frequency (significance level 5%) of rainfall events during monsoon months (June to September) for 40 years. Class-1 shows positive Sen's slope and positive Kendall's tau, which indicates the trend is positive. Hence, it is concluded that class-1 is a positive trend. Whereas class-2 and class-3 shows negative trend as Sen's slope and Kendall's tau are negative. Thus, nonparametric test (Mann-Kendall and Sen's slope estimator) is concluded to be the better method for analysing extreme rainfall trend as these methods provides better results than simple methods.

Table 4.4: Estimated Sen's slope from data 1971-2010 with particular class

	Class-1	Class-2	Class-3
Minimum	67.000	5.000	1.000
Maximum	97.000	19.000	10.000
Mean	86.025	12.769	3.256
Std. deviation	6.322	2.933	1.901
Kendall's tau	0.169	-0.105	-0.268
Sen's slope	0.115	0	-0.043

4.3.4 Summary of Results

An attempt has been made to interpret the results obtained from the above methods. Table 4.5 shows the class wise coefficient of determination by frequency distribution method and Kendall's tau (statistical correlation coefficient) by the Sen's Slope estimator test.

In the case of frequency distribution method, coefficient of determination value is considerably less. Therefore, it is difficult to interpret the result with this. Hence, Interpretation of results has been made using Sen's slope and GEV distribution. In GEV distribution method, the coefficient of determination obtained by scale and shape parameter for class-1, class-2 and class-3 are respectively0.942, 0.729, and 0.648.

The graphical representation of linearity between scale and shape parameter shows that the linear relationship between scale and shape parameter is decreasing from class-1 to class-3. The Kendall's tau varies between -1 to +1 and positive value shows positive trend and negative value shows negative trend.

Table 4.5 Interpretation of results based on three methods

Class	Frequency Distribution	Sen's slope Estimator	GEV Distribution
	Coefficient of Determination	Kendall's tau	Coefficient of Determination
Class-1	0.067	0.169	0.948
Class-2	0.027	-0.105	0.729
Class-3	0.150	-0.268	0.648

4.4 Conclusions

An attempt has been made to study the extreme rainfall trend using frequency distribution and statistical techniques like GEV distribution, Mann-Kendall and Sen's slope estimator test over Nethravathi river basin. From the analysis, the following conclusions are drawn:

- In the present study, Kendall's tau values were found to be 0.169, -0.105 and -0.268 for class-1, class-2 and class-3 respectively. Therefore, over the Nethravathi river basin class-1 is concluded to be positive and class-2 & class-3 are concluded to as negative trend over the Nethravathi river basin.

- The coefficient of determination (R^2) obtained by a plot of the scale and shape parameter found 0.942, 0.729 and 0.648 for class-1, class-2 and class-3 respectively in the GEV distribution method. The result of linear relationships concluded that there is a decreasing trend in all three classes. However, class-3 shows more variations compare to class-1 and class-2 due to low R^2 value.

- Among all the three methods, Mann-Kendall and Sen's slope estimator test showed better results in identifications of the extreme rainfall trend in the Nethravathi river basin.

CHAPTER 5

DEVELOPMENT OF HYDROLOGICAL MODELS

5.1 Introduction

As the second largest populated country in the world, with giant and flourishing economy, India’s future food and water supply are indecisive. It is not surprising that some Indian river basins are already experiencing physical water scarcity due to changes in the hydrological regime. Human induced land use changes such as deforestation, afforestation, agriculture and urban development in the river basin can affect the hydrological regime. Hence, it is important to understand the hydrological responses of streamflow to climate and land use changes for developing sustainable river basin management strategies.

Hydrological models are the mathematical description of the inter-relationships between major physical elements (rivers, lakes, groundwater, soil, etc.) in the water system. Catchment hydrological cycle describes the water balance associated with the processes being taking place in the river basin. In this chapter, an attempt has been made to develop a hydrological model to predict the streamflow using SWAT model. The study also employs a newly proposed Runoff Coefficient Routing Model (RCRM) to simulate streamflow.

5.2 Methodology

The present chapter describes development of SWAT and proposed rainfall-runoff model. The overall methodology of the present study is presented in Figure 5.1. The methodology consists of the development of hydrologic model with ArcSWAT and newly proposed RCRM. ArcSWAT is a universally used model, which is based on the inputs of meteorological, topographical, hydrological, soil and LULC data. However, much meteorological data is not being monitored at the basin or sub-basin level. Therefore, it is difficult to apply SWAT. In order to overcome this difficulty, an attempt has been made to develop RCRM, which requires only rainfall, streamflow, soil and LULC data. Firstly, SWAT model has been developed for Nethravathi river basin. The developed SWAT model has been calibrated and validated. Secondly, RCRM has been developed and then calibrated and validated. The results of the SWAT and RCRM have been compared with observed data. Finally, the impact of LULC change on streamflow is carried out.

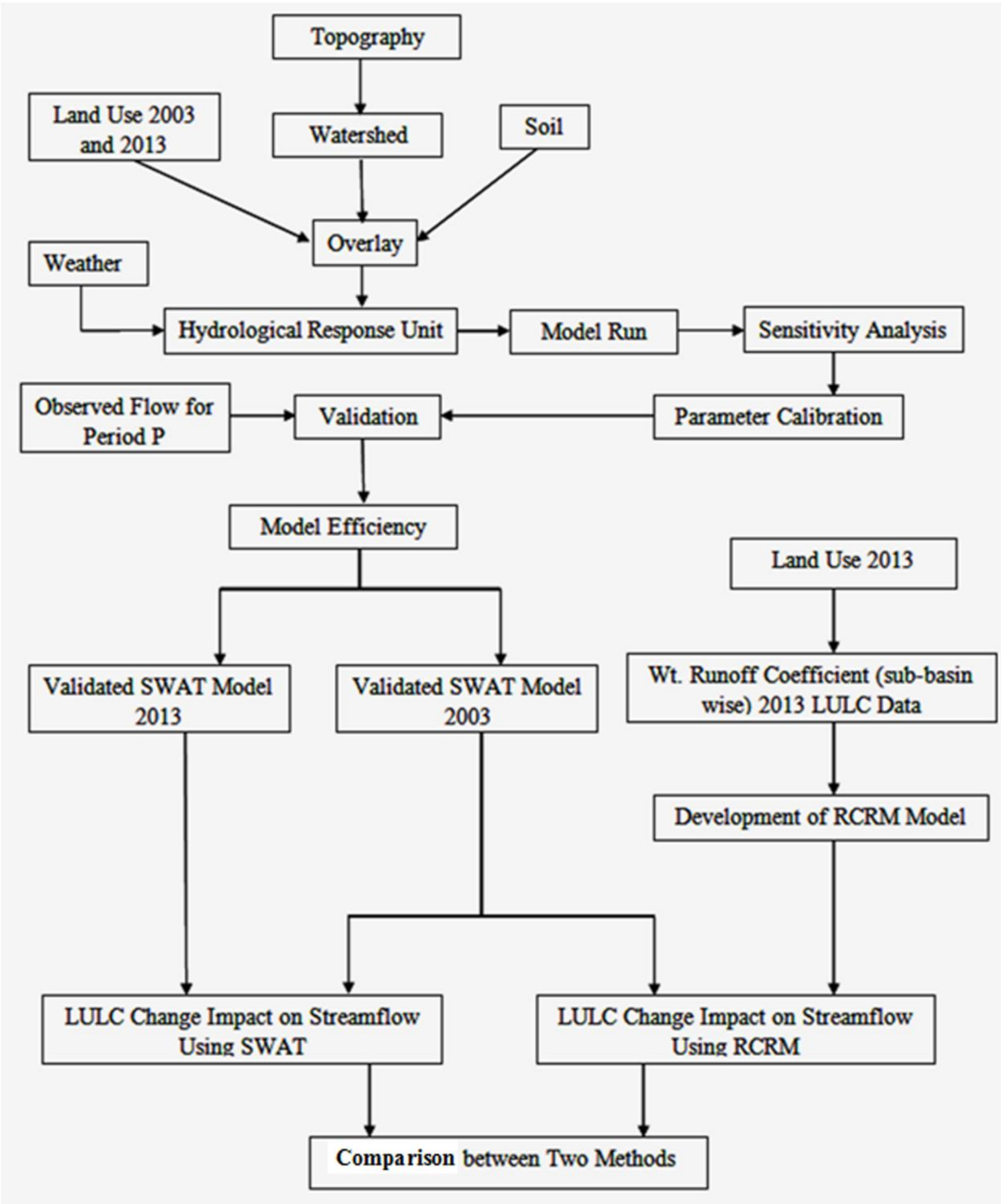


Figure 5.1: Flow chart of methodology

5.3 Selection of Model

The Soil and Water Assessment Tool (SWAT) has been widely used for evaluating hydrologic regimes at daily, monthly and yearly time scales (Bouraoui et al. 2005). The SWAT model has been widely accepted model as a cost effective tool because of its advanced model configuration and impressive function such as modeling the scarce data regions and evaluating various scenes and agricultural managements (Engle et al. 1993; Spuill et al. 2000; Bosch et al. 2004; Sang et al. 2010). The SWAT has been used as an effective tool to model the impacts of climate and LULC changes on hydrologic and biogeochemical cycle (Arnold and Fohrer, 2005). In SWAT, the watershed is discretized into sub-basins and these sub-basins are typically further discretized into hydrologic response units (HRUs). HRUs are considered to be homogeneous with unique values of LULC, soil type and terrain slope. Thus, SWAT requires more number of input data such as precipitation, LULC, digital elevation model, streamflow, meteorological data, soil data etc. Based on availability of data, and capability of accounting LULC, meteorology, soil and hydrology, SWAT model has been selected and used in the present study.

5.4 SWAT Model Description

ArcSWAT (Soil and Water Assessment tool, version SWAT2009) is used in the present study. It is a physically based continuous event hydrologic model developed by the U.S. Department of Agriculture Research Service (USDA-ARS). The SWAT model operates on a daily time step and uses physiographical data such as elevation, land use and soil properties as well as meteorological and river discharge data for calibration (Arnold and Allen, 1996; Arnold et al. 1998). SWAT model is mainly used to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large basins with varying soils, land use and management over the long periods of time (Neitsch et al. 2001a, 2001b).

The hydrological processes included in the model are surface runoff, evapotranspiration (ET), percolation, infiltration, aquifers flow (shallow & deep) and channel routing (Arnold et al. 1998). The computation of hydrologic processes operates in five phases viz., (i) precipitation and interception, (ii) surface runoff, (iii) soil and root zone infiltration, (iv) evapotranspiration, soil and snow evaporation, and (v) groundwater flow.

The effects of spatial variations in topography, LULC, hydrologic soil types and other characteristics of watershed hydrology are incorporated in the present study by dividing the basin into several sub-basins, which are based on stream drainage areas. Further, the sub-basins are divided into a number of hydrological response unit (HRUs) within each sub-basin, based on LULC and hydrologic soil types. The land use, soil, topography and climate are considered spatially uniform for each HRU. The subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils.

All model computations are performed at the HRU level. The runoff is predicted separately for each HRU and routed to obtain the total runoff at the outlet of a watershed. The SWAT model uses Natural Resources Conservation Service (NRCS) curve number method (SCS, 1972) for estimating surface runoff (Q_{surf}). The fundamental hydrological equation of a watershed used in SWAT is based on the water balance eq. (5.1) which is based on mass balance, which calculates the change in soil water content (SW_t).

$$SW_t = SW_0 + \sum_{t=1}^{i}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (5.1)$$

Where,

SW_t = The final soil water content (mm),

SW_0 = The water content available for plant uptake, defined as the initial soil water content minus the permanent wilting point water content (mm),

t = Time in days,

R_{day} = Rainfall (mm),

Q_{surf} = Surface runoff (mm),

E_a = Evapotranspiration (mm),

w_{seep} = Percolation (mm)

Q_{gw} = Return flow (mm)

5.5 Model Setup

5.5.1 Watershed Delineation

The watershed delineation aids the user to segment the watershed into several hydrologically connected sub-basins for use in hydrological modeling with SWAT. The delineation process requires a digital elevation model (DEM) in ArcInfo grid format. The delineation process creates a detailed topographic report. The topographic report describes the statistical summary and distribution of discrete land surface elevation within the watershed along with all the sub-basins. The sub-basin outlets are the points in the drainage network where all the runoff over sub-basin pooled and forms streamflow.

The streamflow from the sub-basins outlet are then accumulated at measuring station. This is useful for comparison of simulated flows. In this study, six sub-basins have been created based on the topography. The Nethravathi stream network and sub-basins have been delineated using ArcSWAT-2009. The sub-basins outlet constitutes the drainage area of 269.65, 756.08, 362.09, 460.87, 736.91, and 604.74 km^2, for sub-basins 1, 2, 3, 4, 5, and 6 respectively.

5.5.2 Land Use and Soil Definition

SWAT uses Natural Resources Conservation Service Curve Number (NRCS-CN) method to calculate runoff at each sub-basin. The NRCS-CN method requires land use and soil data to determine CN for each combination of land use and soil category. The land use and soil classification tool guides the user through the process of specifying the data to be used. The land use and soil definition allows the models to load land use and soil themes into the project and determine the land use /soil class combinations. Once the application is completed, a detailed report is generated for the current project. The generated report describes land use and soil class distribution for each sub-basin.

