REASSESSMENT OF WATER AVAILABILITY IN INDIA USING SPACE INPUTS

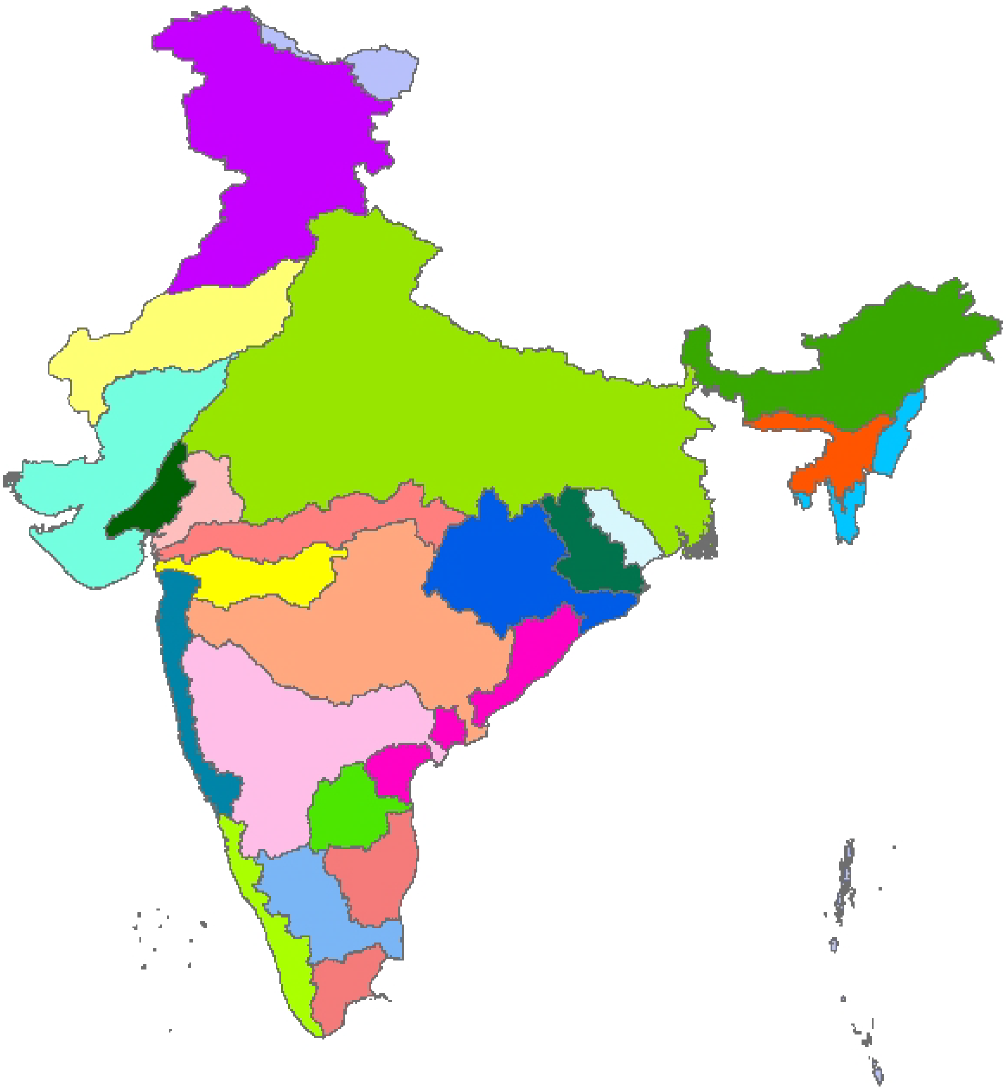
BASIN PLANNING & MANAGEMENT ORGANISATION

CENTRAL WATER COMMISSION

NEW DELHI - 110 066

OCTOBER - 2017

REASSESSMENT OF WATER AVAILABILITY IN INDIA USING SPACE INPUTS



BASIN PLANNING & MANAGEMENT ORGANISATION

CENTRAL WATER COMMISSION

NEW DELHI – 110 066

OCTOBER, 2017

PROJECT TEAM

<table>
<tr><td>Project Execution</td><td><u>Basin Planning & Management Organisation, CWC, Delhi</u>
Dr. Naresh Kumar, Chief Engineer
Dr. R N Sankhua, Director, Basin Planning
Shri Rishi Srivastava, Director, Reservoir Operation
Shri Neeraj Sharma, Deputy Director, Basin Planning
Shri Arkaprabha Majumdar, Deputy Director, Basin Planning
Ms. Deep Shikha, Assistant Director, Basin Planning
Shri Sandeep Bisht, Assistant Director, Basin Planning
Ms. Isly Issac, Assistant Director, Basin Planning
<u>Central Water Commission, Field Organisations</u>

Brahmaputra & Barak Organisation, Shillong
Mahanadi & Eastern Rivers Organisation, Bhubaneswar
Cauvery & Southern Rivers Organisation, Coimbatore
Narmada Basin Organisation, Bhopal
Krishna & Godavari Basin Organisation, Hyderabad
Narmada & Tapi Basin Organisation, Gandhinagar
Indus Basin Organisation, Chandigarh
Upper Ganga Basin Organisation, Lucknow
Lower Ganga Basin Organisation, Patna
Yamuna Basin Organisation, New Delhi</td></tr>
<tr><td>Project Technical Guidance and Support</td><td><u>National Remote Sensing Centre, Hyderabad</u>
<u>National Remote Sensing Centre, Hyderabad</u>
Dr. V. Venkateshwar Rao, Group Director, WRG
Shri P.V. Raju, Head, WRAD, WRG
Dr. K.H.V. Durga Rao, Head, DMSD
Shri B. Simhadri Rao, Sc/Er “SG”, WRAD/WRG
Shri Amanpreet Singh, Sc/Er “SD”, DMSD
Shri Saksham Joshi, Sc/Er “SD”, WRAD, WRG
Ms. Annie Issac, Sc/Er “SD”, WRAD, WRG
Ms. A Shravya, Sc/Er “SC” (formerly with NRSC)</td></tr>
</table>

	Shri Kartik Reddy, Sc/Er "SC" (formerly with NRSC)
Project Overall Co-ordination, Compilation and Editing	**Central Water Commission, Headquarters, New Delhi** Dr. Naresh Kumar, Chief Engineer, BPMO Dr. R N Sankhua, Director, Basin Planning Shri Arkaprabha Majumder, Deputy Director, Basin Planning Ms.Deep Shikha, Asst. Director, Basin Planning Shri Sandeep Bisht, Asst. Director, Basin Planning **National Remote Sensing Centre, Hyderabad** Dr V. Venkateshwar Rao, Group Director, WRG Shri P.V. Raju, Head, WRAD, WRG
Project Report Number	No: CWC/BPMO/BP/WRA/October, 2017/1
Date of Publication	October, 2017

FOREWORD

Changes in water quantity are occurring mainly as consequences of global and local changes actuated by environmental factors, climate change and human induced changes. The rapid growth in population coupled with increasing economic activities has put new challenges on management of available water resources. Although irrigation is the major consumer of water, at present in our country and may continue to be so in the years to come, demands from other sectors such as drinking and industries have been growing significantly. Science-based knowledge to assess water resources over a range of scales both in space and time is essential to develop methodologies for sustainable water resources management.

Efficient use of water is crucial to the survival of the plants, animal life and ultimately human beings. Therefore, every effort must be made to make the best use of water so as to make possible a high level of production. Water conservation measures to improve the efficiency of water use are being stressed upon for meeting the ever increasing demands. Inter-basin transfer of water from surplus basins to deficit basins is being studied as one of the long term strategies.

A proper assessment of water resources potential has, therefore, become a prerequisite. Without a reliable estimate of the availability of the resource, it is impossible to properly plan, design, construct, operate and maintain water resources projects catering to competing demands like irrigation, drought and flood management, domestic and industrial water supply, generation of electrical energy, fisheries and navigation.

In spite of the improvements in the standards of stream flow measurements, some uncertainties still persist in the reassessment study. These relate particularly to the quantum of annual withdrawals of both surface and groundwater for various uses and quantifying the non-consumptive part of the withdrawals which ultimately returns to the river systems. It is very essential to correctly measure the records of diversions from irrigation projects and significant withdrawals directly from the rivers and from groundwater. The reassessment of water potential of all the basins using space inputs has been carried out by Central Water Commission (CWC) with the collaboration from National Remote Sensing Centre (NRSC), Hyderabad. The contribution of Basin Planning & Management Organisation, NRSC, Hyderabad and the regional field offices of CWC to the successful completion of the study deserves high appreciation.

New Delhi
31 October, 2017

(S MASOOD HUSAIN)
Member (Water Planning & Projects) & Ex-Officio
Additional Secretary to Government of India

ACKNOWLEDGEMENT

The study report "**REASSESSMENT OF WATER AVAILABILITY IN INDIA USING SPACE INPUTS**" is the culmination of the tireless efforts put in by the study team of field organisations of Central Water Commission (CWC) under coordinated effort of Basin Planning & Management Organisation (BPMO), CWC carried out with the help of National Remote Sensing Centre (NRSC), Hyderabad under the MOU between BPMO and NRSC, Hyderabad. To fulfil this task, the team has solicited partnerships with the field organisations of CWC to maximize outreach. By the establishment of collective responsibility, the study team was able to lead the project for water availability through this document, and wish to thank the contributors.

The process has greatly benefited from the data, views, comments and support of state authorities for data collected by field organisations of CWC for their diligence in managing, synthesising, coordinating the officers.

The team would like to acknowledge with much appreciation the crucial role of **Dr. Amarjit Singh**, Secretary, Ministry of Water Resources, River Development and Ganga Rejuvenation (MoWR, RD&GR) for his inspiration, and advices in achieving the goal. The team would like to acknowledge with much appreciation the vital role of **Dr. A S Kiran Kumar**, Secretary, Department of Space and Chairman-Indian Space Research Organisation, for his support in achieving the objective.

The team expresses its indebtedness to **Shri Narendra Kumar,** Chairman, CWC, New Delhi, who has invested his full guidance and untiring advices in all the stages to complete the study.

The team would like to tender a special gratitude to **Shri S Masood Husain,** Member (Water Planning & Projects), and **Shri Pradeep Kumar**, Member (River Management), CWC, New Delhi, for their valuable guidance, encouragement and direction and contributed immensely in stimulating suggestions and encouragement.

The team would like to acknowledge with sincere thanks to the eminent experts, **Dr. S R Hashim**, former Chairman, Union Public Service Commission, **Dr. M A Chitale**, former Secretary, Ministry of Water Resources, **Shri A D Mohile**, former Chairman, CWC, **Dr. Ajit Kumar Chaturvedi**, Director, IIT Roorkee, **Shri A B Pandya**, Former Chairman, CWC, Shri M Gopalakrishnan, former Member, CWC and former Secretary General, ICID, **Shri Avinash C Tyagi**, Secretary General, ICID, **Prof P P Mujumdar**, Professor, IISc, Bengaluru, **Prof M Shekhar**, Professor, IISc, Bengaluru, **Dr. Sharad K Jain**, Director, NIH, Roorkee, **Shri R D Singh**, former Director, NIH, and Henritte Faeegeman, Councillor, Environment and Energy and Climate Change, European Union Delegation to India, Guido Schmith, European Union Delegation to India, for their valuable comments in enriching the report.

The project team would like to sincerely thank **Dr. Naresh Kumar**, Chief Engineer, BPMO, CWC and **Shri R K Jain**, former Chief Engineer, BPMO, CWC for their guidance, support and continuous encouragement because of which the work done for the basins could be brought to the current level. Also, the project team would like to sincerely thank the Directors, Deputy Directors and Assistant Directors of CWC, who have made valuable contributions in this endeavour.

In particular, the project team is indebted to NRSC, Hyderabad, National Bureau of Soil Survey & Land Use Planning (NBSS & LUP), Nagpur, and the officers of CWC, individuals for their support, study strategy and outline, efforts, and to produce a smart and holistic framework; and to run workshops with experts, who contributed for the cause.

Our sincere thanks are also due to **Dr. Y V N Krishna Murthy, Director,** National Remote Sensing Centre (NRSC), and **Dr. P V N Rao,** Deputy Director, Remote Sensing Applications Area, NRSC, Hyderabad for their valuable guidance and encouragement. The project team would like to place on record the contributions made by General Managers and staff of regional centres (East, West, North & South) of NRSC in completing the project.

Last but not least, many thanks and appreciations also go to the contributors, who maintained a dignified silence in completing the study and people who have willingly helped out with their abilities.

PROJECT TEAM

EXECUTIVE SUMMARY

[In India, where demands for freshwater are continuously growing, and where limited water resources are increasingly stressed by over-abstraction, pollution and climate change, neglecting the opportunities arising from improved water management is nothing less than unthinkable in the context of Indian economy.]

Sustainable water future for India begins with a vision. With the current state of affairs, correcting measures still can be taken to avoid the crisis to be worsening. There is increasing awareness that our freshwater resources are limited and need to be protected both in terms of quantity and quality. This water challenge affects not only the water community, but also decision-makers and every human being. The surface water and groundwater resources in India play a major role in agriculture, hydropower generation, livestock production, industrial activities, forestry, fisheries, navigation, recreational activities, etc. Potential impact of global climate change on water resources include enhanced evaporation due to warming, geographical changes in precipitation intensity, duration and frequency, together affecting the hydrological parameters such as, discharge, soil moisture, etc. Earlier, different commissions, agencies, researchers have estimated water resources of the country using different approaches. Among these, First Irrigation Commission (1901-03), Dr. A N Khosla (1949), Central Water and Power Commission (1954-66), study done by Dr. K L Rao, National Commission on Agriculture (1976), and Central Water Commission (1988) are very popular. Reassessment of Average Annual Water Resources Potential (1993) is the last study done by CWC.