5.5.3 HRU Definition

The hydrological response units (HRUs) are the portions of a sub-basin possessing unique combinations of soil, land use and slope that are incorporated into the SWAT model to account for the complexity of landscape within the sub-basin. Subdividing the watershed into areas having unique land use and soil combinations enables the model to reflect differences in evapotranspiration and other hydrologic conditions for different land use and soils. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases the accuracy and provides much better description of water balance.

Once the land use and soil data layers have been imported, the distribution of hydrologic response units (HRU) within the watershed must be determined. This process is performed for every sub-basin. In the HRU definition processes, a land use and soil distribution will be obtained. This will provide the detailed description of land use and soil classes after application of HRU overlay for the basin and sub-basin.

The number of HRUs with the land use/soil classes and areal extent are listed for each sub-basin. There are 192 HRUs prescribed in the model to suit the available data to delineate up to the outlet point for each sub-basin in the present study.

5.5.4 Weather Data

The weather data to be used in a watershed simulation is integrated after the HRU distribution has been completed. The weather station locations and weather data is introduced into the sub-basins. The weather data such as measured rainfall, relative humidity, temperature, wind speed, solar radiation are provided to run SWAT model.

5.5.5 SWAT Simulation

After all data such as rainfall, weather, LULC and soil are prepared as per SWAT input format, and then the simulation was carried out. SWAT computes water balance components such as runoff, ET, etc. Runoff is calculated by the NRCS CN method, evapotranspiration (PET) by Hargreaves and channel routing by variable storage routing method (Mengistu et al. 2012). Since solar radiation is not available in the present study area, the Hargreaves method has been used which requires air temperature only.

5.5.5.1 NRCS Curve Number Method

Present study has used the NRCS curve number (SCS, 1972) method. The NRCS curve number method relates calculated CN to runoff for the purpose of accounting initial abstraction losses and infiltration rates of soils. The fundamental rainfall-runoff equation is given by eq. (5.2)

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \tag{5.2}$$

Where,

Q_{surf}= Runoff (mm)

R_{day}= Precipitation (maximum potential runoff) (mm)

S = Potential maximum watershed retention (mm)

I_a= Initial abstraction (mm)

The retention parameter varies spatially due to changes in soils, land use, management practices, slope and temporal changes in soil water content. The retention parameter is defined by the following eq. (5.3).

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{5.3}$$

Where, CN is the curve number. The initial abstraction I_a is commonly approximated as 0.2S and the eq. (5.2) now becomes:

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} - 0.8S)} \tag{5.4}$$

From eq. (5.4) runoff will only occur when $R_{day} > I_a$. The graphical solution of eq. (5.4) for different curve number is represented in Figure 5.2.

The evapotranspiration (PET) will be estimated using three methods based on the available data over the region. The Penman-Monteith method requires solar radiations, air temperature, relative humidity and wind speed. The Priestley-Taylor method requires solar radiations, air temperature and relative humidity. The Hargreaves method requires an air temperature only. The present study has used Hargreaves method to estimate ET. This method is described briefly.

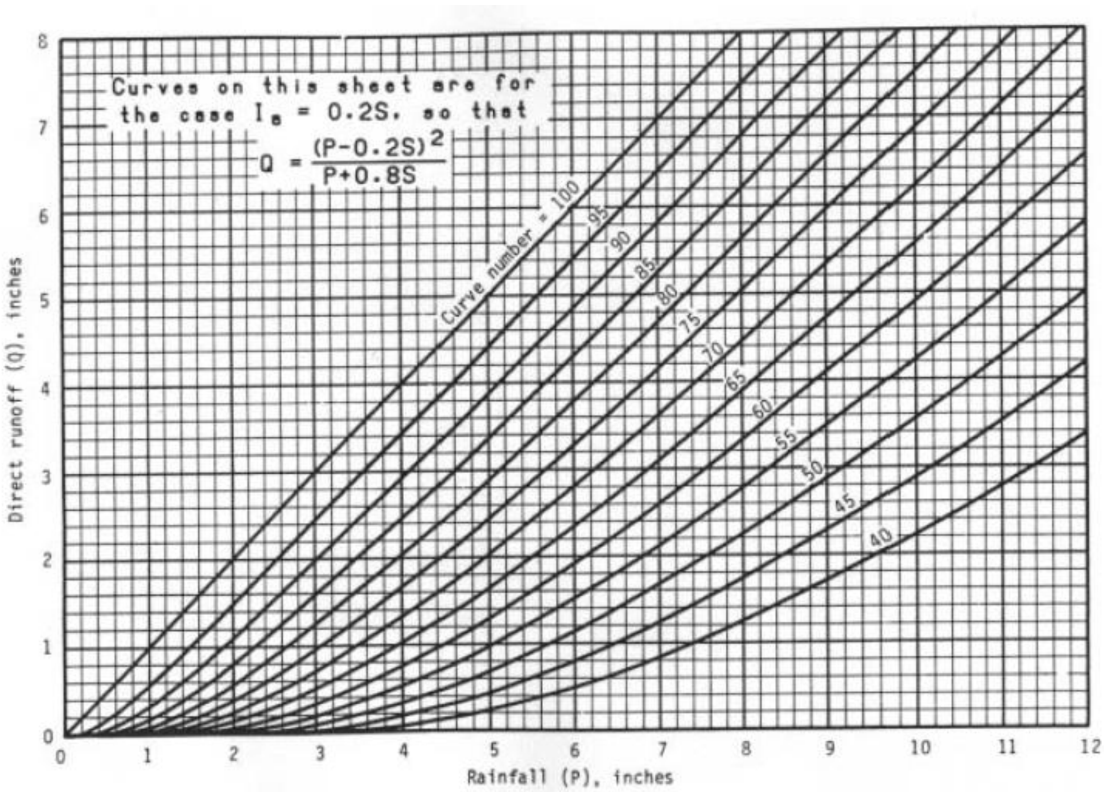


Figure 5.2: Graphical solution of different CN (Biesbrouck et al. 2002)

5.5.5.2 Hargreaves Method

The Hargreaves method was originally derived from eight years of cool-season Alta fescue grass lysimeter data from Davis, California (Hargreaves 1975). Several improvements (Hargreaves and Samani, 1985) were made to the original equation (5.5) and same is used in SWAT.

$$\lambda E_o = 0.023 H_o . (T_{mx} - T_{mn})^{0.5} . (T_{av} + 17.8) \qquad (5.5)$$

Where,

λ= Latent heat of vaporization (MJ d^{-1}).

E_o= Potential evapotranspiration (mm d^{-1})

H_o= Extraterrestrial radiation (MJkg^{-1})

T_{mx}= Maximum air temperature for given day (^{0}C)

T_{mn}= Minimum air temperature for given day (^{0}C)

T_{av}= Mean air temperature for given day (^{0}C)

5.5.5.5 Channel Water Routing Method

In the SWAT model, water is routed through the channel network using variable storage routing method or the Muskingum river routing method. The variable storage routing method was developed by Williams (1969) and used in the Hydrologic Model (HYMO) (Williams and Hann, 1973) and Routing Outputs to Outlet (ROTO) (Arnold et al. 1995) models.

For a given reach segment, storage routing is based on the following continuity eq. (5.6).

$$V_{in} - V_{out} = \Delta V_{stored} \qquad (5.6)$$

Where V_{in} is the volume of inflow during the time step (m^3 H_2O),
V_{out} is the volume of outflow during the time step (m^3 H_2O)
ΔV_{stored} is the change in volume of storage during the time step (m^3 H_2O).

Eq. (5.6) can now be written as eq. (5.7) by considering a particular reach, which has inflow and outflow.

$$\Delta t \cdot \left[\frac{q_{in,1}+q_{in,2}}{2}\right] - \Delta t \cdot \left[\frac{q_{out,1}+q_{out,2}}{2}\right] = V_{stored,2} - V_{stored,1} \qquad (5.7)$$

Where Δt is the length of the time step (s)

$q_{in,1}$ is the inflow rate at the beginning of the time step (m^3/s),

$q_{in,2}$ is the inflow rate at the end of the time step (m^3/s),

$q_{out,1}$ is the outflow rate at the beginning of the time step (m^3/s),

$q_{out,2}$ is the outflow rate at the end of the time step (m^3/s),

$V_{stored,1}$ is the storage volume at the beginning of the time step (m^3 H_2O)

$V_{stored,2}$ is the storage volume at the end of the time step (m^3 H_2O).

Rearranging eq.(5.7) so that all known variables are on the left side of the equation, yields eq. (5.8)

$$q_{in,ave} + \frac{V_{stored,1}}{\Delta t} - \frac{q_{out,1}}{2} = \frac{V_{stored,2}}{\Delta t} + \frac{q_{out,2}}{2} \qquad (5.8)$$

Where $q_{in,ave}$ is the average inflow rate during the time step, is given by eq. (5.9)

$$q_{in,ave} = \frac{q_{in,1}+q_{in,2}}{2} \qquad (5.9)$$

Travel time (T_t) is computed by dividing the volume of water in the channel by the flow rate using eq. (5.10).

$$T_t = \frac{V_{stored}}{q_{out}} = \frac{V_{stored,1}}{q_{out,1}} = \frac{V_{stored,2}}{q_{out,2}} \qquad (5.10)$$

Where T_t is the travel time (s), V_{stored} is the storage volume (m^3 H_2O), and q_{out} is the discharge rate (m^3/s).

To obtain a relationship between travel time and the storage coefficient eq. (5.10) is substituted into eq. (5.8), thus eq. (5.11) is obtained.

$$q_{in,ave} + \frac{V_{stored,1}}{\left(\frac{\Delta t}{T_t}\right) \cdot \left(\frac{V_{stored,1}}{q_{out,1}}\right)} - \frac{q_{out,1}}{2} = \frac{V_{stored,2}}{\left(\frac{\Delta t}{T_t}\right) \cdot \left(\frac{V_{stored,2}}{q_{out,2}}\right)} + \frac{q_{out,2}}{2} \quad (5.11)$$

which simplifies to eq. (5.12)

$$q_{out,2} = \left[\frac{2 \cdot \Delta t}{2 \cdot T_t + \Delta t}\right] \cdot q_{in,ave} + \left[1 - \frac{2 \cdot \Delta t}{2 \cdot T_t + \Delta t}\right] \cdot q_{out,1} \quad (5.12)$$

The above eq. (5.12) is similar to the coefficient method equation, which is given by eq. (5.13).

$$q_{out,2} = SC \cdot q_{in,ave} + (1 - SC) \cdot q_{out,1} \quad (5.13)$$

where, *SC* is the storage coefficient.

Eq. (5.6) is the basis for the SCS convex routing method (SCS, 1964) and the Muskingum method (Brakensiek, 1967). From eq. (5.11), the storage coefficient in eq. (5.12) is defined as

$$SC = \frac{2 \cdot \Delta t}{2 \cdot T_t + \Delta t} \quad (5.14)$$

It can be shown that

$$(1 - SC) \cdot q_{out} = SC \cdot \frac{V_{stored,1}}{\Delta t} \quad (5.15)$$

Substituting eq. (5.15) into eq. (5.6) gives eq. (5.16)

$$q_{out,2} = SC \cdot \left(q_{in,ave} + \frac{V_{stored,1}}{\Delta t}\right) \quad (5.16)$$

To express all values in units of volume, both sides of the equation are multiplied by the time step, results eq. (5.17).

$$q_{out,2} = SC \cdot (V_{in} + V_{stored,1}) \quad (5.17)$$

Therefore, eq. (5.17) is the equation for streamflow available at the outlet after routing.

5.6 Calibrating Water Balance

Conventionally, calibration is performed manually by changing model input parameter values to produce simulated values that are within a certain range of the measured data (Balascio et al. 1998; Arnold et al. 2012). However, when the number of parameters used in the manual calibration is large, especially for complex hydrologic models, manual calibration can become laborious (Balascio et al., 1998; Arnold et al. 2012) and hence, automated calibration methods are preferred. Both manual algorithms and automated methods have been developed for calibration of SWAT simulations.

An iterative approach is usually used for manual calibration. This involves the following steps: (1) perform the simulation; (2) compare measured and simulated values; (3) assess if reasonable results have been obtained; (4) if not, adjust input parameters based on expert judgment and other guidance within reasonable parameter value ranges; and (5) repeat the process until it is determined that the best results have been obtained. Several studies present systematic strategies for performing streamflow calibration and validation.

Coffey et al. (2004) recommend using NSE and R^2 for analysing monthly output and median objective functions, sign test, autocorrelation, and cross-correlation for assessing daily output by comparing SWAT results with measured streamflow.

5.7 Development of Runoff Coefficient Routing Model (RCRM)

Several studies have been carried out on study of streamflow response to climate and LULC change using SWAT model. Since, the input parameters in the SWAT model as more. However, some of the data like radiation, humidity, wind speed, etc. are not being monitored at sub-basin level in many watersheds. In such situation, the SWAT model cannot be used. To overcome this difficulty of providing all meteorological data, an attempt has been made to develop a simple runoff model, which can be applied as a distributed model and it requires only precipitation, land use land cover and the hydrologic soil data to estimate runoff using the proposed model.

The proposed model called "*Runoff Coefficient Routing Model (RCRM)*" and it works based on runoff and weighted runoff coefficients for each sub-basin. The total runoff can be estimated by routing all the sub-basins runoff to the outlet of main basin. The conceptual model of RCRM model is presented in Figure 5.3. The conceptual RCRM model is transformed into a mathematical model as given by eq. (5.18) which estimates the total runoff at the outlet of the main basin.

$$R_T = R_1C_1 + R_2C_2 + R_3C_3 + \cdots + R_nC_n \quad (5.18)$$

Where, R_T = total runoff at the Outlet in mm, $R_{1\ldots n}$ = runoff at sub-basin (1-n) in mm and $C_{1\ldots.n}$ = weighted runoff coefficient at sub-basin 1-n,

Since this model is based on runoff coefficients, which can be derived from the land use land cover map. Weighted runoff coefficients for each sub-basins (Dhakal et al., 2012) are computed from basin runoff coefficients of each land cover category using eq. (5.19).

$$C_i = \frac{\sum_{i=1}^{n} k_i a_i}{\sum_{i=1}^{n} a_i} \quad (5.19)$$

Where C_i = Weighted runoff coefficient for i^{th} sub-basin. And the total sum of C should not exceed one as indicated by eq. (5.20).

$$\sum_{i=1}^{n} C_i \leq 1 \quad (5.20)$$

k_i= Runoff coefficient of i^{th} LULC in the sub-basin; a_i = Area of the i^{th} LULC in the sub-basin.

The runoff coefficients (k_i) for different LULC category given by Dhakal et al. (2012) are used in the present study. Weighted runoff coefficients (C) of each sub-basins calculated by the eq. (5.19) are then used as an initial value for calibration.

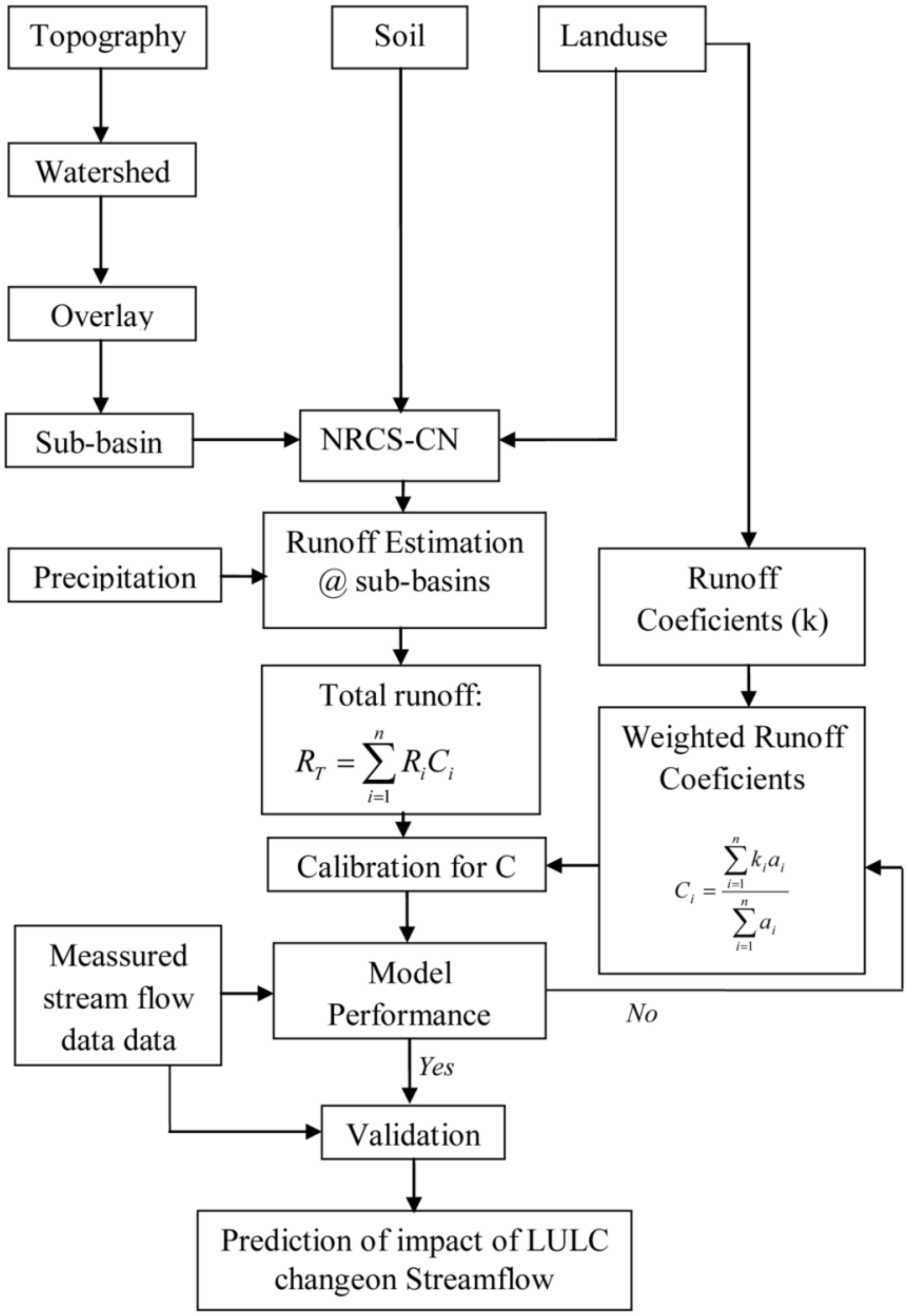


Figure 5.3: Development of proposed RCRM model

Ideally, the runoff from each sub-basin was routed along the flow channel to the outlet. However, in the proposed method, runoff calculated by the NRCS-CN method is multiplied by weighted runoff coefficients. These weighted runoff coefficients act as roughness coefficients in the river reach from outlet of one sub-basin to another sub-basin outlet.

5.8 Model Calibration and Validation

The model calibration procedure is developed based on optimization techniques (Guo et al. 2008) with the assumption that an optimal set of parameters exists in the model to describe the hydrology of the river basin. Calibration is the process of adjusting the model parameters. Calibration has been divided in two sub-processes: parameter identification and parameter estimation. Parameter identification consists of defining and choosing the most sensitive parameters of the model, and parameter estimation consists of fixing the values of the chosen parameters. Parameter identification has been performed through a sensitivity analysis, which estimates the rate of change in the output (Streamflow) with respect to changes in the input (parameter value). This analysis has been applied in order to limit the number of optimized parameters required to obtain a good fit between the simulated and observed data. Hence, the numbers of parameters to be adjusted are considerably reduced.

Results from these permutations have suggested that the set of optimal values of model parameters allows the model to optimally describe the basin hydrology, in the sense to have the least error between the simulated and the observed streamflow at gauging station. Although this set of model parameters optimizes model condition for the period of calibration and validation, it offers little insight of model performance in predictive mode (Guo et al. 2008).

5.9 Model Performance

The performance of any mathematical model will be assessed by statistical parameters such as Nash-Sutcliffe model Efficiency coefficient (NSE), the coefficient of determination (R^2), and Root mean square error (RMSE). However, NSE and R^2 were used as statistical parameters to assess the performance of SWAT and RCRM model results in the present study.

NSE is calculated using eq. (5.21) as given by ASCE (1993) after plotting a graph of observed and simulated streamflow.

$$NSE = 1 - \frac{\sum_{i}^{n}(\text{obs}_{i} - \text{sim}_{i})^2}{\sum_{i}^{n}(\text{obs}_{i} - \text{obs}_{mean})^2} \qquad (5.21)$$

Where i = time step; n = total number of simulated time steps; obs_i and sim_i= the observed and simulated values of streamflow; and obs_{mean} = Mean of the observation for the simulated time period.

5.10 Results and Discussions

5.10.1 Calibration Result

The sensitivity analysis (Wu and Johnston, 2008; Li et al. 2009) has been carried out with combined Latin hypercube and one-factor-at-a-time (LH-OAT) sampling methods developed by Van Griensven and Meixner (2005). The adjustments of model outputs to the observed values were estimated with an objective function as the sum of squared residuals (SSQ). A restricted set of 27 parameters have been used for the sensitivity analysis. From the sensitivity analysis, 11 parameters out of 28 parameters were found as most sensitive parameters. The calibration has been carried out for the years 2001-2005 considering only the 11 sensitive parameters as shown in Table 5.1 with final calibrated values.

Table 5.1: Sensitive parameters and ranges by sensitivity analysis

Sr. No	Parameter Name	Description	Bounds of values		Calibrated Values
			Min	Max	
1	Alpha_Bf	Base flow alpha factor (days)	0.1	1	0.22

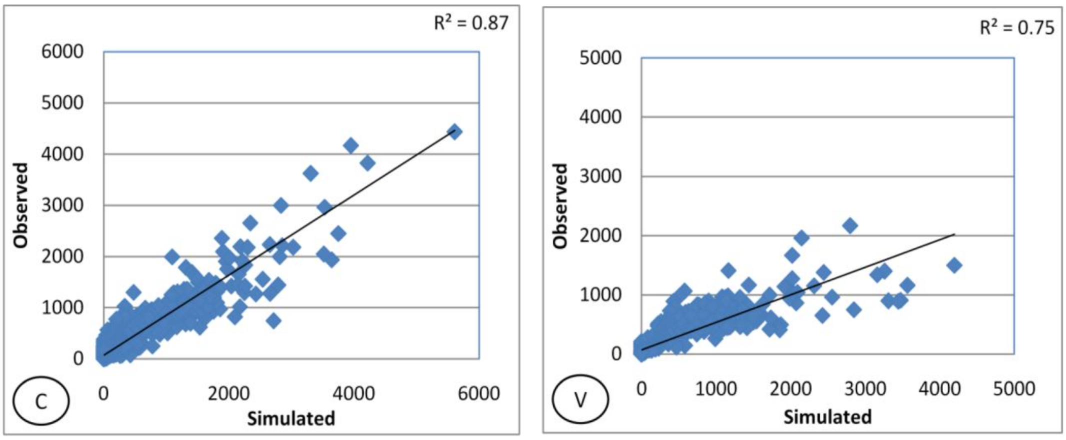
2	Canmx	Maximum canopy storage index (unit less)	0	100	82.09
3	Ch_K2	Effective hydraulic conductivity in main channel alluvium (mm/hr)	0.01	500	349.54
4	Cn_N2	Manning's n for the main channels (unit less)	0.01	0.3	0.11
5	Cn2	SCS runoff curve number for moisture condition II	-20%	20%	-0.06
6	Esco	Soil evaporation compensation factor (unit less)	0	1	0.18
7	Gwqmn	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0	5000	1304.54
8	Revapmn	Threshold depth of water in the shallow aquifer required for revap to occur (mm)	0	500	91.36
9	GW_Delay	Ground Water Delay	0	500	28.63
10	Sol_K	Soil hydraulic conductivity (mm/hr)	0	2000	20.12
11	Surlag	Surface runoff lag time (days)	0.05	24	11.52

After obtaining and processing input data, the SWAT model has been calibrated from year 2001 to year 2005 and then validated from year 2006 to year 2009. The LULC used in the calibration and validation is of the year 2003. The only LULC data acquired from IRS 1D LISS -3 in the year 2003 is of good coverage and free from clouds.

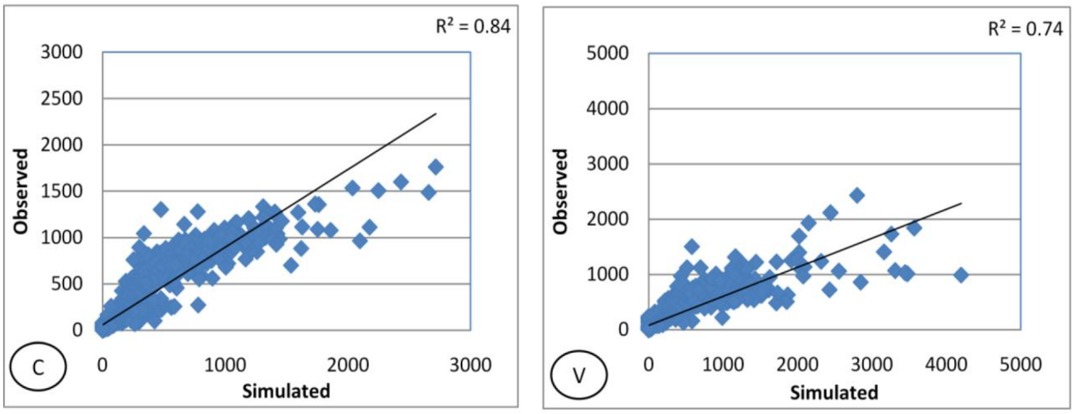
The model has been run on a daily time step. It is also observed that the daily observed streamflow have shown a considerably good (R^2) of 0.87 and 0.84between simulated streamflow vs. observed streamflow by SWAT and RCRM as shown in a scatter plot (Figure 5.4). The model performances such as the coefficient of determination (R^2) and Nash-Sutcliffe efficiency during calibration are tabulated in Table 5.2. The daily observed streamflow are closely matched with simulated streamflow during calibration as shown in time series (Figure 5.5).