Considering the importance of fresh reassessment of water resources availability in the country, Ministry of Water Resources, River Development and Ganga Rejuvenation (MoWR, RD & GR), Government of India had approved study for "Reassessment of Water Availability of River Basins in India using Space Inputs" for assessing the average annual water resources in the country by CWC with technical support of NRSC on similar lines to that of the pilot studies completed in June 2013 by CWC and NRSC on Godavari and Brahmani-Baitarani river basins.

As a consequence of the above, the present study emphasises on quantifying basin scale water wealth by transformation from presently adapted basin terminal gauge site discharge, aggregation to meteorological data based water budgeting exercise through hydrological modelling approach.

Daily rainfall data of 0.25^{o} X 0.25^{o} grids, daily temperature data of 1^{o} X 1^{o} grids were obtained from the India Meteorological Department (IMD) and converted into GIS format. Land Use and Land Cover (LULC) map for the period from 2004-05 to 2014-15 prepared under Natural Resources Census (NRC) project of NRSC using IRS AWiFS satellite data (56 m resolution) were used in the study. Command area boundaries for irrigation support estimation, water body maps for estimating standing water evaporation losses were used. SRTM DEM (90 m resolution) was used for basin/sub-basin boundary delineation. Soil textural map, LULC map, daily rainfall map, daily temperature map, water body map and command area maps were integrated in modified Thornthwaite-Mather modelling framework to compute the monthly soil moisture, evapotranspiration, surface runoff. In this study, Thornthwaite-Mather method of Potential Evapotranspiration (PET) was modified by incorporating land cover coefficients for taking into account the variations in vegetation types and crop season.

A software tool namely Water Resources Assessment Tool (WRAT) was developed by NRSC for computation of water balance components in modified Thornthwaite-Mather modelling framework using geo-spatial datasets. The tool integrates all input images such as basin boundary, LULC, soil, rainfall, temperature; command area and reservoir mask and generates the outputs in the form of image layers and text files. The abstractions such as domestic, industrial and livestock consumptive demand were estimated for the 30-year period for each sub-basin. The groundwater fluxes were computed for each year using the information provided by Central Ground Water Board (CGWB). The surface storage fluxes were also estimated during the study period for major and medium reservoirs located in the basins. The model computed surface discharge was calibrated and validated with observed discharge at G&D sites within the basin/sub-basin. The calibration and validation was done by trial and error method by varying the model parameters to match model estimated discharge and observed discharge after accounting upstream abstractions. The validated model outputs were then used to assess water resources availability in the basin.

The average annual water resource of the basins for the study period of 30 years (1985-2015) has been assessed as **1913.60 BCM.** The mean annual rainfall of the basins for the study period of 30 years is **3880 BCM**.

TABLE OF CONTENTS

LIST OF FIGURES

Sl. No. Description Page No.

LIST OF TABLES

LIST OF ABBREVIATIONS

AET	Actual Evapotranspiration
BCM	Billion Cubic Meter
BPMO	Basin Planning & Management Organisation
CGWB	Central Ground Water Board
CWC	Central Water Commission
DIL	Domestic, Industrial and Livestock
ECII	Estimated Consumptive Irrigation Input
EFR	East flowing rivers
ET	Evapotranspiration
G&D	Gauge and Discharge
GDQ	Gauge, Discharge and Water Quality
GDSQ	Gauge, Discharge, Sediment and Water Quality
ha	Hectare
IS	Irrigation Support
km	Kilometer
LPCD	Litres per capita per day
LULC	Land Use and Land Cover
MCM	Million Cubic Meter
MoWR, RD & GR	Ministry of Water Resources, River Development and Ganga Rejuvenation
NRSC	National Remote Sensing Centre
P	Precipitation
PET	Potential Evapotranspiration
SM	Soil Moisture
W	Water Holding Capacity
WFR	West Flowing Rivers
WRA	Water Resources Assessment

NOTATIONS USED

f	Factor to correct for unequal day and lengths between months
j	Monthly Heat Index
J	Annual Heat Index
L_a	Accumulated Potential Water Loss
t_n	Monthly Mean Temperature

CHAPTER 1

BASELINE AND CONTEXT

1.0 Prologue

[The prologue provides a brief overview of core aspects of the state of the India's water resources that are directly related to water availability. While water is a resource that can be used to address water supply shortages, with implications on water availability. The external drivers that will dictate trends in water availability are described, with a special focus on spatial and temporal variations of water cycle dynamics and climate change for a period of 30 years (1985-2015).]

Water resources (surface water and groundwater) are renewed through the continuous cycle of evaporation, precipitation and runoff. The water cycle is driven by global and climatic forces that introduce variability in precipitation and evaporation, which in turn define runoff patterns and water availability over space and time (modulated by natural and artificial storage). Observations over the past decades and projections from climate change scenarios point towards an exacerbation of the spatial and temporal variations of water cycle dynamics (IPCC, 2013). As a result, discrepancies in water supply and demand are becoming increasingly aggravated. On the basis of the water balance approach, it is possible to make a quantitative evaluation of water resources in the basins and their change under the influence of people's activities (McCabe, G.J. and Markstrom, S.L., 2007). In the attempted study of water balance, river basins, reservoirs, and groundwater forms a basis for the hydrological substantiation of projects for the rational use, control and redistribution of water resources in time and space.

Assessment of water scarcity in all the basins of India is essential, as the water stress that results from dry periods can be masked by annual averages of water availability. Land use changes, including urbanization, river channelization and other human activities, modify the storage capacity of catchments and impact high flows as well as groundwater recharge and low flows. This study is a reassessment of country's water availability, mean state considering the recent three decades and would help in evaluating the country's existing and planned water system future demands over the years under a range of hydrologic conditions.

1.1 Background

Central Water Commission (CWC) and National Remote Sensing Centre (NRSC) had initiated a pilot study on Godavari and Brahmani-Baitarani river basins for assessing the water resources availability using satellite based inputs and the study was completed in June 2013 (NRSC, 2013). The study methodology and results was reviewed and ratified by an Expert Committee constituted by Ministry of Water Resources, River Development and Ganga Rejuvenation (MoWR, RD & GR) and suggested to upscale the same methodology for all river basins in the country. As a result of this, CWC has initiated this study on "Reassessment of Water Availability in India using Space Inputs" in July 2016 with technical guidance and support of NRSC.

With a view to address the climate change related issues; the National Action Plan on Climate Change (NAPCC) has been prepared by the Government of India. The NAPCC has laid down the principles and has identified the approach to be adopted to meet the challenges of impact of climate change through eight National Missions namely, (a) National Solar Mission, (b) National Mission for Enhanced Energy Efficiency, (c) National Mission on Sustainable Habitat, (d) National Water Mission, (e) National Mission for Sustaining the Himalayan Eco-system, (f) National Mission for a Green India, (g) National Mission for Sustainable Agriculture, and (h) National Mission on Strategic Knowledge for Climate Change.

One of the strategies identified for implementation under the Comprehensive Mission Document of National Water Mission was - Reassessment of basin-wise water situation under present scenario including water quality by using latest techniques, which inter-alia may include:

- Development or adoption of comprehensive water balance based model,
- Fitting models to basin using current data, and
- Assessment of likely future situation with changes in demands, land use, precipitation and evaporation

This report presents the results of reassessment of water availability of all the basins of India considering the period of 30 years (1985-2015). As a first major step towards these initiative detailed water assessments for these years were taken up for all river basins in India. A simplified but more broad-based model called basin-wide Water Resources Assessment (WRA) model was developed considering the specific objectives of the study and applied to each of these river basins.

1.2 Objective and Scope of the Report

This report on WRA is prepared with the main objective of highlighting the water availability of all the Indian basins and thereby deduces relevance and efficacy of the plausible policy options available for water management and with a view to supporting overall and countrywide water policy issues. The report covers the methodological approach of the model to assess the availability. The report also covers the calibration and validation of the model through the developed WRA tool by NRSC, Hyderabad, which used various input datasets like hydro-meteorological data for a 30-year period (1985-2015), soil texture data and land use data for the period from 2004-05 to 2014-15.

1.3 Capacity building initiatives

Four training programmes for CWC officers involved in the study were conducted at NRSC, Hyderabad and CWC, New Delhi. The 1st programme was a 5-day orientation training programme conducted for 34 CWC officers during 25 to 29, May 2015. The 2nd training programme (hands-on with practical exercises) was conducted for 28 CWC officers during 05 to 16 October, 2015. The 3rd training programme was conducted at CWC, New Delhi during 18-20 October, 2016. The 4th training programme was conducted during the mid-term review workshop held at NRSC during 05 to 09 December, 2016. Two review workshops were held at New Delhi under the chairmanship of Chairman, CWC to review and monitor the progress of work in field units.

1.4 India's water availability

Water problems are precarious in the population sector but, as a whole, the country has been facing a water crisis both for agriculture as well as for basic needs. Water demand is predicted to increase significantly over the coming decades. In addition to the agricultural sector, which is responsible for 70% of water abstractions nationwide, large increases in water demand are predicted for industry and energy production. Accelerated urbanization and the expansion of municipal water supply and sanitation systems also contribute to the rising localised demand. Climate change scenarios project an exacerbation of the spatial and temporal variations of water cycle dynamics, such that discrepancies between water supply and demand are becoming increasingly aggravated. Table - 1 depicts the per capita water availability in India.

Table – 1: Per capita water availability in India

Year	Population (Million)	Per capita water availability (m^3/year)	Remarks
1951	361	5178	
1955	395	4732	
1991	846	2210	
2001	1027	1820	
2011	1211	1544	water stressed#
2015	1326*	1441$	water stressed#
2021	1345[a]	1421$	water stressed#
2031	1463[a]	1306$	water stressed#
2041	1560[a]	1225$	water stressed#
2051	1628[a]	1174$	water stressed#

Source: Government of India, 2009 (NCIWRD Report, 1999), *projected from 2011 census

[a] Population figures for 2021 to 2051 are taken from projected population by Planning Commission available at http://planningcommission.nic.in/aboutus/committee/ strgrp/ stgp_fmlywel/sgfw_ch2.pdf

[$] *The per capita availability from 2015 onwards has been calculated from 2017 WRA estimate*.

#According to the Falkenmark Water Stress Indicator, a per capita availability of less than 1700 cubic metres (m^3) is termed as a water-stressed condition, while if per capita availability falls below 1000 m^3, it is termed as a water scarcity condition.

1.5 Challenges in Water Sector

The water availability in India is going to be a serious challenge due to various reasons. The most serious concern is the growing population which is likely to increase to 1.66 billion by 2050. With the increasing population, the annual food requirement in the country will exceed 250 million tons by 2050. The total demand for grains will increase to 375 million tons including grain for feeding livestock by 2050. With the growth in the National GDP, at 6.8% per annum, during the period from 2000 to 2025 and 6.0% per annum, during the years 2025 to 2050, the per capita income is bound to increase by 5.5% per annum. This will increase the demand for food. While the per capita consumption of cereals will decrease by 9%, 47% and 60%, with respect to rice, coarse cereals and maize, the per capita consumption of sugar, fruits and vegetables will increase by 32%, 65% and 78% respectively, during the period from 2000 to 2050. This will create an additional demand for water. The requirement of water for livestock will rise from 2.3 BCM in 2000 to 2.8 BCM in 2025 and 3.2 BCM in 2050.

Over-exploitation of groundwater is another concern. Presently, there are over 20 million wells pumping water with free power supply, provided by the Government. This has been depleting groundwater, while encouraging wastage of water in many States. As a result, the water table in the country is dipping every year by 0.4 m. In many coastal areas, there has been heavy intrusion of sea water, making fertile agricultural lands unfit for cultivation. By and large, the infrastructure development in the water sector has been extremely slow and investment has not been optimum. Furthermore, the utilization of created water facilities has been sub-optimal because of poor catchment area development resulting in heavy soil erosion and siltation. Further, there is inefficient use of water because of distribution of water in open canals, flood irrigation and charging for water on the basis of area irrigated instead of quantity of water supplied. It has been estimated that over 70% of the irrigation water is wasted by depriving irrigation to other dry areas. Farmers in India have been traditionally practicing flow irrigation which is resulting in huge wastage of water, while causing severe soil erosion, leaching of fertilizers, increasing the infestation of pests, diseases and weeds and suppressing the crop yields. Nevertheless, farmers as well as policy makers are not serious about the discontinuation of this unscientific practice. Immediate attention is needed to shift from flood irrigation to micro-irrigation and to increase the water use efficiency, which can ease the water scarcity to a great extent (Rosegrant *et al*. 2002).