5.10.2 Validation Result

The model performances such as the coefficient of determination (R^2) and Nash-Sutcliffe efficiency during validation are tabulated in Table 5.2. Validation has been carried out for the years 2006-2009 after calibration. The daily streamflow obtained during validation by the SWAT model have been compared with observed streamflow. Model performance statistics shown in Table 5.2 shows that R^2 value equal to 0.75 and 0.74between simulated by SWAT and RCRM Vs observed streamflow. Therefore, the validated model can be used for prediction of streamflow for different LULC change.



(a). SWAT model results



(b). RCRM model results

Figure 5.4: Calibration (C) and Validation (V) results of SWAT and RCRM model.

Table 5.2: Statistical performance of model result

Time scale (Daily)		Observed Vs. Simulated streamflow (SWAT)	Observed Vs. simulated streamflow (RCRM)
Calibration period 2001-2005	R^2	0.87	0.84
	NSE	0.83	0.81
Validation period 2006-2009	R^2	0.75	0.74
	NSE	0.71	0.70

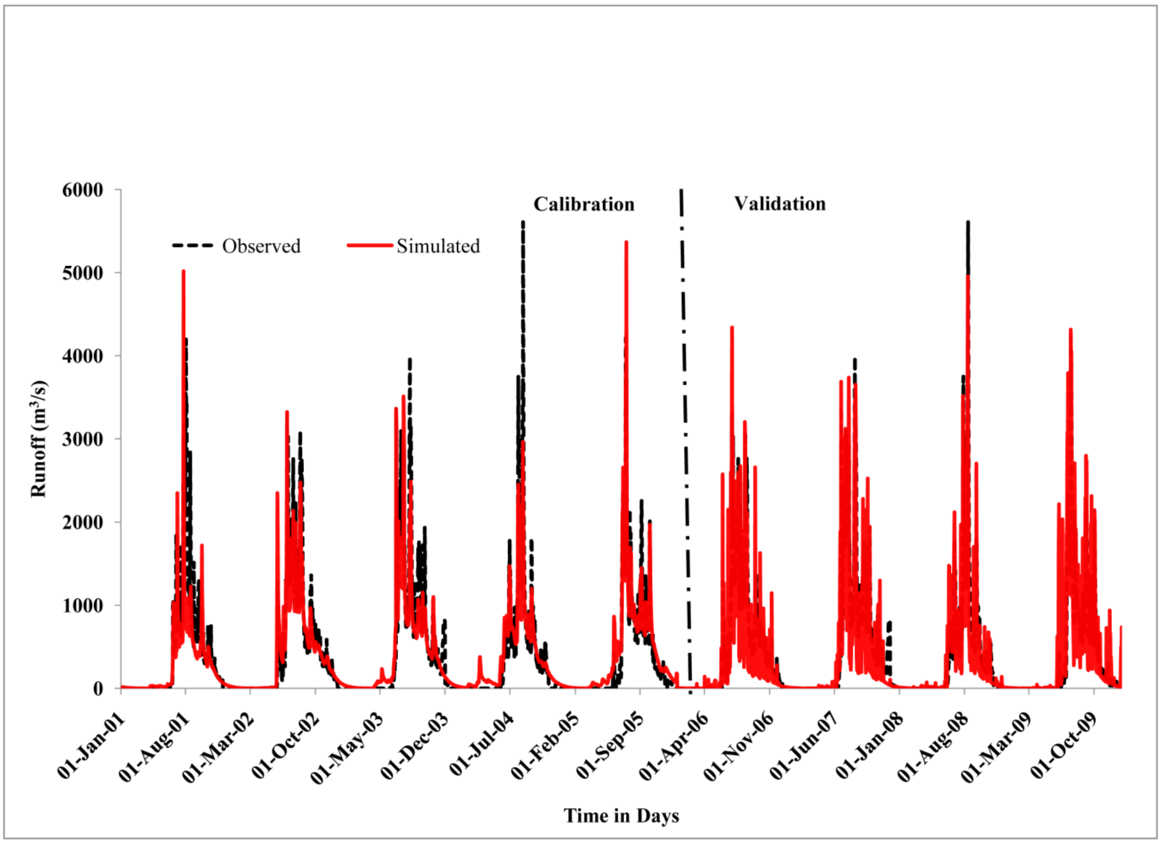


Figure 5.5 Time series plot of simulated and observed runoff

Similarly, the RCRM model has been calibrated for weighted runoff coefficients computed from eq. (5.19) is used as an initial values. The calibration has been carried out manually by trial and error method. The final calibrated weighted runoff coefficients are obtained and tabulated in Table 5.3.

Table 5.3: Initial and calibrated runoff coefficient used in RCRM model

Runoff coefficients for different LULC (Dhakl et al. 2012)		Sub basin No.	Initial weighted runoff coefficient (C)	Final calibrated C values
LULC class description Initial runoff coefficient		1	0.46	0.52
Forest	0.48	2	0.47	0.49

Agriculture	0.40	3	0.46	0.51
Wasteland	0.3	4	0.48	0.48
Water	1.0	5	0.47	0.47
Urban	0.65	6	0.48	0.49

5.11 Extraction of LULC map

Supervised classification has been used in the analysis to extract LULC change as the classifier allows the user to define the training data set (or signature). Details about the area, knowledge about ground truth and experience in image interpretation permit pixels with specific characteristics to be selected for a better classification of the image (Coppin and Bauer, 1996). After identifying the signatures, the pixels of the image have been sorted into classes based on the signatures using a classification decision rule. According to Coppin and Bauer (1996), the decision rule is a mathematical algorithm that uses data contained in the signature and performs the actual sorting of pixels into distinct class values.

5.11.1 Training Data Sets and Signatures

After sub-setting the image to the study area, the training data sets have been created with the help of Google Earth and ground truth data collected by GPS. The photographic interpretation information has been used as a guide for defining the feature classes in the satellite images. The classes identified through ground truth survey are agricultural land, wasteland, forest, water and built up land. These classes have been sampled from the satellite image using the polygon (Area of Interest) method. The method simply allows drawing a polygon that defines the location of the pixels, which signify the particular spectral class. Once the base training sets have been established, each training set is stored in signature and assigned the desired colour for the visual interpretation of a feature class. The training data sets have been used to generate class signatures and classify the rest of the image into meaningful information classes.

5.11.2 Accuracy Assessment of Image Classification

The accuracy assessment of an image classification has been carried by creating the classification error matrix or confusion matrix**.** In this confusion matrix, classification results are compared with ground truth data obtained during field visits. This is carried out by verifying the ground coordinates of the ground truth samples (stored in Excel file), which is already stored in text format. The Kappa coefficient expresses the proportionate reduction in error generated by a classification process compared with the error of a completely random classification (Coppin and Bauer, 1996). Kappa that is estimated as K reflects the difference between actual agreement and the agreement expected by chance. In the present study, the Kappa is calculated for 2003 and 2013 satellite images. The error matrix of classified images of year 2003 and 2013 are presented in Table 5.4 and Table 5.5 respectively. The Kappa values are 0.82and 0.84 for 2003 and 2013 satellite images respectively. The LULC maps for the years 2003 and 2013 of Nethravathi river basin shown in Figure 5.6

Table 5.4: Error Matrix 2003 Image

Class Name	Forest	Agriculture	Wasteland	Urban land	Water	Row Total
Forest	36	02	01	00	00	39
Agriculture	01	32	02	00	00	35
Wasteland	00	01	22	02	02	27
Urban land	00	00	01	12	00	13
Water	00	01	00	00	18	19
Column Total	37	36	26	14	20	133

Overall accuracy = 90.22 %

Kapa statistics = 0.84

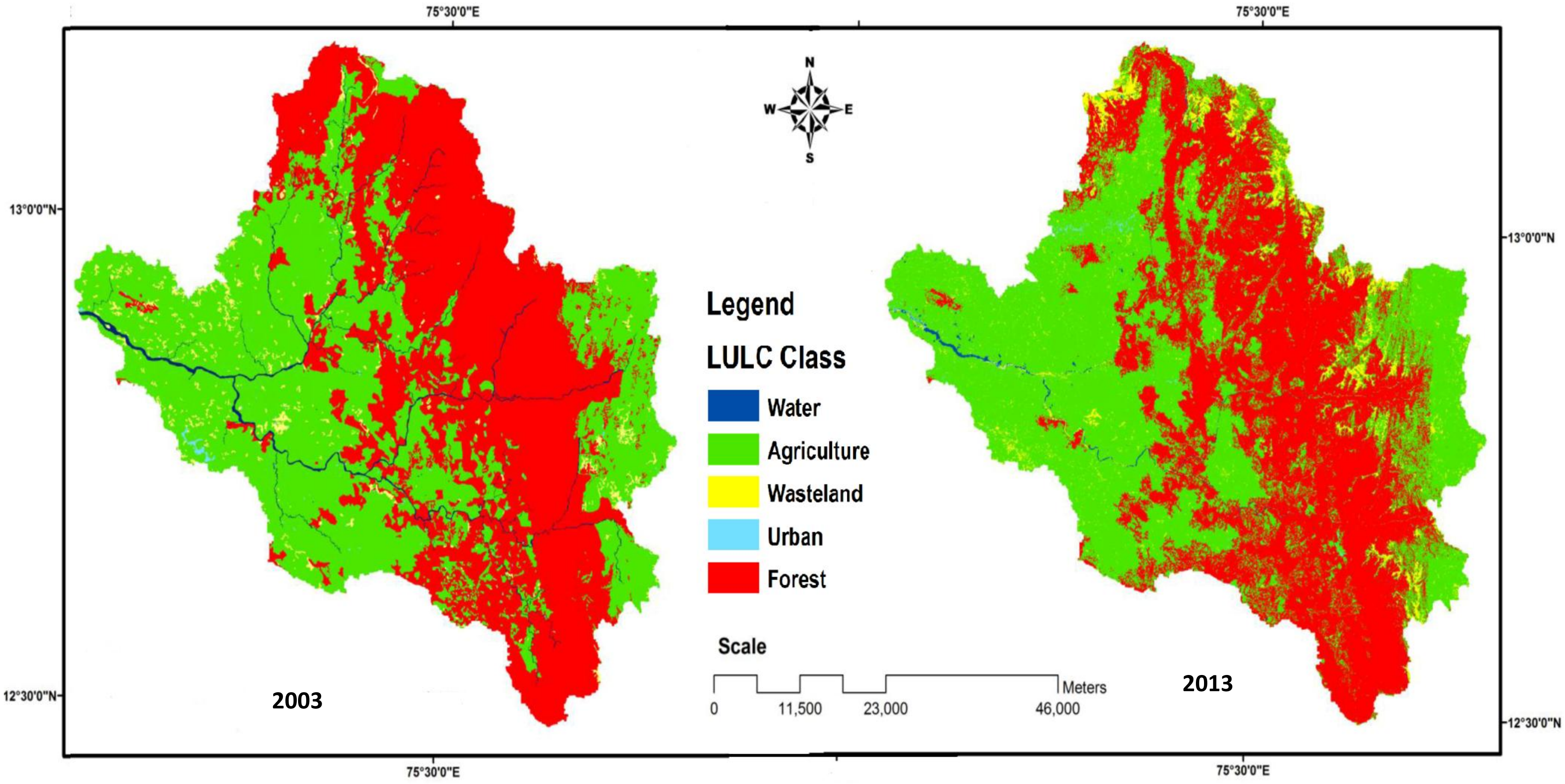


Figure 5.6: LULC map of the Nethravathi basin

Table 5.5: Error Matrix 2013 Image

Class Name	Forest	Agriculture	Wasteland	Urban land	Water	Row Total
Forest	42	02	02	00	00	46
Agriculture	02	38	02	01	00	44
Wasteland	01	02	27	01	02	33
Urban land	00	00	01	18	00	19
Water	00	00	01	01	24	26
Column Total	46	42	33	21	26	168

Overall accuracy = 88.60 %

Kapa statistics = 0.82

5.11.3 Change Detection

The LULC change detection was carried out by comparing 2003 image with 2013 image using matrix operation from GIS. By comparing two classified data sets, the matrix operation was able to show all the changes from one class to another class. For interpretation of images and change detection, a post classification comparison was also applied.

Post-classification is the most widely applied technique for change detection purpose (Singh, 1989; Coppin and Bauer, 1996). The analysis of LULC change maps involved technical procedures of integration using the ArcGIS software. The outcome of the changes provides useful information to understand human interference on the sub-catchment over years and its possible influence on the water flow in the river systems.

LULC change over Nethravathi river basin was analysed by processing IRS 1 D-LISS-3 satellite image acquired on March 2003 and Landsat image acquired in January 2013. Both the images were classified using Maximum likelihood classifier of supervised classification algorithm into forest, agriculture, wasteland, water and urban categories. Finally, LULC change was assessed and tabulated in Table 5.6. It is observed that forest and water body have decreased by 3.2% and 1.17% respectively from 2003 to 2013. At the same time, agricultural land, wasteland and urban areas have increased by 2.73%, 1.6% and 0.16% respectively.

Table 5.6: LULC Change in the study area

LULC Class description in SWAT	Description of LULC	2003 area (%)	2013 area (%)	Change in LULC (%)
FRSE	Forest	47.31	44.11	(-)3.20
AGRR	Agriculture	48.70	51.44	2.73
INDN	Wasteland	2.14	3.74	1.60
WATR	Water	1.61	0.44	(-)1.17
URMD	Urban	0.23	0.40	0.16

5.12 Conclusions

The present research is aimed to study the LULC change between the year 2003 and 2013 and its impact on streamflow. The impact of this LULC change on streamflow has been assessed using hydrological models such as SWAT and RCRM, which is newly proposed in this study. The following conclusions are drawn based on the analysis and results obtained from models.

- From the results, it is concluded that the parameters such as Alpha-Bf, Canmax, Ch_K2, Ch_N2, Cn2, ESCO, Gwqmn, Revapmn, Gw_Dalay, Sol_K and Surlag are found as most sensitive parameters for the Nethravathi river basin by the SWAT model.

- The results of the newly developed RCRM model show better agreement with SWAT model results in both calibration and validation period with R^2 and NSE greater than 0.70. Therefore, it is concluded that the RCRM model is capable of predicting the streamflow at par with SWAT model with only few input parameters such as precipitation, LULC, whereas SWAT require more input parameters. Hence, newly developed RCRM can be used to simulate and predict the streamflow in the data scarce region or basin.

- The LULC analysis between the year 2003 and 2013 has been prepared from the satellite images. The change in LULC from 2003 to 2013 was extracted. The resultant LULC map has shown that, there is a gain in agriculture land (2.73%), urban (0.17%) and wasteland (1.60%) by reducing Forest (3.20%) and water body (1.17%) during the year 2013.

CHAPTER 6

IMPACT STUDIES

6.1 Introduction

Change is a natural phenomenon and it needs to be adopted. However, the rate at which the change occurs will have an impact on other dependants of the system directly or indirectly. There is a need to analyse the impact to determine possible conflicts and design alternatives influenced by the changes (Heerwagan et al 2007). LULC change takes place due to forest clearance, replacing grasslands to cropland or grazing lands to urbanization, wetlands reduction, developments of road network for transportation and mining in quarries. These LULC changes bring changes in water resources.

Land use change is a major force altering the hydrological processes such as streamflow, interception, infiltration, and evaporation (Potter, 1991; Defries and Eshleman, 2004; Chen et al. 2009) over a range of temporal and spatial scales. Good estimate of future streamflow is an important result from the study of impacts of LULC change. It is well documented that LULC changes have profound impacts on river basin hydrology, primarily through changes in flood frequency base flow (Brath et al. 2006; Wang et al. 2006), and annual mean discharge (Costa et al. 2003).

Several studies across the globe have revealed the intricate interrelationship between LULC change and various aspects of regional hydrological cycle (Roberts and Harding, 1996; Wooldridge et al. 2001; Costa et al. 2003; Legesse et al. 2003; Croke et al. 2004; Woldeamlak and Sterk, 2005; Mutie et al. 2006; Siriwardena et al. 2006; Zhang and Schilling, 2006; Fang et al. 2007; Choi and Deal, 2008; Guo et al. 2008; He et al. 2008; Ma et al. 2008; Sang et al. 2008; Mueller et al. 2009; Savary et al. 2009; Delgado et al. 2010;Gebresamuel et al. 2010; Moiwo et al. 2010; Sang et al.

2010; Mango et al. 2011; Tao et al. 2011; Zhang et al. 2011; Wang et al. 2012; Li et al. 2013; Li et al. 2013a; Fang et al. 2013).

Regarding research methodologies, hydrologic models are considered to be powerful tool for predicting impacts of climate and LULC change on watershed hydrology (Whitehead and Robinson 1993; Fang et al. 2013).

6.2 Effects of LULC Change on Streamflow

Land covers change and its effects/impacts on streamflow, runoff generation mechanisms are of widespread concern and become a major challenge to the researchers and policy makers (Ma et al. 2008). SWAT has been used to study the impacts of LULC change on streamflow of Nethravathi river basin. Effects of LULC change on streamflow of the Nethravathi river basin has been studied by using 2003 and 20013 LULC maps, which is prepared by processing IRS 1D LISS III and Landsat image. The climate condition considered for the year 2013 is same as that of 2003 in SWAT model. The effect of this LULC change on hydrological parameters have been calculated and tabulated in Table 6.1.

Table 6.1: Effect LULC Change on hydrological model parameter

LULC Class description in SWAT	Description of LULC	Change in LULC from 2003 to 2013 (%)	Change in ET (%)	Change in runoff (%)	Change in Ground water (%)
FRSE	Forest	(-)3.20	(-) 4.5	(+) 0.9	(+) 1.12
AGRR	Agriculture	2.73			
INDN	Wasteland	1.60			
WATR	Water	(-)1.17			
URMD	Urban	0.16			

It is observed from the Table 6.1 that the hydrological parameter such as ET is decreased by 4.5%, the runoff is increased by 0.9% and groundwater is increased by 1.12%. Therefore, it is concluded that a small change in LULC could cause an impact on hydrological parameters. However, the impact is not significant in this study as LULC is not significantly changed. The results also show that there is a good agreement between observed and simulated streamflow as evident by a scatter plot shown in Figure 6.1 with R^2 equal to 0.87 and NSE equal to 0.85 using SWAT model. Where as in the case of RCRM model, R^2 and NSE are found to be 0.85 and 0.81 respectively as indicated in Figure 6.2.

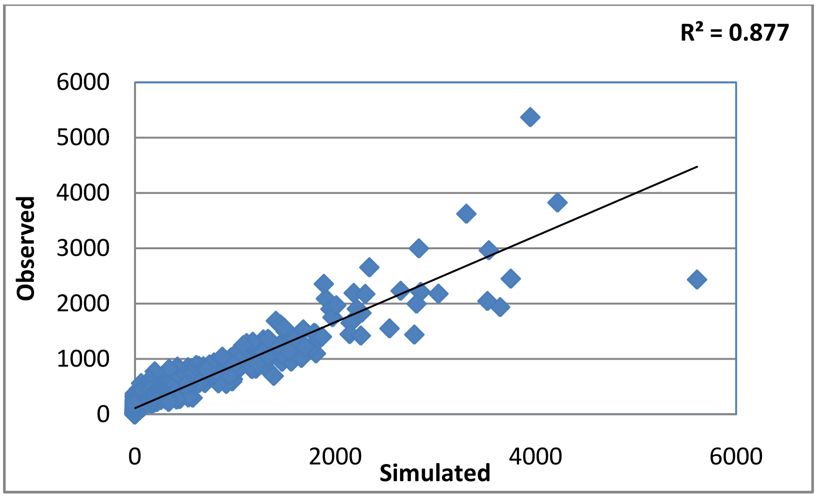


Figure 6.1: Plot of observed and simulated streamflow from SWAT

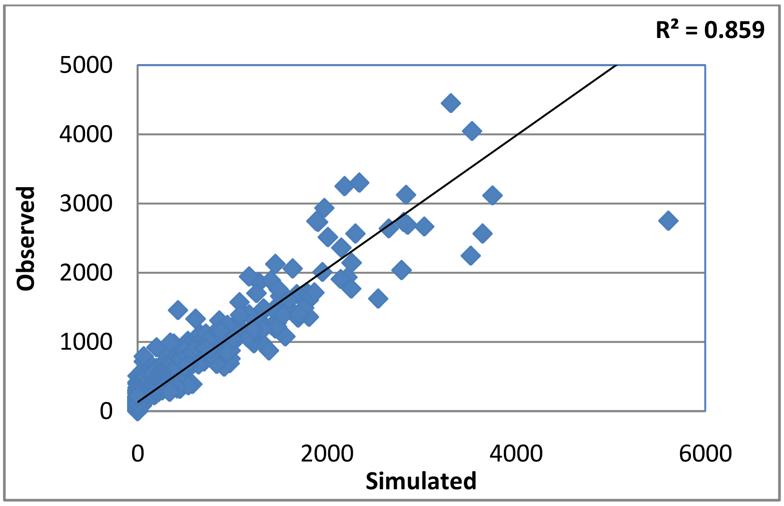


Figure 6.2: Plot of observed and simulated streamflow from RCRM

Then, the results of SWAT and RCRM models have been compared using a scatter plot and found that RCRM model results are closely matching with SWAT model results. The effect of LULC of 2003 and 2013 on streamflow has been predicted and plotted as a time series as shown in Figure 6.3. After validation and performance indices of the model, the time series plotting has been carried out with the help of SWAT simulated streamflow for the year 2003 and year 2013. It is clearly observed that there is an early response in streamflow initially, in the month of June – July itself and slowly reduces after July. This has been noticed mainly because of the change in LULC from 2003 to 2013. The change was mainly due to conversion of forest to agriculture land as noticed in the LULC image of 2013. Therefore, the change in LULC has an implication on early runoff generation mechanism in the basin.

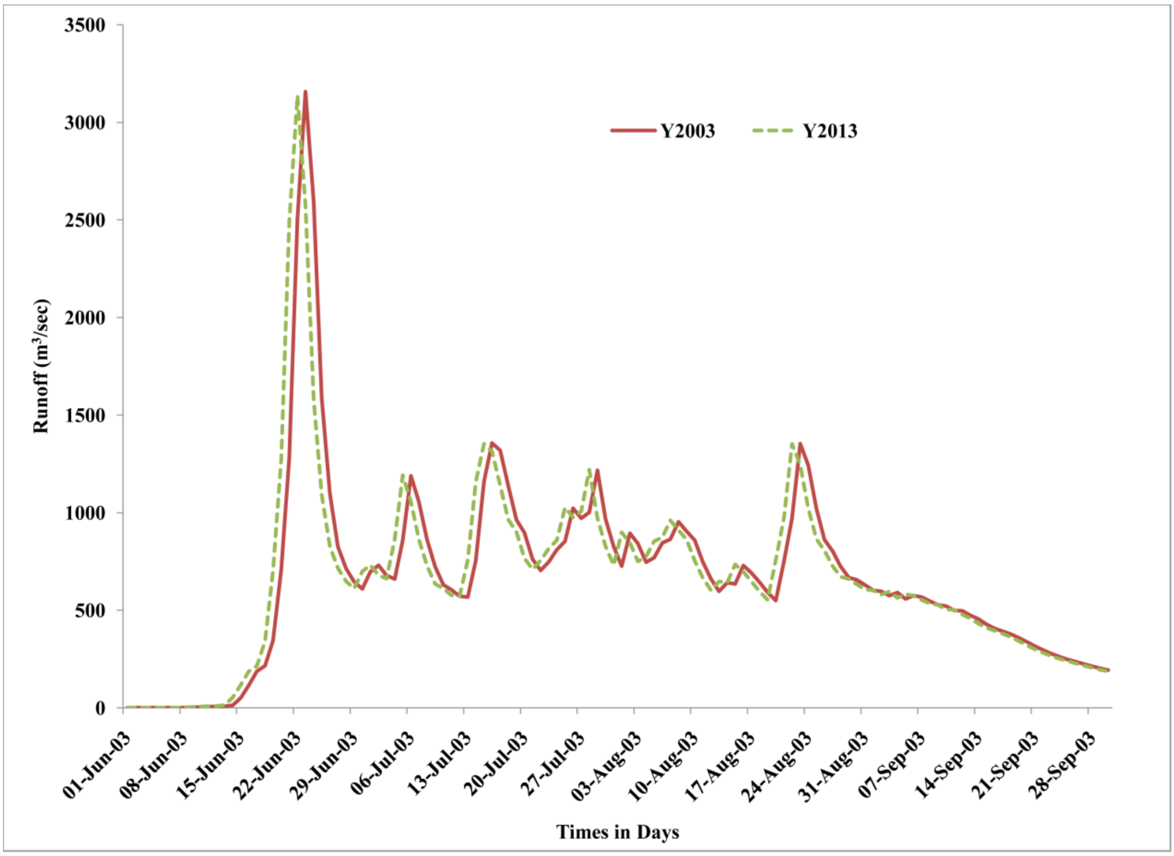


Figure 6.3: Predicted streamflow of LULC-2003 and 2013

Thus, it is concluded that a small change in LULC could cause an impact on runoff mechanisms and temporal variation in runoff as observed in the streamflow's time series graphs.

6.3 Effect of LULC Change on Streamflow due to Extreme Rainfall Event

A large amount of variability in runoff is related to the occurrence of extreme rainfall events. Frequency distribution method of extreme rainfall events have been carried out based on the amount of rainfall occurred in a day. Generally, for extreme event studies (Attri and Tyagi, 2010), the rainfall has been grouped into three broad classes viz.

Class-1 - Light to rather heavy rainfall ($0 < R \leq 64.4$ mm),
Class-2 - Heavy rainfall ($64.4 < R \leq 124.4$ mm),
Class-3 – Very heavy to exceptionally heavy rainfall ($R > 124.4$ mm)

According to Pattanaik and Rajeevan, (2010),rainfall more than 124.4 mm will be referred as extreme rainfall events and same criterion was used in the present study. Extreme rainfall events from 1991 to 2010 were selected for the Nethravathi river basin. Further, these events were studied together with LULC change for analyzing the runoff changes. In addition, temporal variability has been carried out using LULC change occurred between 2003 and 2013.