1.6 India - Physiography

India, with a geographical area of about 329 Million Hectare (M. ha), is a land of many mountains and rivers, some of them figuring amongst the mightiest rivers of the world. Physiographically, India may be divided into seven well defined regions. These are: the Northern Mountains comprising the mighty Himalayan ranges; the Great Plains traversed by the Indus, Ganga and Brahmaputra river systems; the Central Highlands, consisting of a wide belt of hills running east-west between the Great Plains and the Deccan plateau; the Peninsular Plateaus; the East Coast, a belt of land of about 100-130 km wide, bordering the Bay of Bengal; the West Coast, a narrow belt of land of about 10-25 km wide, bordering the Arabian Sea; and the islands, comprising the coral islands of Lakshadweep in Arabian Sea and Andaman and Nicobar group of islands in the Bay of Bengal (Figure 1.1).

For the reassessment of water potential of India, total area of India was taken as 32,34,496 sq. km. This area does not include Area of Indus above border, Lakshadweep Island and Andaman and Nicobar group of islands.

1.6.1 Climate

The great mountain mass of Himalayas in the north and the ocean in the south are the two major influences operating on the climate of India. The Himalaya poses an impenetrable barrier to the influence of cold winds from central Asia and gives the sub-continent the elements of tropical type of climate. The oceans are the source of moisture-laden winds, giving India the elements of the oceanic type of climate.

India has a very great diversity and variety of climate and an even greater variety of weather conditions. The climate ranges from extremes of heat to extremes of cold; from extreme aridity and negligible rainfall to excessive humidity and torrential rainfall. The climatic condition influences to a great extent the water resources utilization in the country.

1.6.2 Rainfall

Rainfall in India is dependent on the South-West and North-East monsoons, on shallow cyclonic depressions and disturbances and on violent local storms which form regions where cool humid winds from the sea meet hot dry winds from the land and occasionally reach cyclonic dimension. Most of the rainfall in India takes place under the influence of South-West monsoon between June to September except in Tamil Nadu where it is under the influence of North-East monsoon during October and November. However, there is considerable spatial variation in rainfall which ranges from less than 100 mm in the western Rajasthan to more than 2500 mm in North-Eastern areas.

The total mean annual rainfall as calculated from IMD data in study area comes out to be 1,105 mm.

Figure 1.1 Geographical Map of India

1.6.3 Rivers of India

India is blessed with many rivers. Land slope determines the river to which the rain falling on an area will eventually flow. A river basin, also called catchment area of the river, is the area from which the rain will flow into that particular river. The shape and size of the river basin is determined by the topography. Figure 1.2 depicts the river basins and major river systems of India. Percentage of geographical area in each basin is shown in Figure 1.3.

1.6.3.1 Indus system

This comprises the river Indus and its tributaries like the Jhelum, Chenab, Ravi, Beas and Sutlej. These originate in the North and generally flow in a West or South-West direction to eventually flow into Arabian Sea through Pakistan.

1.6.3.2 Ganga-Brahmaputra-Meghna system

The main river Ganga and its tributaries like the Yamuna, Sone, Gandak, Kosi and many others; similarly, main rivers Brahmaputra, Meghna and their tributaries. All these eventually flow into Bay of Bengal, through Bangladesh. Some of the tributaries of these rivers are larger than other independent rivers. e.g. Yamuna, a tributary of Ganga, has a larger catchment area than the Tapi, a small peninsula river.

1.6.3.3 Rivers of Rajasthan and Gujarat

Mahi, Sabarmati, Luni etc. These are rivers of arid regions, they carry relatively little flow, some of them flow to Arabian Sea through Gujarat while some are land-locked and their flow is lost through percolation and evaporation in the vast arid regions.

1.6.3.4 East Flowing Peninsular Rivers

The important members of this group are: Damodar, Mahanadi, Brahmani, Baitarani, Subarnarekha, Krishna, Godavari and Cauvery. They all flow into Bay of Bengal at various places along the Eastern Coast of India.

1.6.3.5 West Flowing Peninsular Rivers

Narmada and Tapi rivers originate in Central India and flow in a western direction to meet Arabian Sea south of Gujarat.

1.6.3.6 Western Coast Rivers

There are large number of rivers in the Western Coast - i.e. coastal Maharashtra and Karnataka, and entire Kerala. These rivers are small in length but carry a significant amount of water due to very high rainfall in Western Ghats. They drain only 3% of the India's land area but carry 11% of India's water resources.

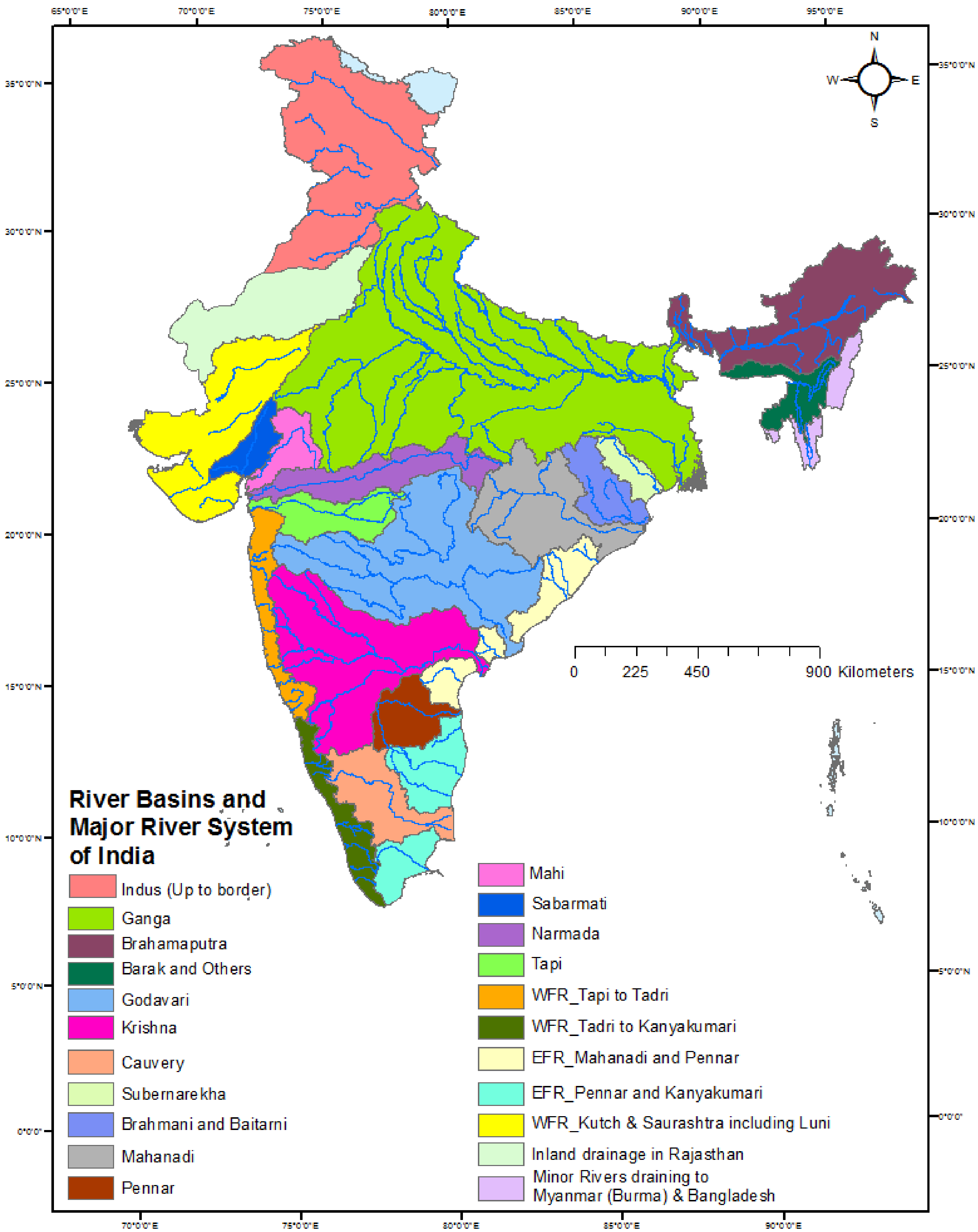


Figure 1.2 River Basins and Major River Systems of India

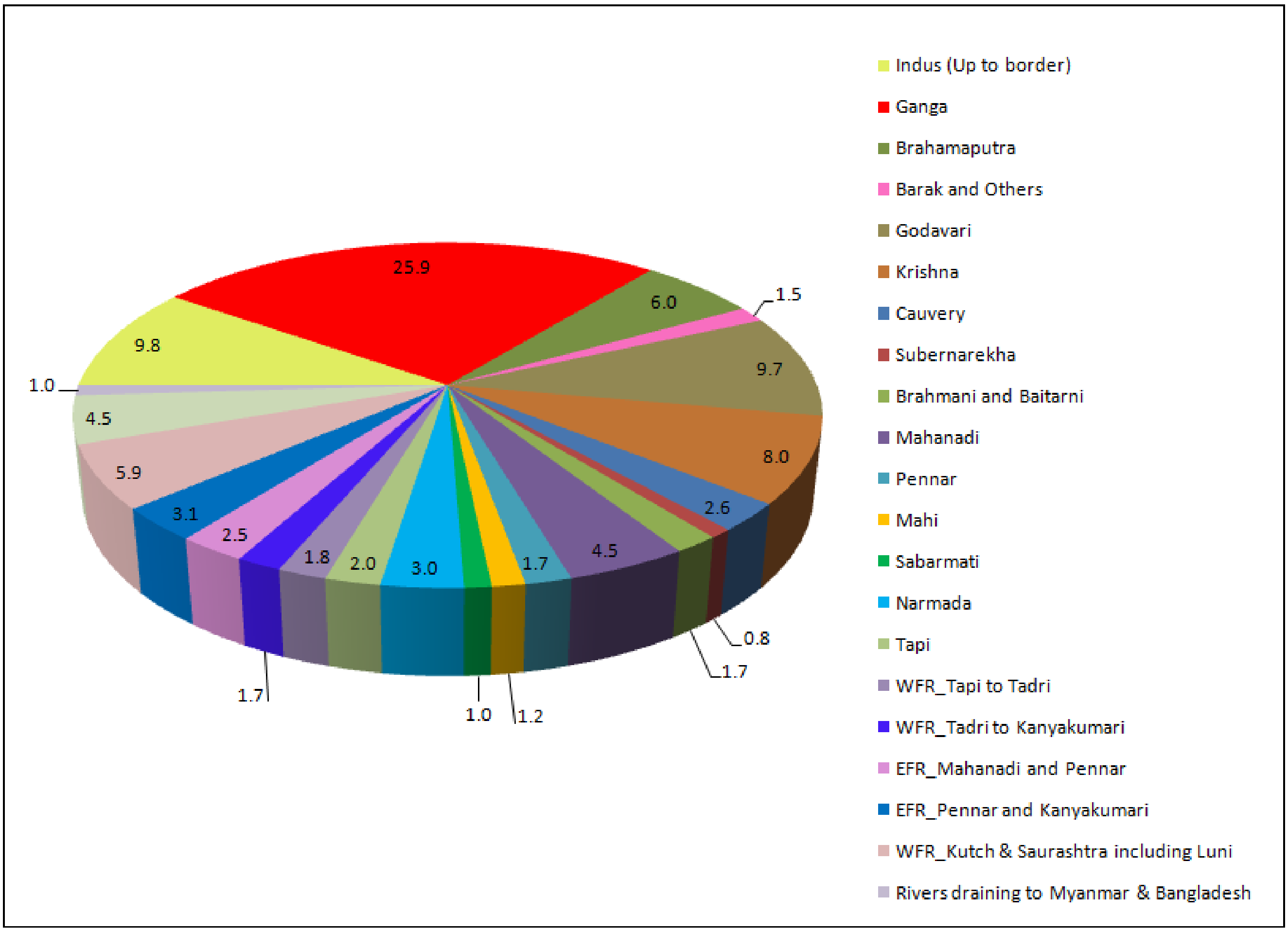


Figure 1.3 Percentage of geographical area in each basin

CHAPTER 2

REVIEW OF EARLIER STUDIES

[Water management decisions to bring solutions with changes in pressures were dependent on the water availability studies carried out at different periods. Natural (virgin) flow in a river basin is reckoned as water resources of basin. The water resources potential in the river basins of the country has been assessed from time to time by various agencies. These studies adopted - empirical formula, aggregation of observed basin terminal flow with upstream abstractions etc. The brief out lines of the previous estimates are described in the following paragraphs.]

2.0 Study by Irrigation Commission (1901-03)

The first ever attempt to assess the average annual flow of all the river systems in India was made by the Irrigation Commission of 1901-03. The major constraint at that time was that while records in respect of rainfall were available, data in respect of river flows were not available even for many of the most important river systems. The Commission, therefore, resorted to estimation of river flows by adopting coefficients of runoff. According to this estimate, the average annual flow of all river systems of India (as it was then, but excluding Burma, Assam and East Bengal) was 1443.2 BCM.

2.1 Study of Dr. A N Khosla

Dr. A N Khosla, Chairman, Central Water and Power Commission (CW & PC) during 1945-53 developed empirical relationship between mean temperature and mean runoff based on his studies on the flows of Sutlej, Mahanadi and other river systems.

On monthly basis the developed relationship is stated as;

$R_m = P_m - L_m$ and

$L_m = (T_m - 32)/ 9.5$

where,

R_m = monthly runoff
P_m = monthly rainfall
L_m = monthly evaporation loss
(all expressed in inches)
T_m = mean monthly temperature in ^oF

For areas where monthly rainfall and temperature data were not available, Dr. Khosla developed a relationship on annual basis as follows:

$R_A = P_A - XT_A$

where,

R_A = annual runoff in inches,

P_A = mean annual precipitation in inches,

T_A = mean annual temperature in ^oF and

X = constant for a given catchment which is to be determined from comparative catchments for which data are available.