Classified satellite images for year 2003 and 2013 were used to study the land use land cover impacts on runoff changes due to extreme rainfall event. The information about occurrence of extreme rainfall event with respect to changes in runoff is provided in Table 6.2 and Figure 6.4.

Table 6.2: Effect of LULC on streamflow due to extreme rainfall event

Event no	Date	Change in runoff m^3/s	Event no	Date	Change in runoff m^3/s
1	27-07-1991	-65	21	22-08-1997	-41
2	28-07-1991	-150	22	30-06-1998	-76

3	21-06-1992	-182	23	16-07-1999	-91
4	27-07-1992	-108	24	18-07-1999	-121
5	12-07-1993	-69	25	08-07-2001	-39
6	05-06-1994	-36.1	26	22-06-2003	-116
7	29-06-1994	-101	27	23-06-2003	-135
8	30-06-1994	-115	28	04-08-2004	-70
9	12-07-1994	-149	29	05-07-2005	-128
10	13-07-1994	-190	30	24-07-2005	-90
11	14-07-1994	-114	31	25-07-2005	-253
12	30-07-1994	-46	32	28-05-2006	-46.7
13	17-07-1995	-26	33	29-05-2006	-114.1
14	14-06-1996	-9.9	34	30-06-2006	-87
15	15-06-1996	-125.1	35	23-06-2007	-237
16	18-06-1996	-85	36	17-07-2007	-140
17	29-06-1997	-136	37	12-08-2008	-130
18	30-06-1997	-104	38	16-07-2009	-143
19	10-07-1997	-90	39	18-07-2009	-158
20	07-08-1997	-84	40	30-07-2010	-104

Figure 6.4 represented as windrose diagram of 40 extreme rainfall events and runoff change occurred due to those extreme rainfall events. The extreme event numbers 1 - 24 are included under decade-1 and extreme event numbers 25 - 40 are included under decade-2. The decade-1 and decade-2 have shown decreased runoff. The runoff is decreased occurred in decade-2 as compared to decade-1.

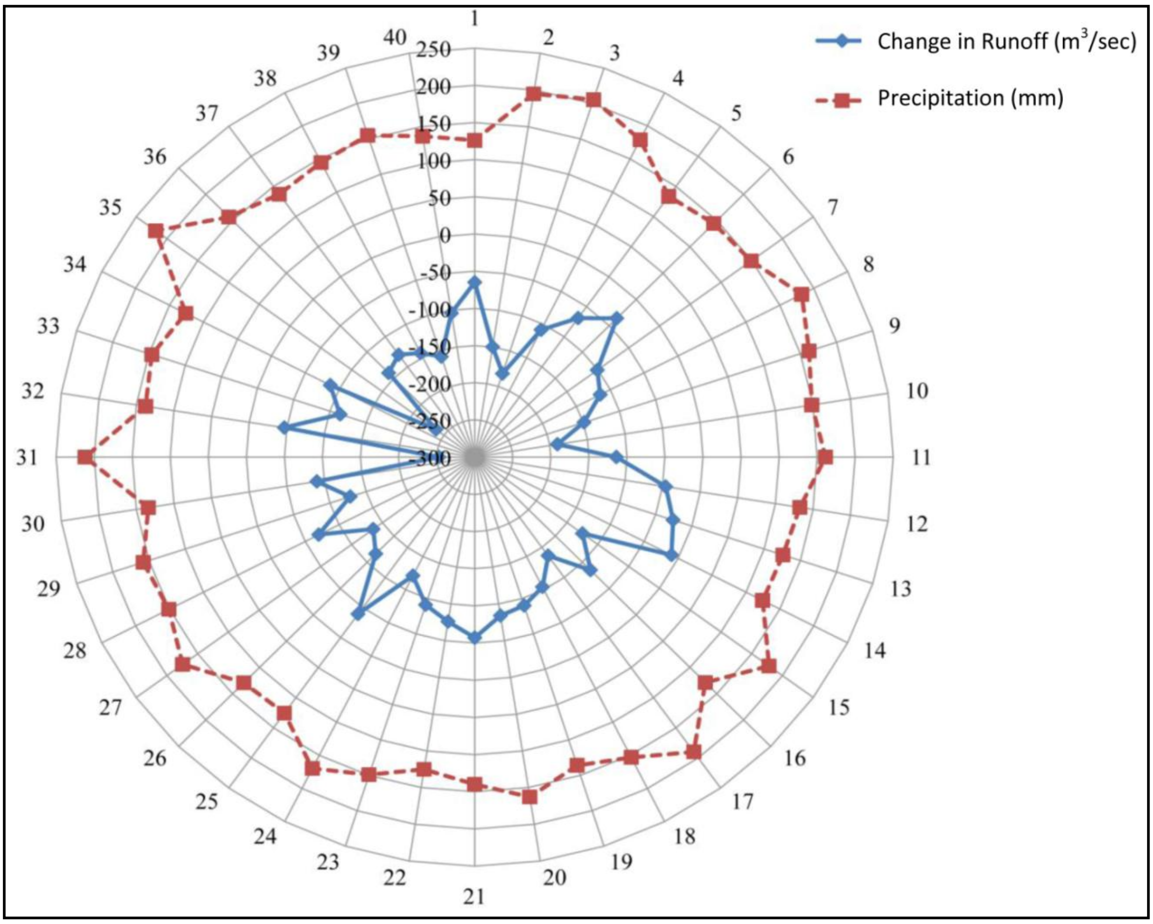


Figure 6.4: Windrose diagram showing change in runoff with respect to extreme event

The Nethravathi river basin was additionally studied from the perspective of temporal distribution of significant precipitation events from May to October (Table 6.3). Decade-1 includes years from 1991 to 2000 and decade-2 includes years 2001 to 2010. Table 6.3 reveals that the extreme precipitation events have been decreased in decade-2 as compared to decade-1. The change in runoff for decade-1 are found to be 970 mm, 1219 mm and 141 mm respectively for the month of June, July and August. The change in runoff in the decade-2 are found to be 575 mm, 1055 mm and 200 mm for the month of June, July and August respectively. The decade-1 shows maximum change in the runoff as compare to decade-2. This is mainly due to decreased extreme rainfall events in decade-2.

Table 6.3: Monthly change in runoff due to extreme rainfall event

No	Decade	Months	No. of events occurred	Total change in runoff (m^3/s)
1	Decade-1 (1991-2000)	May	0	0
2		June	10	970.1
3		July	12	1219
4		August	2	141
5		October	0	0
1	Decade-2 (2001-2010)	May	2	160.8
2		June	4	575
3		July	8	1055
4		August	2	200
5		October	0	0

6.4 Development of LULC Change Scenarios

To explore the sensitivity of model outputs to LULC change, on the streamflow of the Nethravathi river, potential land use land cover change scenarios were developed hypothetically. Attempts were made to develop realistic scenarios in accordance with ongoing trends of land use land cover change within the study area. The land use scenarios presented in Table 6.4 provides information about each LULC change scenario. Three scenarios were proposed in the present study based on available statistics and temporal changes found in the satellite images. The proposed scenarios are as follows.

1. Conversion to Agriculture (CA): In this scenario, land use land cover area is converted into agriculture class from other land use land cover classes.
2. Conversion to Built-up/Urban (CB): In this scenario, land use land cover area is converted into build up class from other land use land cover classes.
3. Conversion to Wasteland (CW): In this scenario, land use land cover area is converted into wasteland class from other land use land cover classes.

Table 6.4: Land use land cover conversion

No	Land use scenario	From wasteland (%)	From forest (%)	From agriculture (%)	Total area (%)
1	CA	1.46	1.11	--	2.57
2	CB	0.05	0.02	0.38	0.45
3	CW	--	1.53	--	1.53

For the analysis, change in runoff X (m^3/sec) has been divided into 4 classes Table 6.5, 6.6 and 6.7 stretches information such as frequency, mean and standard deviation about change in runoff for each class to scenario- CA, CB and CW respectively. The Figures 6.5, 6.6 and 6.7 shows the graphical representation of runoff change with respect to scenario- CA, CB and CW.

Table 6.5: Class statistics in scenario- CA

No	Class	Frequency	Mean	Std. deviation
1	$X \geq 20.000$	10	21.50	4.83
2	$0.001 \leq X \leq 19.999$	1918	0.70	3.22
3	$-19.999 \leq X \leq 0$	1703	-0.50	3.49
4	$X \leq -20.000$	21	-24	5.28

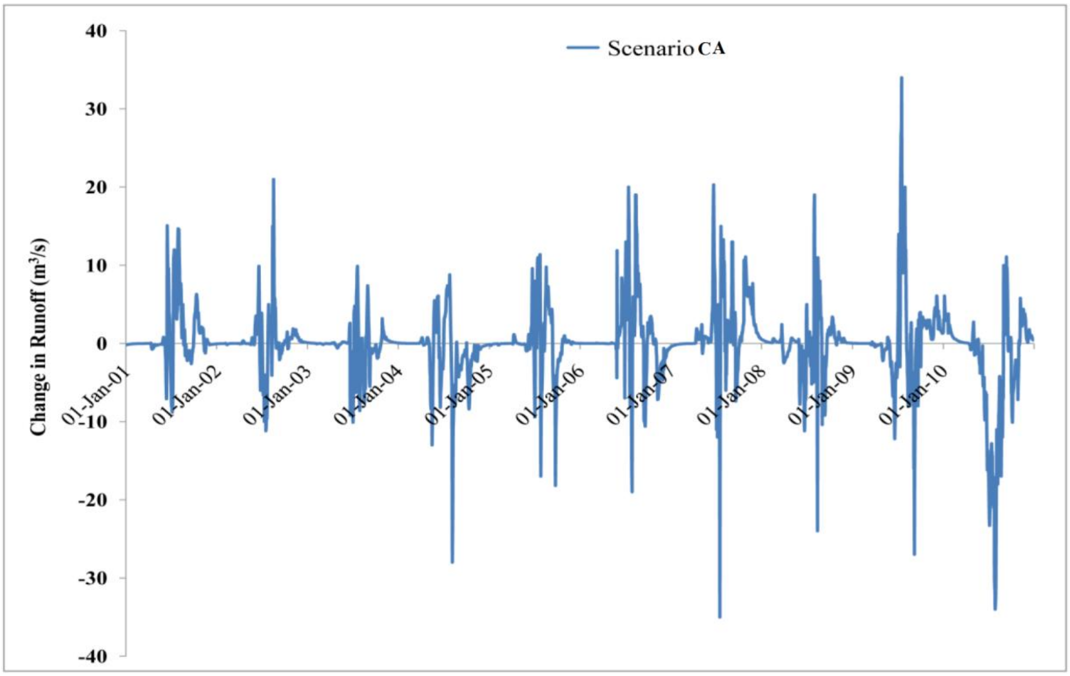


Figure 6.5: Change in runoff (scenario- CA)

Table 6.5 shows the runoff change statistics and Figure 6.5 shows graphical representation of runoff change for scenario-CA. The statistics such as frequency, mean and standard deviation calculated were also found for each class and presented in Table 6.5.

Table 6.6:Class statistics in scenario - CB

No	Class	Frequency	Mean	Std. deviation
1	$X \geq 20.000$	21	22	4.82
2	$0.001 \leq X \leq 19.999$	1683	0.80	3.35
3	$-19.999 \leq X \leq 0$	1930	-0.30	3.29
4	$X \leq -20.000$	18	-24	4.36

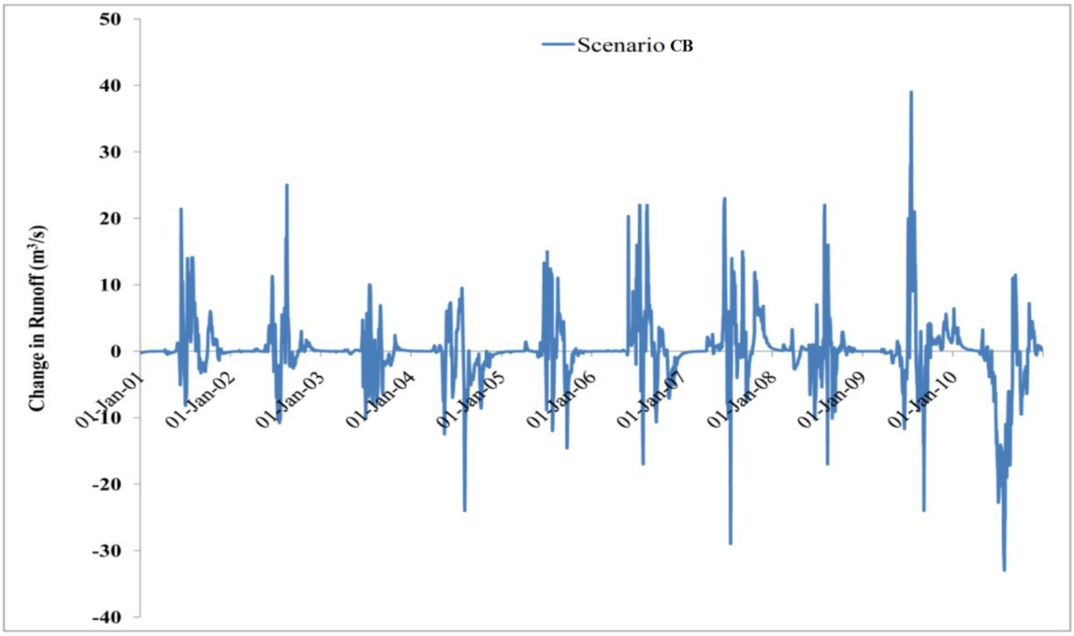


Figure 6.6: Change in runoff (scenario - CB)

Table 6.6 shows the runoff change statistics and Figure 6.6 shows graphical representation of runoff change for scenario-CB. The statistics such as frequency, mean and standard deviation calculated were also found for each class and presented in Table 6.6.

Table 6.7: Class statistics in scenario - CW

No	Class	Frequency	Mean	Std. deviation
1	$X \geq 20.000$	13	21.50	4.70
2	$0.001 \leq X \leq 19.999$	1831	0.76	3.30
3	$-19.999 \leq X \leq 0$	1788	-0.38	3.37
4	$X \leq -20.000$	20	-24.5	5.02

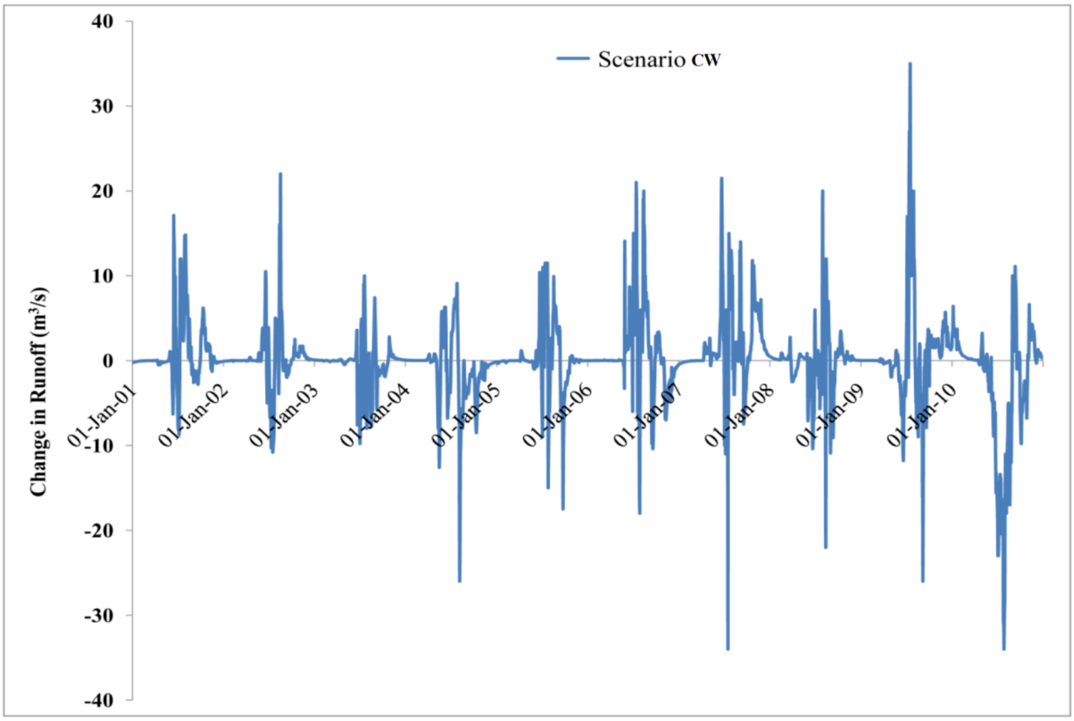


Figure 6.7: Change in runoff (scenario - CW)

Table 6.7 shows the runoff change statistics and Figure 6.7 shows graphical representation of runoff change for scenario-CW. The statistics such as frequency, mean and standard deviation calculated were also found for each of the class and presented in Table 6.7. The class-1 statistics from all the three scenarios has not shown much degree of variation in the standard deviation and mean values. However, it shows much degree of variation in frequency. The CA, CB and CW scenarios show 10, 21 and 13 number of frequencies.

The land use scenario conversion to built-up land (CB) shows occurrence of more number of frequencies (21) in class-1 as compared to other LULC scenarios. The Table 6.8 shows that, small conversion into built up land has increased runoff as compared to other scenarios. Similarly, the scenario-CA and CW have also produced an increased runoff.

Table 6.8: LULC change scenario impact on streamflow

Sr. No	Scenarios	Time	Total change in area (%)	Total change in runoff (m^3/s)
1	CA	Decade-1 (2001-2010)	2.57	+ 0.012
2	CB		0.45	+ 0.014
3	CW		1.53	+ 0.018

6.5 Hydropower Potential

6.5.1 Introduction

Hydropower is a clean and renewable energy that do not contaminate the environment. The hydropower development shows the advantages based on economic, environmental and social front as the reliable service, long life (50 to 100 years). Hydropower projects do not produce atmospheric pollution and it can create a new freshwater ecosystem with increased productivity.

Hydropower projects often provides flood protection (Nguyen Dung, 2009) in many places. Many studies on identification of hydropower sites and hydropower potential have been carried out using GIS and remote sensing methodology (Arun et al. 1995; Pannathat et al. 1998; Ballance et al. 2000; Kupakrapinyo and Chaisomphob, 2003; Das and Paul, 200; Choong-Sung et al. 2010; Vani, 2010 and Shobitha, 2012).

Increasing supply of renewable energy would allow to replace carbon-intensive energy sources such as carbon dioxide (CO_2). Renewable energy such as wind, solar, hydroelectric, tidal energy and biomass provide substantial benefits in environmental and health's perspective. The renewable energy helps to mitigate an energy demand in developing countries. In India, energy demand is increasing due to population growth, industries and living standards. Hydropower generation typical operates on availability of guaranteed flow and the head of water.

6.5.2 Head

Hydropower can be captured wherever a flow of water falls from higher level to a lower level. The vertical fall of the water, known as the “head”, is essential for hydropower generation; fast-flowing water on its own does not contain sufficient energy for useful power production except on a very large scale (Shobitha, 2012). Hence, two quantities are required: a flow rate of water (Q), and head (H). Generally, it is to have more head than more flow, because this keeps the equipment size small. The head is the vertical distance that waterfall. It is usually measured in meters. For determining head, both gross head and net head need to be considered. The gross head is found by considering the difference of head between weir and power house. Net head equals gross head minus losses due to friction and turbulence in the piping.

The gross head (H) is the maximum available vertical fall in the water, from the upstream level to the downstream level. The actual head seen by a turbine will be slightly less than the gross head due to losses occurred when transferring the water into and away from the turbine. This reduced head is known as the net head as shown in Figure 6.8.

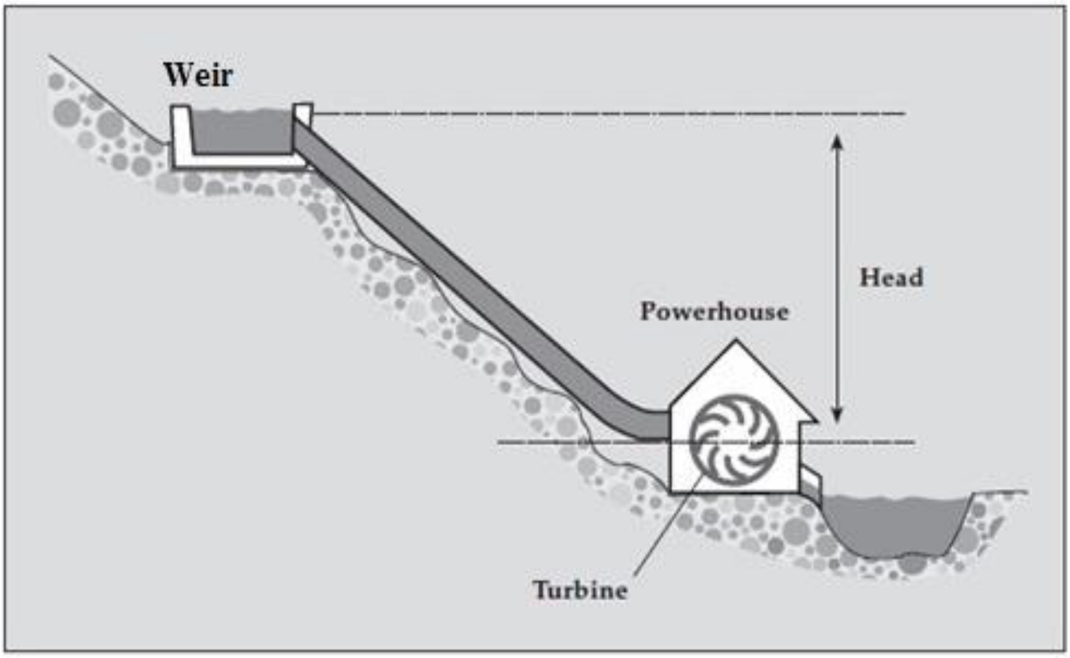


Figure 6.8: Measurement of head in a hydropower station(Sale Michael et al. 2006)

6.5.3 Characteristics of Hydropower Site

Hydropower is a clean, eco-friendly, renewable, easy to maintain and sustainable power compared to other types. Hence, hydropower generally has the following characterises.

- Hydroelectric plants do not cause pollution to air, land, or water.
- Projects have long lives relative to other forms of energy generation.
- Hydroelectric generators respond quickly to changing system conditions.
- Hydropower sites have low failure rates, low-operating costs, and are reliable.

6.5.4 Identification of Sites Having a Suitable Head

To identify a suitable head, the following procedure was used.

- The possible potential sites for power houses along the streams based on the gross head were located at the intersection points of contour lines and streams.
- For this purpose a set of contour lines with intervals of 6, 10 and 20 m were generated from ASTER DEM.
- The flow accumulation map has been created using flow direction map. The accumulated flow is calculated, as the accumulated weight of all cells flowing towards down slope cell.
- Then flow accumulation map was used to locate weir and powerhouse on the high flow accumulated stream.

6.5.5 Flow-Duration Curves (FDC)

Guaranteed flow for Hydropower projects is assessed through flow duration curve. FDC is one of the popular methods of studying the streamflow variability. The FDC of a stream is based on daily mean discharges (not peak flows) and shows the percentage of time that a given daily mean discharge is equalled or exceeded. A flow-duration curve is a plot of discharge against the percent of time the flow has equalled or exceeded. Using the flow duration curve, it is possible to estimate the percentage of time that a specified flow is equalled to or exceeded.

In the calculation of flow duration curve, the streamflow data is arranged in a descending order of discharges using class intervals. The data can be daily, weekly or monthly. The monthly streamflow data satisfy the basic data requirement for the water resource projects. If N numbers of data points are used in the listing, the plotting position of any discharge Q is designed based on flow duration curve using eq. (6.1).

$$P_p = \frac{m}{N+1} * 100 \tag{6.1}$$

Where,

Pp = percentage of probability of the flow magnitude being equalled or exceeded,

m = the order number of the discharge,

N = Total count (Number of data)

6.5.6 Estimating Power

The runoff discharge (Q) at each hydropower location has been calculated using SWAT model. Dependable flows at 90%, 80% and 75% (Q_{90}, Q_{80}, and Q_{75}) computed separately which decides the operation and size of the turbines. The dependable flows and head (H) are substituted in eq. (6.2) to determine the hydropower.

$$P = \eta \rho Q g H \tag{6.2}$$

Where,

P = mechanical power produced at the turbine shaft (Watts),

η = hydraulic efficiency of the turbine,

ρ = density of water (1000 kg/m^3),

g = acceleration due to gravity (9.81 m/s^2),

Q = volume flow rate passing through the turbine (m^3/s),

H = head of water across the turbine (m)

6.5.7 Hydropower Potential

The streamflow data is arranged in a descending order of discharges, using class intervals. The data used can be daily, weekly or monthly measured values. Table 6.9 shows the flow quantiles on a monthly scale derived from the flow duration curves for

90%, 80% and 75% dependable yield for each sub-basin. These flow quantiles have been used for power estimation using eq. (6.2).

Table 6.9: Flow quantiles from each sub-basin

Hydropower Station No	Discharge Q (m^3/sec)		
	Q_{90}	Q_{80}	Q_{75}
HP1	452	670	792
HP2	110	172	195
HP3	570	920	1025
HP4	568	822	944
HP5	456	763	841

6.5.8 Hydropower Calculation (P)

The flow quantiles estimated from FDC and water head determined from DEM are substituted in eq. (6.2) to estimate power in watts for each hydropower site. In the present study, head of water (H) is considered as 20 meter for each hydropower site with the help of DEM. The hydropower site is assumed as runoff river project (without storage of water) and the turbine efficiency (η) was taken as 85%. The hydropower potential for each sub-basin was estimated and tabulated in Table 6.10.