While applying these relationships to the entire country, Dr. Khosla divided the country into just six regions viz., (i) Rivers falling into Arabian Sea (excluding Indus), (ii) Indus Basin (in India), (iii) Rivers falling into Bay of Bengal other than Ganga-Brahmaputra system, (iv) Ganga, (v) Brahmaputra and (vi) Rajputana. According to these studies, the total annual flow of all the systems worked out to 1673 BCM.

2.2 Studies by CW & PC (1954-66)

Later the CW & PC again worked out the surface water resources of different basins during the period from 1954 to 1966. This study was mostly based on statistical analysis of the flow data wherever available and rainfall-runoff relationships wherever data were meagre. The country was divided into 23 sub-basins/basins. Ganga was divided into as many as ten sub-systems. Other major peninsular river basins like Narmada, Tapi, Godavari, Krishna, Pennar and Cauvery were considered separately. Other river systems were combined together suitably into a few composite systems. According to these studies in the year 1960, the water resources of various basins amounted to 1881 BCM.

2.3 Subsequent assessments

Subsequent to the above, some studies were done from time to time in respect of a few basins for specific purposes. Indus study was undertaken by Indus Commission in 1960. For instance, the water resources potential of the Indus basin up to Indian border was estimated by Indus Commission and governed by the provisions of the Indus Water Treaty, 1960 between India and Pakistan. In the case of Godavari basin, Krishna-Godavari Commission estimated in 1962 the average annual runoff in Godavari. Cauvery Fact Finding Committee estimated the runoff in Cauvery in 1972. Similarly, an estimate of Krishna flows was made in 1973 for Krishna Water Disputes Tribunal and of Narmada flows in 1979 for the Narmada Water Disputes Tribunal. CWC made fresh studies in respect of a few river basins such as Mahanadi, Subarnarekha, Sabarmati and Tapi. Ganga Brahmaputra Water Studies (GBWS) Organisation estimated the average flows in Ganga (1982). Barak & other rivers study was carried out by Irrigation Commission in 1972. In respect of Brahmaputra, the Brahmaputra Board carried out assessment in 1987.

2.4 Central Water Commission (1988)

When CWC was compiling material for the chapter on water resources potential sometime in 1987-88 for their publication on "Water Resources of India", they realized that the assessment studies made on the basis of observed river flows needed some correction since over the years groundwater extraction had increased to a significant extent and the observed river flows were corrected for the additional evapotranspiration that was occurring due to the use of groundwater.

As per the report "Water Resources of India", the natural runoff of a basin could be computed by adding to the surface flow measured at the terminal site, the net export of the surface water out of the basin, the net increase of surface water storage, additional evapotranspiration caused by use or storage of surface water, direct groundwater flow from the river basin below or along the terminal site, the net export of groundwater out of the basin, the net increase in groundwater storage and soil moisture storage and the additional evapotranspiration caused by use or storage of groundwater. This is general water balance approach, applicable to any basin for any period. However, if averages over a long time period are taken, storage change would be zero or negligible. Also assuming a case of no export or import, and neglecting the groundwater flow below or along the terminal site, a simplification is possible. With this simplification, the average annual natural flow can be computed by adding to the average annual surface flow measured at the terminal site, the average annual extra evaporation/ evapotranspiration due to use or storage of surface water and the average annual extra evaporation/evapotranspiration due to storage or use of groundwater.

Earlier estimate of runoff have been made by two approaches. The approach adopted by Dr. Khosla does not directly use the measured surface flow at terminal site but works out the natural runoff as the difference between precipitations received and estimated natural evapotranspiration. This approach would, thus require no correction for utilisation of surface or groundwater. The second approach utilises the observed flow record and thus gives a more realistic estimate. In this approach, the observed surface flow at the terminal site is corrected for extra evapotranspiration due to utilization of water. However, mostly the correction due to additional evapotranspiration due to storage or use of groundwater was not done in actual working. This was not attempted.

District-wise estimates of withdrawal from groundwater storage had already been worked out by CGWB for the year 1983-84. 1983-84 district-wise figures were converted into basin-wise figures. The total draft for the country for the year 1983-84 was about 100 BCM/year.

Similar Estimates for 1967-68 as available in Irrigation Commission, 1972 report indicate the draft for that year was about 58 BCM/year. Assuming linear variation, the annual draft for any year can be calculated. Basin-wise figures for any other year can be estimated on the same proportions the overall national figures. It is assumed that the consumptive use of groundwater is 70% of the withdrawal. For each basin, where the natural runoff is being worked out from the terminal site flows, the period of data available has been considered for obtaining the average annual natural runoff. The correction for the consumptive use i.e. extra evaporation use to groundwater is to be adjusted to the mid-point of the observed data period by the procedure stated above. Thus, depending upon the mid-point of the observed data period, different corrections were worked out. For basins such as Godavari and Krishna, where mid-point fell around 193, the required correction was negligible and not done.

The basin-wise average annual water resources were estimated as 1880 BCM following the above procedure. The above, however excluded the groundwater which flows directly to the sea or to the neighbouring countries bypassing the terminal site. Studies, carried out elsewhere indicate that this quantum is not appreciable and would be around 5% of the runoff.

2.5 Reassessment of Average Annual Water Resources Potential (1993)

Basin-wise reassessment of water resources potential in the country was carried out by CWC in 1993 and given in the report entitled “Reassessment of Water Resources Potential of India”. The water resources potential of the country was reassessed as 1869 BCM against an earlier assessment of 1880 BCM done by CWC in 1988.

CWC’s publication No. 30/88 “Water Resources of India”, April 1988 has standardized the river basins of India. The country was divided into 20 river basins comprising of 12 major basins and 8 composite river basins.

The twelve major basins are: (1) Indus; (2) Ganga-Brahmaputra-Meghna; (3) Godavari; (4) Krishna; (5) Cauvery; (6) Mahanadi; (7) Pennar; (8) Brahmani-Baitarani; (9) Sabarmati; (10) Mahi; (11) Narmada and (12) Tapi.

The eight composite river basins are: (1) Subarnarekha – combining Subarnarekha and other small rivers between Subarnarekha and Baitarni; (2) East flowing rivers between Mahanadi and Pennar; (3) East flowing rivers between Pennar and Kanyakumari; (4) Area of Inland Drainage in Rajasthan Desert; (5) West flowing rivers of Kutch and Saurashtra including Luni; (6) West flowing rivers from Tapi to Tadri; (7) West flowing rivers from Tadri to Kanyakumari; and (8) Minor rivers draining into Myanmar (Burma) and Bangladesh.

Natural (virgin) flow in the river basin is reckoned as water resources of a basin. The average annual flow of a basin is normally obtained on pro-rata basis from the average annual flow at the terminal site. The natural flow at any location on a river is obtained by summing up the observed flow, upstream utilization for irrigation, domestic and industrial uses both from surface and groundwater sources, increase in storage of reservoirs (both surface and subsurface) and evaporation losses in reservoirs, and deducting return flows from different uses from surface and groundwater sources.

The observed flows at terminal sites of the basins were corrected for upstream abstractions to arrive at the natural flows by adopting the following equation:

$$R_n = R_O + (R_{IR} + R_D + R_{GW}) - R_{RI} - R_{RD} - R_{RG} \pm S + E$$

R_n = Natural flow	R_O = Observed flow
Withdrawal	**Return flow**
R_{IR} = Irrigation	R_{RI} = Irrigation
R_D = DIL consumption	R_{RD} = DIL consumption
R_{GW} = Groundwater	R_{RG} = Groundwater
S = Change in reservoir storage	E = Net evaporation from reservoirs

Basins not assessed in 1993 study are presented in Figure 2.1. Based on the above methodology, CWC assessed the average annual water resources potential of the country as 1869 BCM in the 1993 study (Figure 2.2).