Table 6.10: Hydropower potential from each hydropower station

Hydropower StationNo	Power in Mega Watts		
	Q_{90}	Q_{80}	Q_{75}
HP1	75.38	111.73	132.08
HP2	18.34	28.68	32.52
HP3	95.06	153.43	170.94
HP4	94.72	137.08	157.43
HP5	76.048	137.08	140.25

6.6 Impact of Hydropower and Vented Dams on Streamflow

Five medium size hydropower dams are being proposed in the Nethravathi river basin for hydropower generation. Out of five, one hydropower project (Kempuhole hydro project) is constructed and power is being generated. These hydropower dams may store some amount of water and therefore may cause an impact on the streamflow of Nethravathi river basin. The imbalance between demand and supply of water can be met with the constructions of dams. But dams may not be always feasible due to lack of sites and oppositions to construction of dams (Shetkar, 2009).

However, the proposed hydropower projects are not yet implemented as the local stakeholders are against to construction of dams, which cause environmental damage to Western Ghats and imbalance in hydrological regime of the river. Therefore, the present study is not considered storage structures and thus, a runoff river type project, which is an alternate technique to medium hydropower projects has been considered. Another kind structure called “Vented dam” are being constructed across the tributary of Nethravathi river. Vented dam is a structure with several openings called as “vents” through which water flow is allowed during the rainy season without causing obstruction.

The storage of water is achieved by closing the gates during lean period (Shetkar, 2009). The location of proposed hydropower sites and existing vented dam sites are given in Figure 6.9. The Table 6.11 provides the information of hydropower station site and vented dams (green colour).

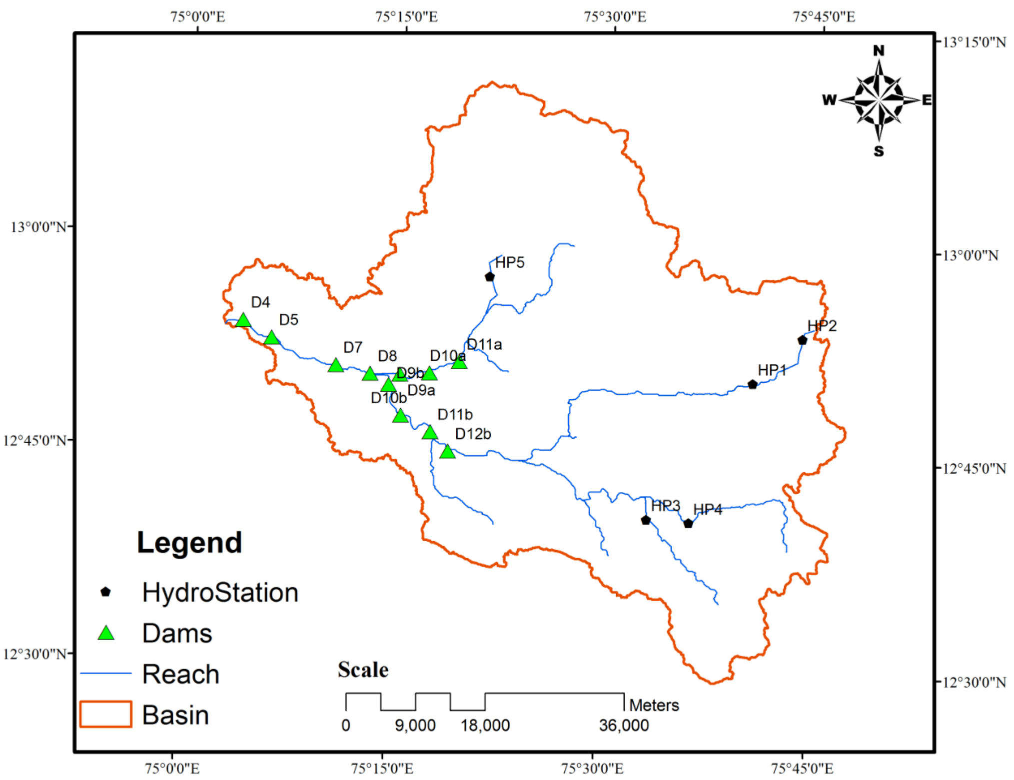


Figure 6.9: Vented dam and hydropower locations

Table 6.11: Hydropower dam and Vented dam information

Sr No	Hydropower/Vented dam Id	Latitude	Longitude	Storage (Mm^3)	Height (m)
1	HP1	12.8419	75.6773	River runoff project	--
2	HP2	12.8956	75.7351		--
3	HP3	12.6791	75.5551		--
4	HP4	12.6765	75.6056		--
5	HP5	12.9583	75.3594		--
1	D4	12.8977	75.0664	9.89	5

2	D5	12.8786	75.1007	7.75	6
3	D7	12.8488	75.1786	7.07	10
4	D8	12.8401	75.2201	4.45	9
5	D9a	12.8402	75.2555	5.09	6
6	D9b	12.8278	75.2426	7.87	2
7	D10a	12.8426	75.2907	3.81	5
8	D10b	12.7921	75.2580	3.4	4
9	D11a	12.8571	75.3258	2.07	7
10	D11b	12.7738	75.2938	1.84	2
11	D12b	12.7519	75.3156	0.87	5

The operating schedule of vented dams is given in the Table 6.12. The operating schedule has been prepared based on the 95% dependable daily river flow. The 20% of existing flow are considered for environmental flow maintenances. Based on the projected total storage and the probable water levels at various time intervals, the decision about the dam operation has been taken.

Table 6.12: Schedule of operation of vented dams (Shetkar, 2009)

Sr. No	Dam Name	Date on which to be Closed	No. of days required to fill
1	D12b	23rd November	1
2	D11b	23rd November	2

3	D10b	24th November	2
4	D9b	25th November	4
5	D11a	23rd November	2
6	D10a	24th November	3
7	D9a	26th November	4
8	D8	28th November	2
9	D7	30th November	3
10	D5	2nd December	3
11	D4	7th December	4

Based on the dam storage capacity and operation of dams, the change in streamflow has been calculated. The results of streamflow change due to hydropower and vented dams are tabulated in Table 6.13. An attempt has been made to study the response of streamflow due to these proposed hydropower and existing vented dams by simulating the streamflow of Nethravathi river using SWAT. The result shows that the streamflow has been reduced by 0.283 % due to vented dam operation within the Nethravathi river basin whereas, no change in streamflow was observed for the runoff river hydropower dams.

Table 6.13: Impacts potential LULC change and human activities on streamflow

Sr. No	Scenarios	Time	Total change in area (%)	Total change in runoff (m^3/s)
1	CA	Decade 2	2.57	+ 0.012

2	CB	(2001 to 2010)	0.45	+ 0.014
3	CW		1.53	+ 0.018
4	Vented Dams		--	- 0.283
5	Hydropower (Runoff-river type)		--	No change

6.7 Conclusions

The purpose of the present study was to assess the streamflow response to LULC changes in the humid catchment using SWAT model. In addition, an attempt has been made to investigate the effects of LULC changes and vented dam construction (storage) on Nethravathi river flow through hydrological modeling coupled with GIS with an input from remote sensing. The following conclusions are drawn based on the hydrological modeling results.

- The resultant LULC map derived from the satellite image, conclude that there was a gain in agricultural land by 2.73%, urban by 0.17% and wasteland by 1.60% and reduction in Forest by 3.20% and water by 1.17%from 2003 to 2013.

- From the impact studies of LULC change on streamflow, conclude that the hydrological parameters such as ET is decreased by 4.5%, the runoff is increased by 0.9% and groundwater is increased by 1.12%. Therefore, it is concluded that a small change in LULC could cause change in hydrological regime. It is also concluded that a small change in LULC could cause an early response of simulated streamflow of 2013 with observed streamflow.

- The impact of extreme precipitation on streamflow has shown a considerable change in runoff for both decades. The number of extreme precipitation event has been decreased in decade-2 compare to decade-1. However, the severity in runoff change has increased in decade-2 as compare to decade-1.

- In the potential LULC change scenarios and their impacts on streamflow analysis, the scenario-CB has shown more severity compared to other scenarios. The scenario-CB shows small conversion into built up land increases the frequency into the positive runoff change as compared to other scenarios. There is the positive change in runoff of about 0.012%, 0.014% and 0.018% respectively for scenario-CA, scenario-CB and scenario-CW.

- The impact of vented dams has shown the negative change in streamflow within the Nethravathi river basin. The runoff decreased by 0.283% due to vented dam construction and no change has been observed due to runoff river hydropower dams.

CHAPTER 7

SUMMARY

7.1 General

The increasing population growth, expansion of industries and agricultural sector puts greater pressure on the availability of water resources. Thus, efficient hydrological modeling is necessary for development and management of water resources. This research has studied the effects of LULC change, vented dams and runoff-river hydropower dams on streamflow response through GIS coupled hydrological model with an input from remote sensing such as LULC, DEM.

The primary objective of the present study is to develop a hydrological model of Nethravathi river basin using SWAT to investigate the effects of LULC change on streamflow. SWAT model has been used in the present study. SWAT is constructed, calibrated and validated successfully to simulate streamflow. However, SWAT requires large number of data such as hydrological, metrological, soil and LULC. SWAT model cannot be used with the absence of any above data. Hence, an alternate model called RCRM is developed from conceptual model to estimate runoff, which works on LULC, soil and rainfall data. The study has been divided into four phases according to objectives.

In the first phase, the observed daily meteorological (rainfall) data from year 1971 to year 2010is divided into four decades: 1971–1980, 1981–1990, 1991–2000, and 2001–2010 for extreme rainfall analysis. The result shown that, the Mann-Kendall and Sen’s slope estimator test proves the best techniques to identify the extreme rainfall trend in the study area.

In the second phase, the SWAT and RCRM hydrological model have been developed to investigate the effects of LULC change on streamflow. Different LULC scenarios have been developed based on LULC change observed between year 2003 and year 2013. The classified LULC maps are interpreted. Distinct LULC changes are found throughout the basin from year 2003 to year 2013.

After calibration and validation of SWAT model, this study found the effects of LULC changes on ET, streamflow and groundwater in the Nethravathi river basin. Based on the outcomes, this study derived some specific conclusions. The decreased forest cover and increased agriculture and urban land, led to an increase in streamflow. It has also led to decreased ET and increased ground water storage. This study provides useful information about impact of LULC change on streamflow, which may further helpful for flood mitigation and efficient water resources planning and management in the region.

In the third phase, temporal variation in extreme precipitation events have been analysed for two decades (1991 -2010). The decade-2 (2001 -2010) results shown that extreme rainfall events have been reduced when compare to decade-1 (1991-2000). Further, the study analysed the impact of extreme precipitation on streamflow using SWAT model. Three LULC scenarios have been developed such as Conversion to Agriculture (CA), Conversion to Built-up (CB) and Conversion to Wasteland (CW).The model has shown a minor change in streamflow for all the LULC scenarios. Among three scenarios, the scenario-CB is found to be more sensitive compared to scenarios-CA and CW.

The fourth phase of study focused on the impact of vented dams and runoff-river hydropower dams on streamflow. The impact of vented dams has shown negative change in streamflow in the Nethravathi river basin and runoff-river has shown no change.

7.2 Future Scope

- Impact of climate change such as temperature on streamflow can be introduced along with LULC to understand realistic response of streamflow. This study can be continued to study the impacts of complete hydrologic regime of a river basin due to climate change and LULC change.

- Government of Karnataka has designed an interbasin water diversion project for drinking purpose for Eastern districts from Nethravathi basin. The project is planned to lift 24 TMC of water in the upper elevation (700 meter above MSL) in Nethravathi river basin during monsoon period. In this concern, the present study can be extended to study the possible impacts/effects of interbasin water diversion of 24 TMC of water on complete hydrologic regime of Nethravathi river basin including climate change.

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List of Publication from Present Research

Journals

1. Babar, S. and Ramesh H. (2015). "Streamflow Response to Land Use-Land Cover Change over the Nethravathi River Basin India" *Journal of Hydrologic Engineering*, 20 (10), 05015002(1-11), Doi:10.1061/(ASCE)HE.1943-5584.0001177, 05015002

2. Babar, S., Shobhita, M. P. and H. Ramesh (2015). "Assessment of Hydropower Potential in Nethravathi River Basin Using SWAT model". *International Journal of Earth Sciences and Engineering,* 8 (2), 696-702.

3. Babar, S and H. Ramesh (2014). "Extreme Rainfall Analysis over the Nethravathi Basin". *Journal of Hydraulic Engineering,* ISH, Taylor and Francis, 20 (2), 202-212.

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Conferences

1. Babar, S. F. And H. Ramesh (2013). "Distribution of High Streamflow and Relative High Precipitation Event Using Directional Statistics". *Proceedings of International conference on Hydraulics, Water Resources and Coastal and Environmental Engineering (HYDRO-2013)* (ISBN 978-93-80689-18-0), Dec 4-6 2013, IIT Madras, Dept. of Ocean and Civil Engineering and ISH, IAHR, Madras, Page No. 1198-1203.

2. Babar, S. F., H. Ramesh. (2013). "Analysis of south west monsoon rainfall trend using statistical techniques over Nethravathi Basin." *International conference on Recent Trends in Engineering and Technology (ICRTET 2013)*", SNJB, Nashik, Page No. 964-971.

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