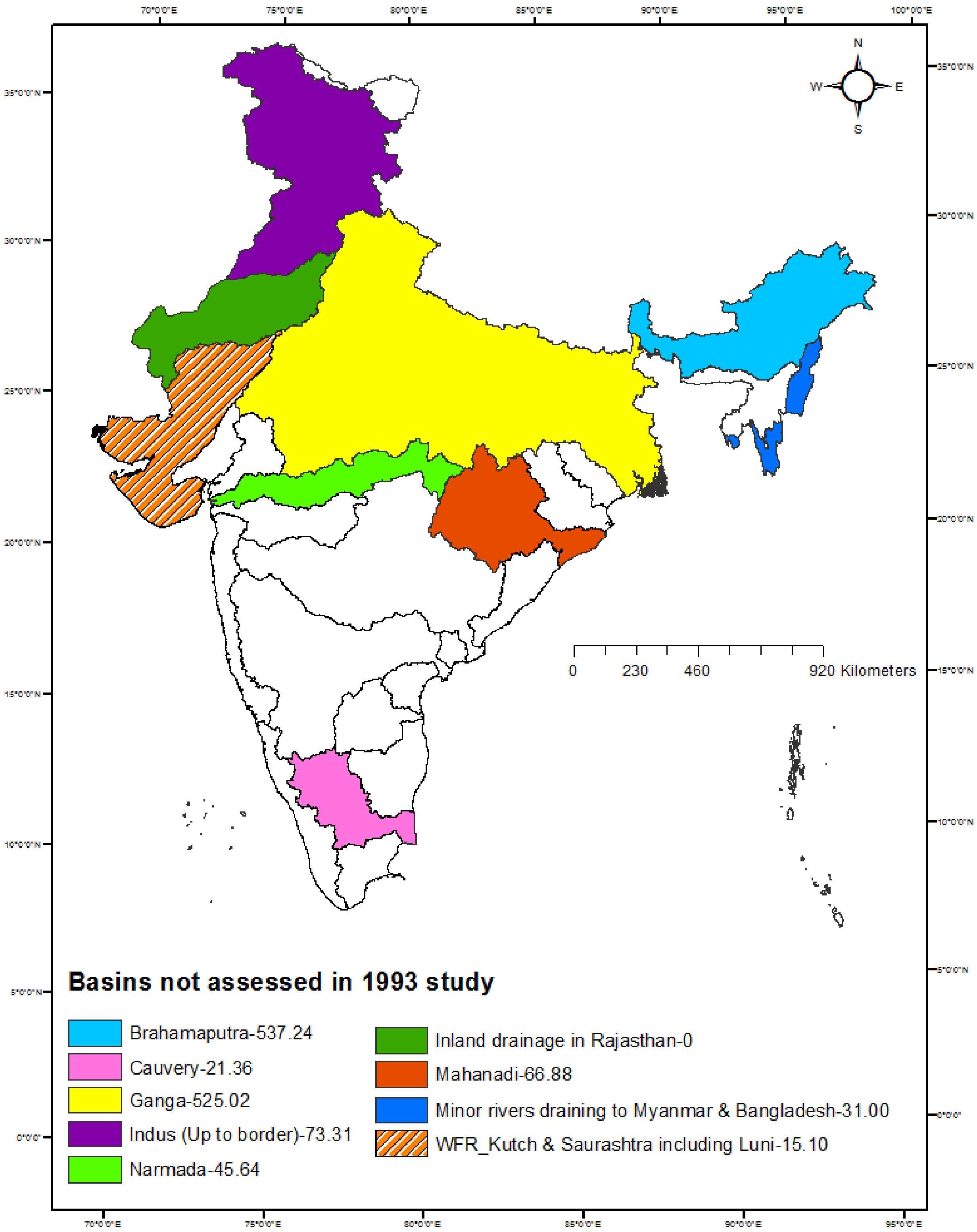


Figure 2.1 Basins not assessed in 1993 study

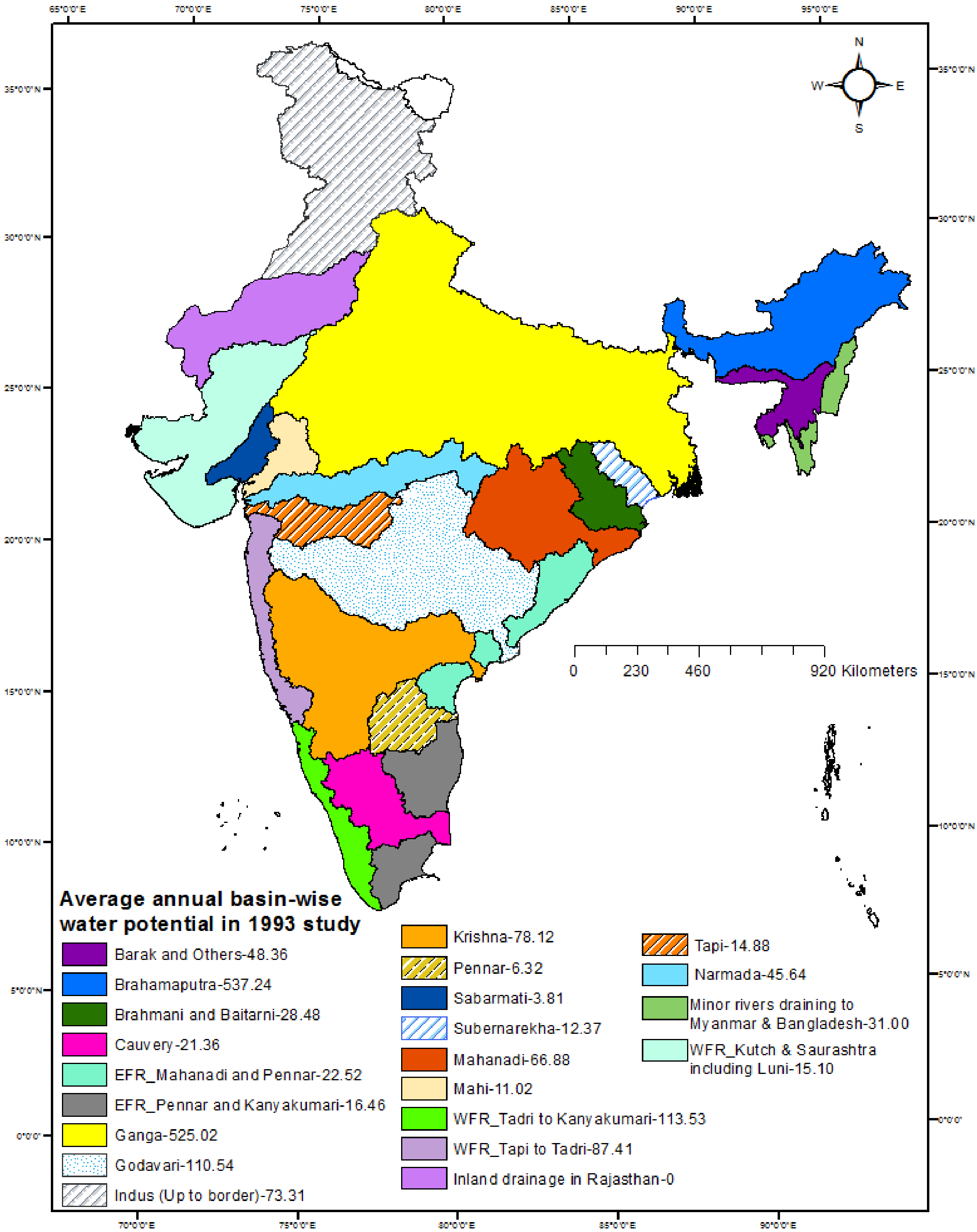


Figure 2.2 Average annual basin-wise water potential in 1993 study

2.6.1 Limitations of the 1993 study

The broad limitations of the study are as follows.

(1) For working out the upstream abstractions, for various uses, assumptions had to be made depending upon the type of data that could be obtained for the abstractions. Uniform procedure could not naturally be adopted for all the river basins. Particularly for estimating withdrawals for irrigation which is the major consumer of water varying assumptions had to be made. In many cases while diversions from major and medium irrigation projects were available, those from minor schemes were seldom available. The duty/delta were assumed constant among the study years with no variation during dry/wet years.

(2) In most of the cases the year-wise withdrawal from groundwater has been estimated approximately assuming linear variation between the state-wise draft given by the Irrigation Commission of 1972 for the year 1967-68 and by the CGWB for the year 1983-84, and interpolating for other years.

(3) Return flows have been assumed to be 10% in the case of irrigation (major and medium) and 80% in the case of domestic and industrial supplies which are only approximate.

(4) There was no hydrological process involved in the methodology. Also there was no cross check mechanism in the study and the method was not suitable to adopt under climate change scenarios.

(5) The method adopted lumped values at the outlet only and mainly irrigation utilization was considered as rough estimate of upstream withdrawals.

(6) No meteorological data (including precipitation) was considered, thus not accounting for the yearly variation in irrigation demand.

2.7 Assessment by NCIWRD (1999)

The National Commission for Integrated Water Resources Development (NCIWRD) while assessing the potential, agreed with the estimates of the Reassessment study carried out by CWC (1993) excepting the cases of Brahmaputra and Krishna basins. In case of Brahmaputra basin, the NCIWRD assessment included additional contribution of 91.81 BCM which was estimated to be the flow of the 9 tributaries joining Brahmaputra downstream of Joghighopa site. In the case of Krishna basin, the figure adopted by the NCIWRD was based on the average flow of the yield series that is accepted by the Award of the Krishna Water Disputes Tribunal. Taking into account the above two variations, the estimation of NCIWRD yielded that the average annual water resources potential of the country is 1953 BCM (NCIWRD, 1999).

2.8 Pilot studies in Godavari and Brahmani-Baitarani river basins

2.8.1 Assessment of National Water Resources- R&D Programme under Earth Observation Application Mission (EOAM) Programme of NRSC, Hyderabad

NRSC, Hyderabad initiated a R&D Project titled -Assessment of National Water Resources using Space Inputs under Earth Observation Application Mission (EOAM) funding for integrating space technology, geographical information tools, hydro-meteorological data and hydrological models (NRSC, 2009). In this context, a Brain-Storming Session on Water Resources Assessment was also organized by NRSC at Hyderabad on 24th March, 2009 in which officers from IITs, IISc, Regional Remote Sensing Service Centre (RRSSC), CWC, and NRSC participated and discussed various issues related to water resources assessment in the country.

The need for reassessment of water resources in the country, methods, models, time scale, spatial scale, input data, quality of data, impact of climate change on water resources, and other key aspects were discussed during the sessions. During the session two Committees namely the Drafting Committee and Expert Committee were constituted to bring out a technical document (Guide) for research and practice on water resources assessment in the country. Based on the discussions held during the Brain-Storming Session, literature study and further discussion among the various authors, a technical guide for research and practice titled -Water Resources Assessment - The National Perspective was brought out by NRSC, Hyderabad in October, 2009. The technical guide includes: Water Resources Assessment – Indian Perspective containing hydrological setting of the country, need for water resources assessment at the national level, previous studies for assessment of water resources, international practices, etc.; Methodology for Integrated Water Resources Assessment containing approach and models, review of available models and software, snowmelt runoff - methods and models, criteria and selection of model(s), model calibration and validation, etc.; Data requirements containing spatial data, time series data, gauge and discharge data, meteorological data, groundwater data, topographic data, satellite based products of meteorological parameters, satellite based rainfall product sources, etc.; Review of water availability estimates; Operational aspects; and Recommendations.

2.8.2 NRSC-CWC Joint Pilot studies –Assessment of Water Resources at basin scale using space inputs in Godavari and Brahmani-Baitarani river basins

NRSC and CWC jointly executed demonstrative pilot studies in Godavari and Brahmani-Baitarani river basins wherein space based geo-spatial inputs were used to estimate basin-level mean annual water resources. IMD gridded meteorological data, NRSC Land Use and Land Cover, NBSS&LUP soil, CGWB GW flux data and CWC river discharge data were used. The period considered was 1988-2008. The mean annual water resource was assessed as 113.09 BCM and 35.129 BCM for Godavari and Brahmani-Baitarani river basins, respectively.

The pilot studies established and provided much needed paradigm shift for quantifying national water wealth with a transformation from basin terminal runoff aggregation to precipitation based water budgeting exercise. The previously adopted approach of terminal discharge based resources abstraction can be replaced with source (precipitation)- use (consumptive use)- storage (surface/ground) - surplus (runoff/stream flow) account through hydrological modelling.

The study results and methodological aspects were reviewed by a Committee for re-assessment of water availability in India constituted by MoWR, RD & GR under the Chairmanship of Chairman, CWC. The committee recommended to upscale the study to other river basins of the country for estimating annual water resources availability.

A Working Group comprising Officers from NRSC and CWC, jointly deliberated and drafted the Project Proposal and action plan for taking up reassessment of water availability study in the country.

2.9 Global Efforts in Water Resources Assessment

Globally in many countries, attempts were made in assessing water resources in their regions. Towards this, standardised procedures and methodologies were developed for water resources assessment at national and international level. WMO and UNESCO (1997) prepared a report on water resources assessment, Handbook for review of National Capabilities discussing on water resources assessment aspects. This report brings out data collection processes, areal assessment of hydrological elements and institutional frame work. Milorad M and Prvoslav M (1998) documented guidelines for conducting water resources assessment as contribution to International Hydrological Programme (IHP-IV). This report describes the theoretical principles and evaluation for a water resources balance study. These guidelines include both surface water and ground water components with evaluation of water quantity and quality. Department of International Development of UK (2003) compiled a Handbook for the assessment of catchment water demand and use with the aim of the handbook is to support professionals and practitioners in sub-Saharan Africa responsible for the management of water resources at a catchment and sub-catchment level. The Handbook provides practical guidance for assessing and forecasting water demands and use for the Environment, Agriculture, Rural domestic, Urban, Industry sectors. Anisimov et al (2012) prepared technical report covering data collection, processing and quality control for undertaking the water resources assessment study. Data to be collected for the study includes biophysical, hydro-meteorological, socio-economic, water-use data. Elaborative information precipitation analysis, estimation of evaporation, surface water and ground water estimation procedures were discussed. The report is aimed primarily at staff of agencies working in the water sector, water resources managers, water suppliers and water users responsible for quantifying available surface water and groundwater resources. The Australian Water Resources Assessment (2012) report presents assessments of Australia's climate and water resources over the 2011–12 year. It discusses regional variability and trends in water resources and patterns of water use over recent seasons, years and decades, using currently accessible data.

The glimpse of earlier assessment studies of basins has been presented in Table – 2.

Table – 2: Glimpse of earlier assessment studies

S. No.	Year	Authority/Method of estimation	Quantity (BCM)
1.	1901 - 03	First Irrigation Commission/using coefficients of runoff	1443.2
2.	1949	Khosla's empirical formula	1673
3.	1960	CW & PC/Statistical analysis of flow data wherever available and rainfall-runoff relationships wherever data were meagre	1881
4.	1988	Central Water Commission/General water balance approach	1880
5.	1993	Central Water Commission	1869
6.	1999	National Commission for Integrated Water Resources Development (NCIWRD)	1953

CHAPTER 3

INPUT DATA, METHODOLOGY AND THEMATIC FOCUS

[This chapter offers a review of input data used, broad methodology combining in knowledge, research building and management, with a focus on current gaps and barriers. Responses to these challenges are presented in terms of highlighting the potential for improving earlier limitations and applying technological responses at appropriate scales.]

3.0 Objectives of the present study

Considering the need and data availability in the river basins, the following main objectives were set for the study:

i) To assess the long-term average annual water resources availability in the river basins of India during the period from 1984-85 to 2014-15 (30 years).

ii) To compute water resources in the basins during extreme dry and wet conditions (minimum and maximum rainfall scenarios) during the last 30 years.

3.1 Geo-Spatial Database

3.1.1 Land Use and Land Cover

The Land Use and Land Cover (LULC) data prepared by NRSC using Indian Remote Sensing (IRS) Advanced Wide Field Sensor (AWiFS) data was used in this study. The LULC data was available for the period of 11 years (2004-05 to 2014-15). Distribution of LULC pattern in the India during 2004-05 is given in Figure 3.1. Percentage-wise distribution of LULC pattern is given in Figure 3.2. Kharif only is the predominant land use in India accounting for more than 18% of the total area. This extent varies slightly from year to year. Next dominating class is Double/Triple crops. These two land use patterns contribute maximum evapotranspiration. Deciduous forest is major land class in forest cover classes, contributing to more than 10% of total forest cover in India.

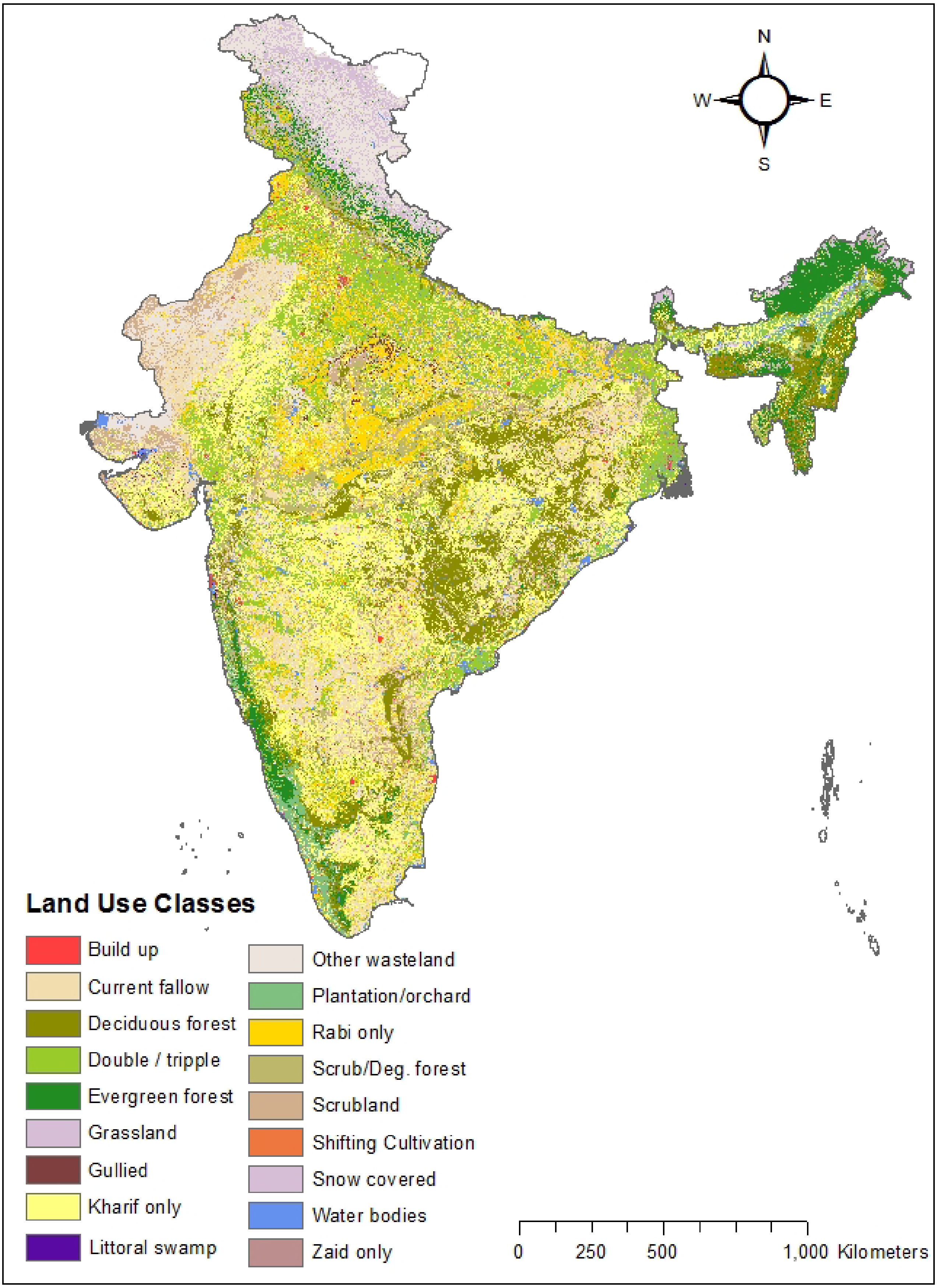


Figure 3.1 LULC map of India (2004-05)

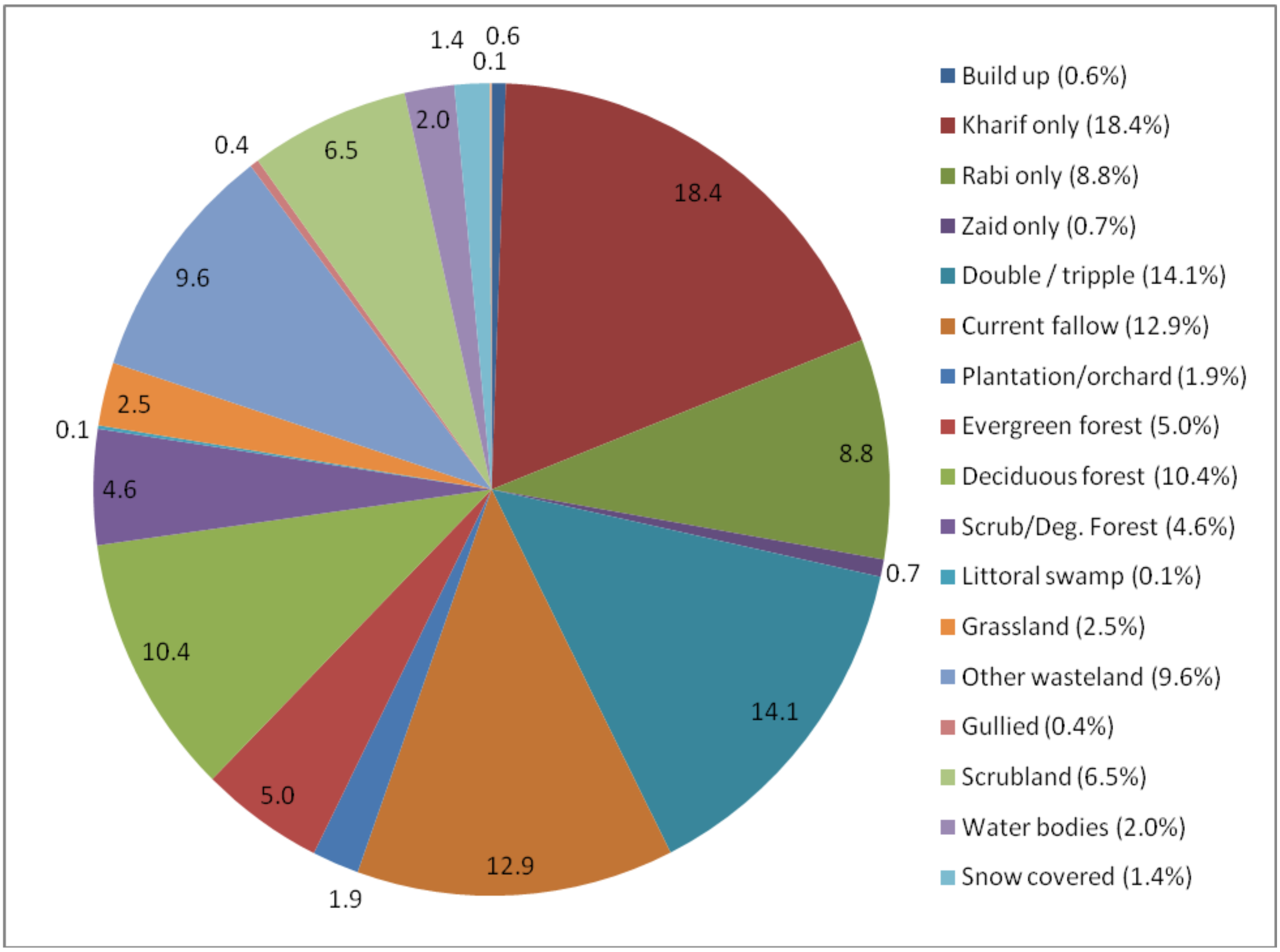


Figure 3.2 Distribution of LULC in the year 2004-05

3.1.2 Soil texture

The soil map generated by National Bureau of Soil Survey & Land Use Planning (NBSS & LUP) was used in this study. Loamy and clayey soils are the main soil textural classes in India. Predominant soil texture is loamy that accounts for low infiltration rate and more runoff in the basin. Soil textural classes in the country are shown in Figure 3.3.

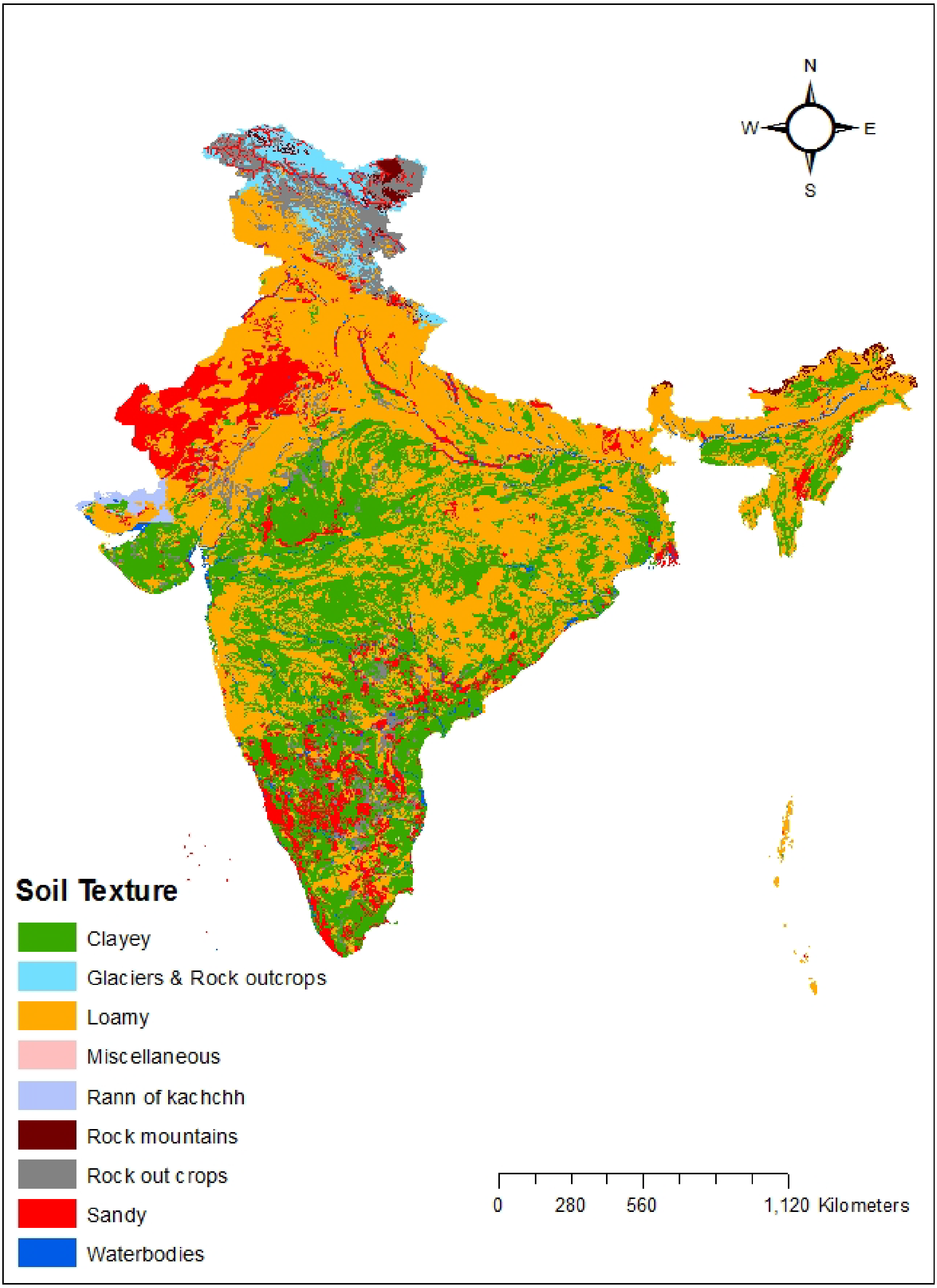


Figure 3.3 Soil textural map of India

3.1.3 Digital Elevation Model (DEM)

Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) with 90 m resolution was used for delineating basin/sub-basin boundaries of Indian river basins. DEM map of India is shown in Figure 3.4.

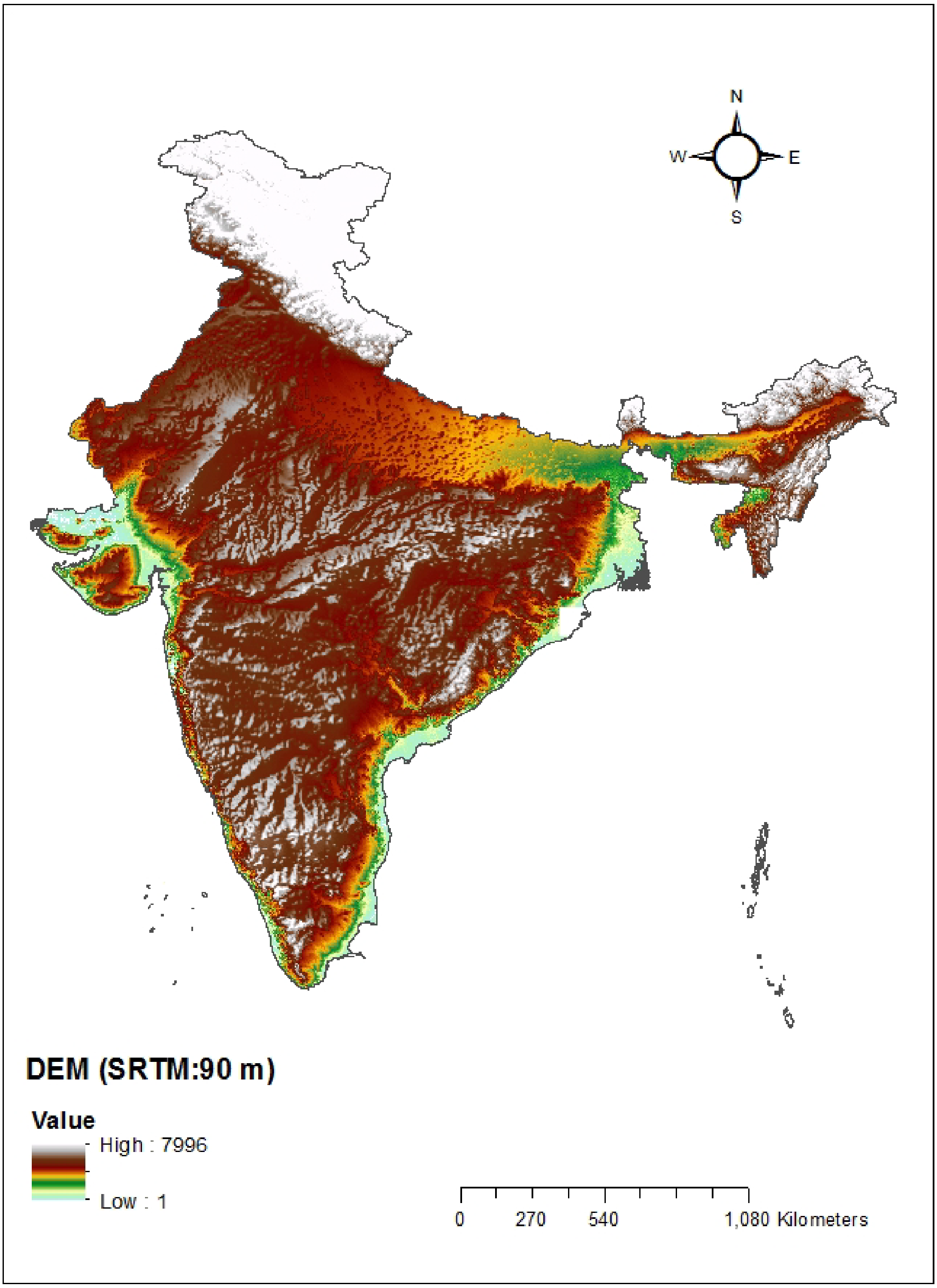


Figure 3.4 SRTM DEM map of India

3.2 Hydro-Meteorological and other Input Data

3.2.1 Rainfall grids

High spatial resolution (0.25^{o} X 0.25^{o}) daily gridded rainfall data sets for the period of 30 years (1985-86 to 2014-15) over India prepared by India Meteorological Department (IMD) were used in this study (Rajeevan M. and Jyote Bhate, 2008). The daily data has been processed and converted into the annual scale. A sample data for the year 2004-05 has been shown in Figure 3.5. The annual rainfall of the study area is about 1105 mm. Variation of mean annual rainfall over 30 years is shown in Figure 3.6.

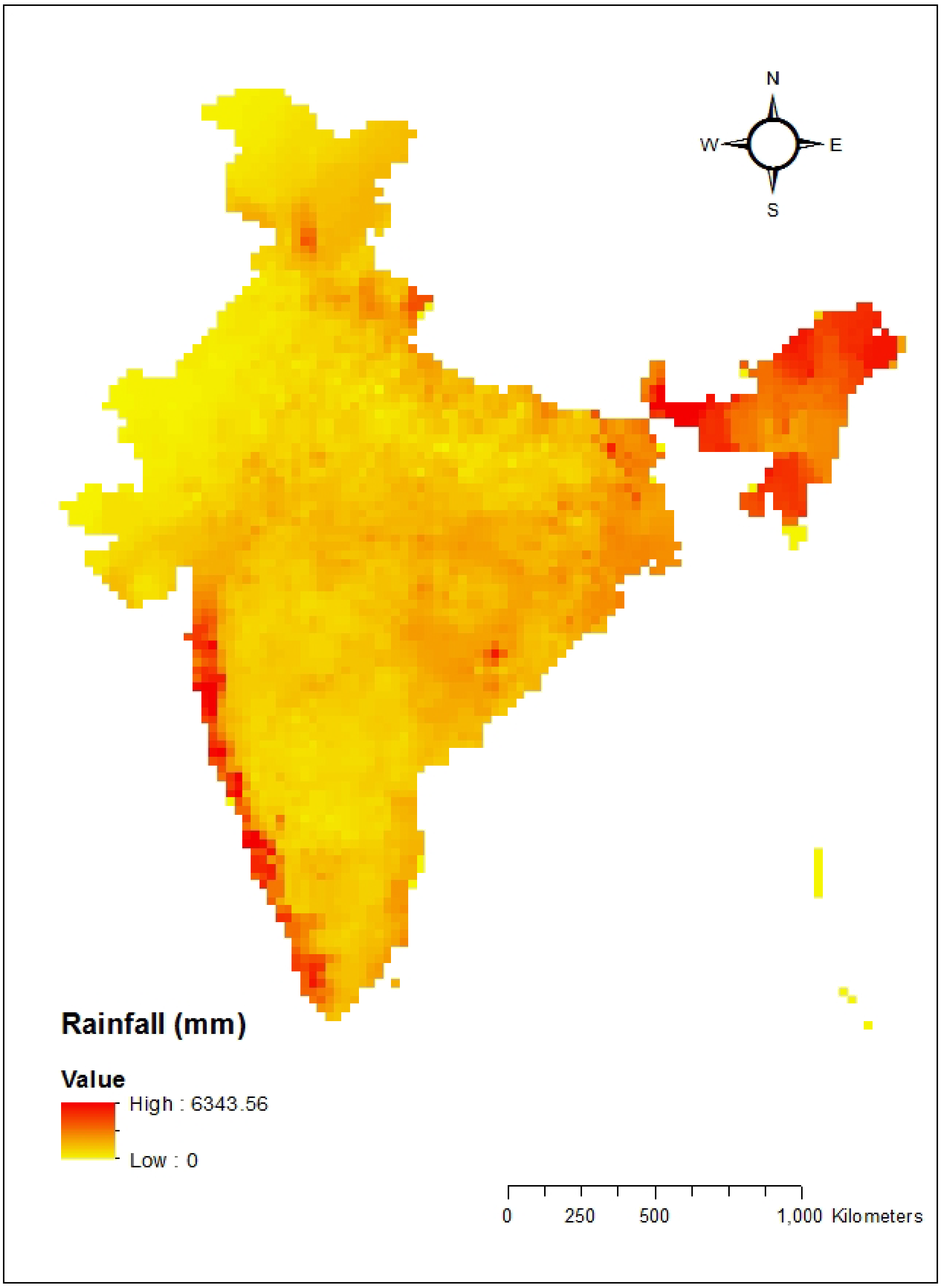


Figure 3.5 Gridded rainfall of India (2004-05)

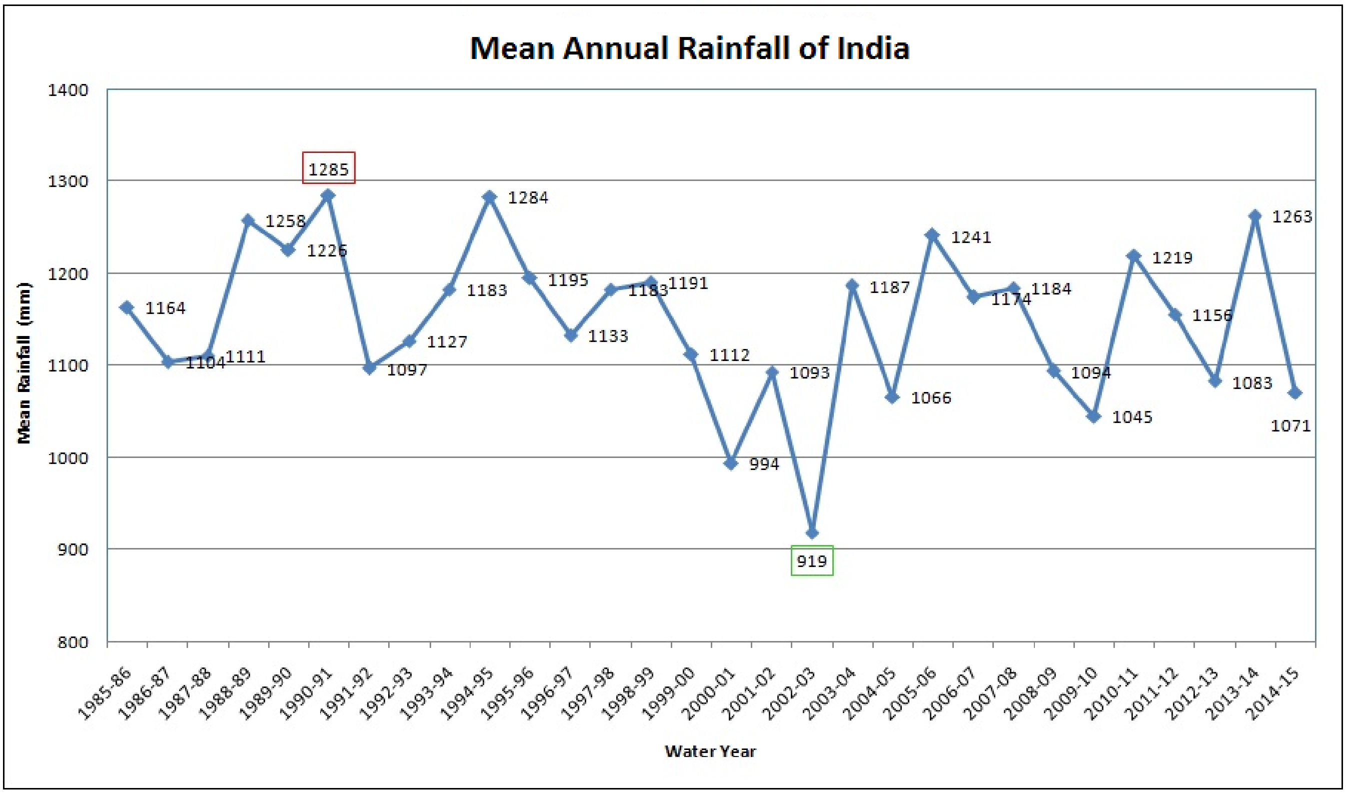


Figure 3.6 Mean annual rainfall of India (1985-86 to 2014-15)

3.2.2 Temperature grids

1^{o} X 1^{o} spatial resolution daily gridded temperature data sets over India prepared by IMD were used in this study (Figure 3.7). The daily data has been processed and converted into the annual scale. The mean annual temperature during 2004-05 was about 23.61°C.

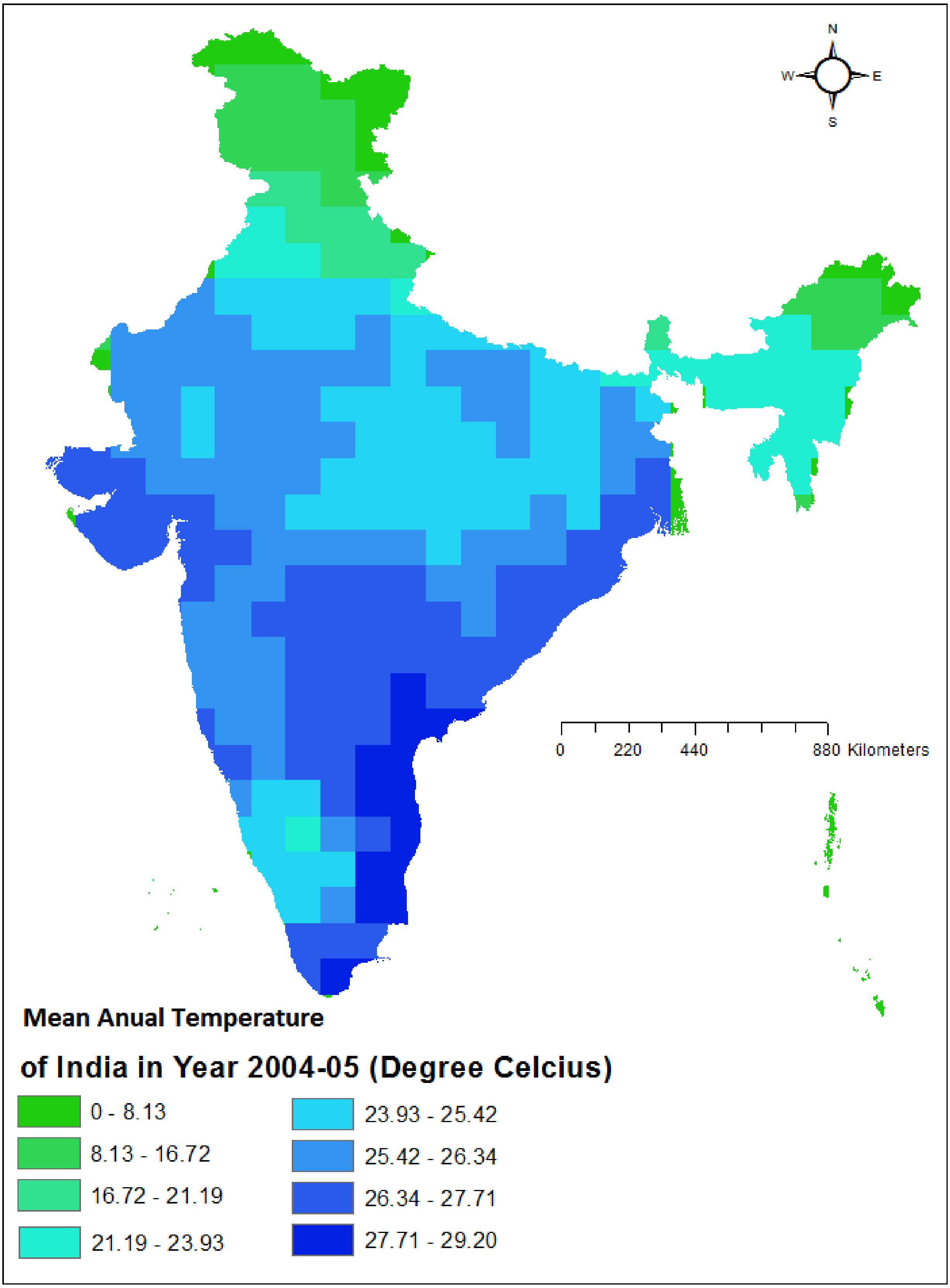


Figure 3.7 Gridded mean annual temperature of India (2004-05)

3.2.3 River discharge

The daily discharge data was aggregated to annual scale and was used for calibration and validation of model computed runoff at sub-basin level.

3.2.4 Reservoir flux

Monthly reservoir level data were collected from CWC for the basins. The reservoir level and corresponding volume data for the water year (June to May) was used in estimating the carryover of reservoir storage from one year to another year during the study period of 30 years. Reservoir flux is computed by subtracting the reservoir volume in May of succeeding year from June of current year as mentioned below.

Reservoir flux = Reservoir volume in June of current year - Reservoir volume in May of succeeding year.

3.2.5 Groundwater flux

The groundwater flux data prepared by CGWB was used in this study for estimating yearly groundwater fluxes. Water-year wise groundwater flux was available in shape file format. The sub-basin wise yearly groundwater flux is calculated as detailed below:

1. Each district area is extracted using groundwater flux district shape file provided by CGWB.
2. Groundwater flux district shape file is generated by sub-setting using sub-basin layer for each sub-basin and area of the district shape file is calculated.
3. The area fraction of each district in the sub-set groundwater flux district shape is computed and the area fraction is multiplied with the groundwater flux value given in the attributes for each year. The sum of all districts in sub-basin gives the total groundwater flux for a sub-basin.
4. The negative groundwater flux computed indicates withdrawal of water from the last year groundwater storage, whereas positive flux indicates increase in groundwater recharge from the last year.

Figure 3.8 depicts the groundwater flux (spatial data) estimated during 2004-05.

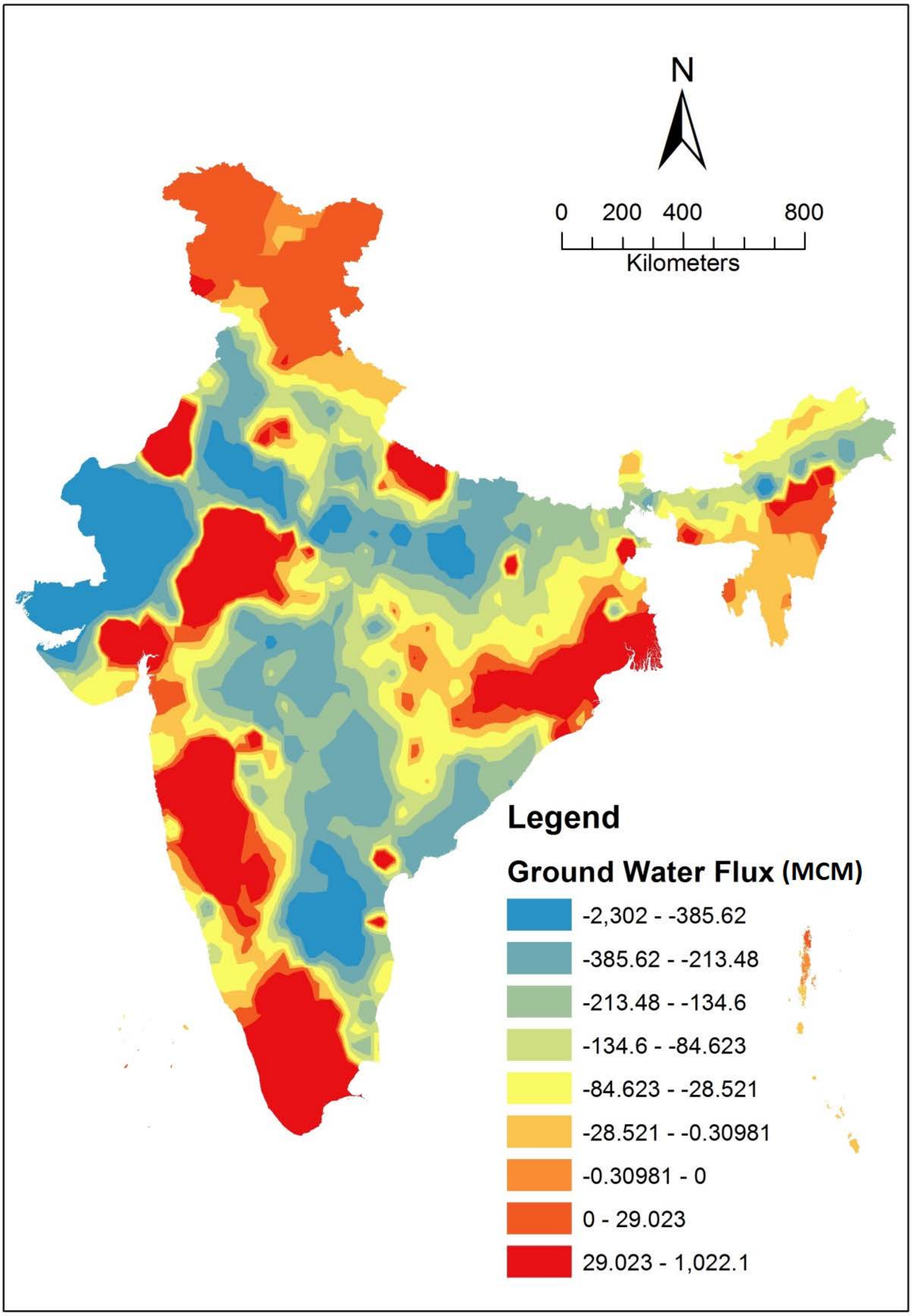


Figure 3.8 Groundwater flux (spatial data) estimated during 2004-05

3.2.6 Land Cover Coefficients

Based on the district-wise crop area statistics, district wise major crops for each crop season were identified. The basins were divided into regions based on the historic district-wise crop statistics collected from various sources (http://lus.dacnet.nic.in/ dt_lus.aspx). Each region specifies a unique crop for each crop season both spatially and temporally within the basin. The coefficients were taken as per the crop in that particular region/district. Different major crops for each season are emerged. On examining the cropping pattern within the basins, crop growing seasons are decided.

Considering all the above factors land cover coefficients are taken based on the report of FAO 56. The revised Potential Evapotranspiration (PET) values for each month were estimated by multiplying PET computed from Thornthwaite formula with the land cover coefficients. Figure 3.9 shows the variation of crop coefficients during the crop period.

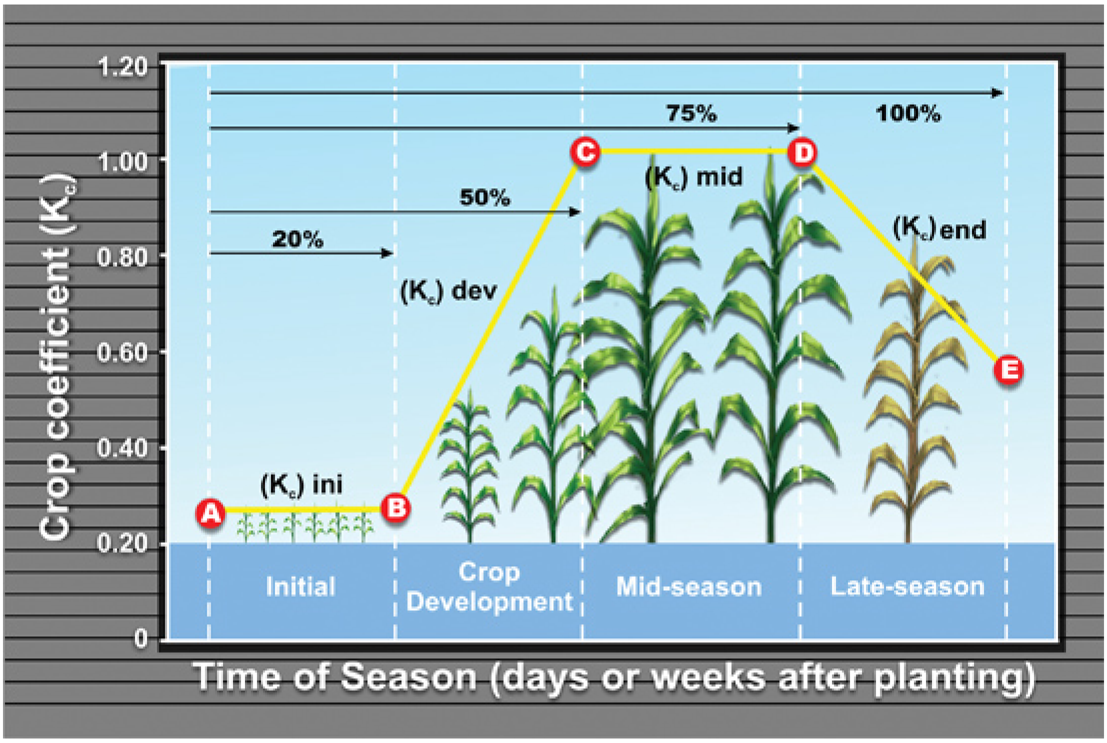


Figure 3.9 Crop coefficients

3.2.7 Water Holding Capacity

A particular soil textural class can have particular water holding capacity, and a certain vegetation type can have a certain root zone depth. The water holding capacities for different soils are taken from available literature.

The water available for vegetation is computed as follows.

Available water (mm) = Water holding capacity (% volume) x Root zone depth (mm)

3.2.8 Irrigation command area

The irrigation command areas in the basins were accounted for as depicted in Figure 3.10. The total command area of completed irrigation/multipurpose projects up to 2015 is about 2,75,798 sq.km.

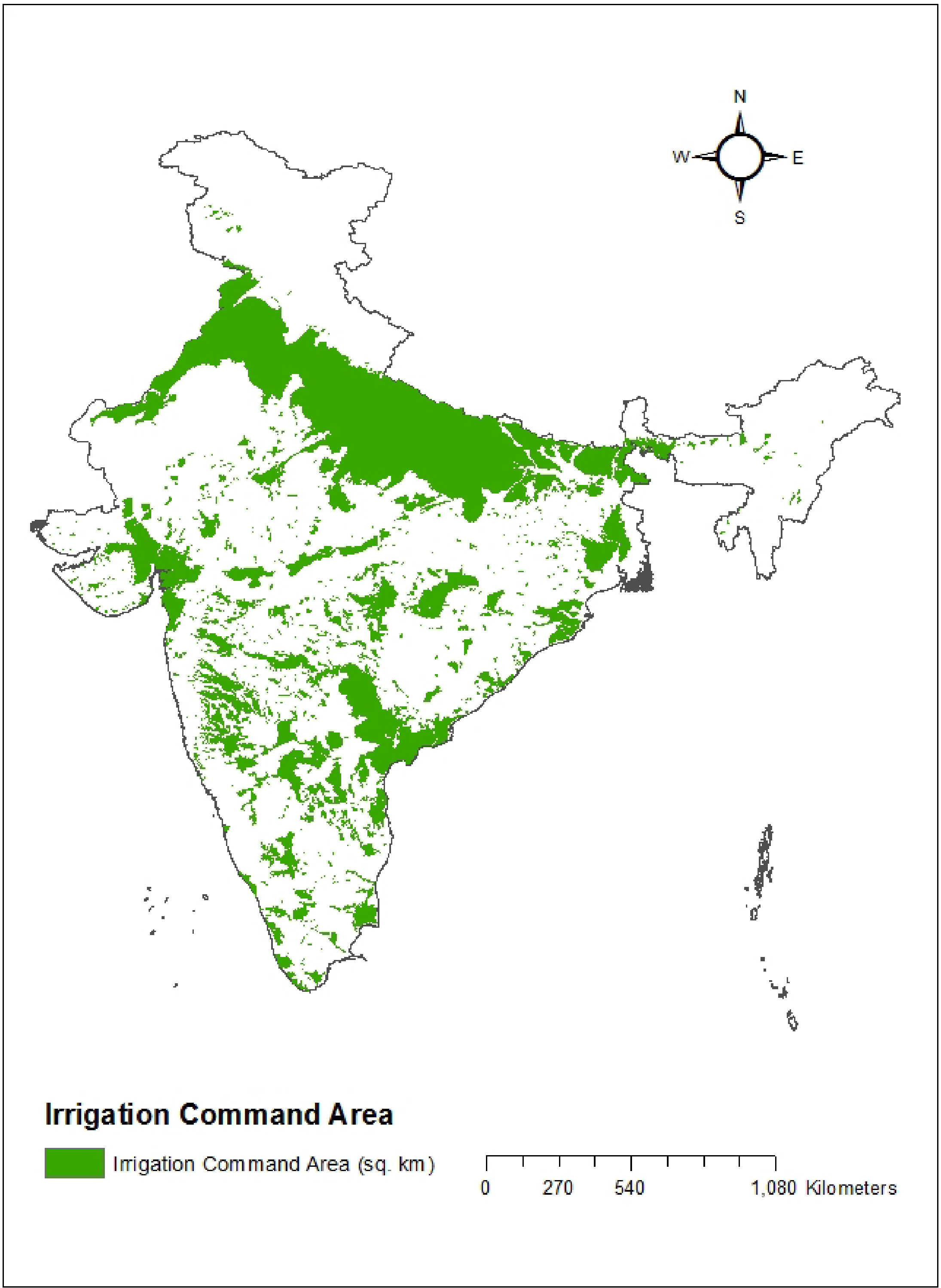


Figure 3.10 Irrigation Command area of India (Source: India-WRIS)

3.2.9 Domestic, industrial and livestock demand

The population of each district (2011 census) is provided as an attribute in the layer (Figure 3.11). The domestic demand is estimated taking into account the district boundaries of the year 2001 and 2011. Population statistics for intervening period and for the period beyond census years were calculated using geometric progression method. Domestic demand of 140 litres per capita per day (LPCD) for urban population, 70 LPCD for rural and 30 LPCD for livestock demand have been considered. Consumption at 15% of this demand is considered in the study. Since industrial demand statistics were not available, the same is assumed as 50% of the domestic demand for each year.

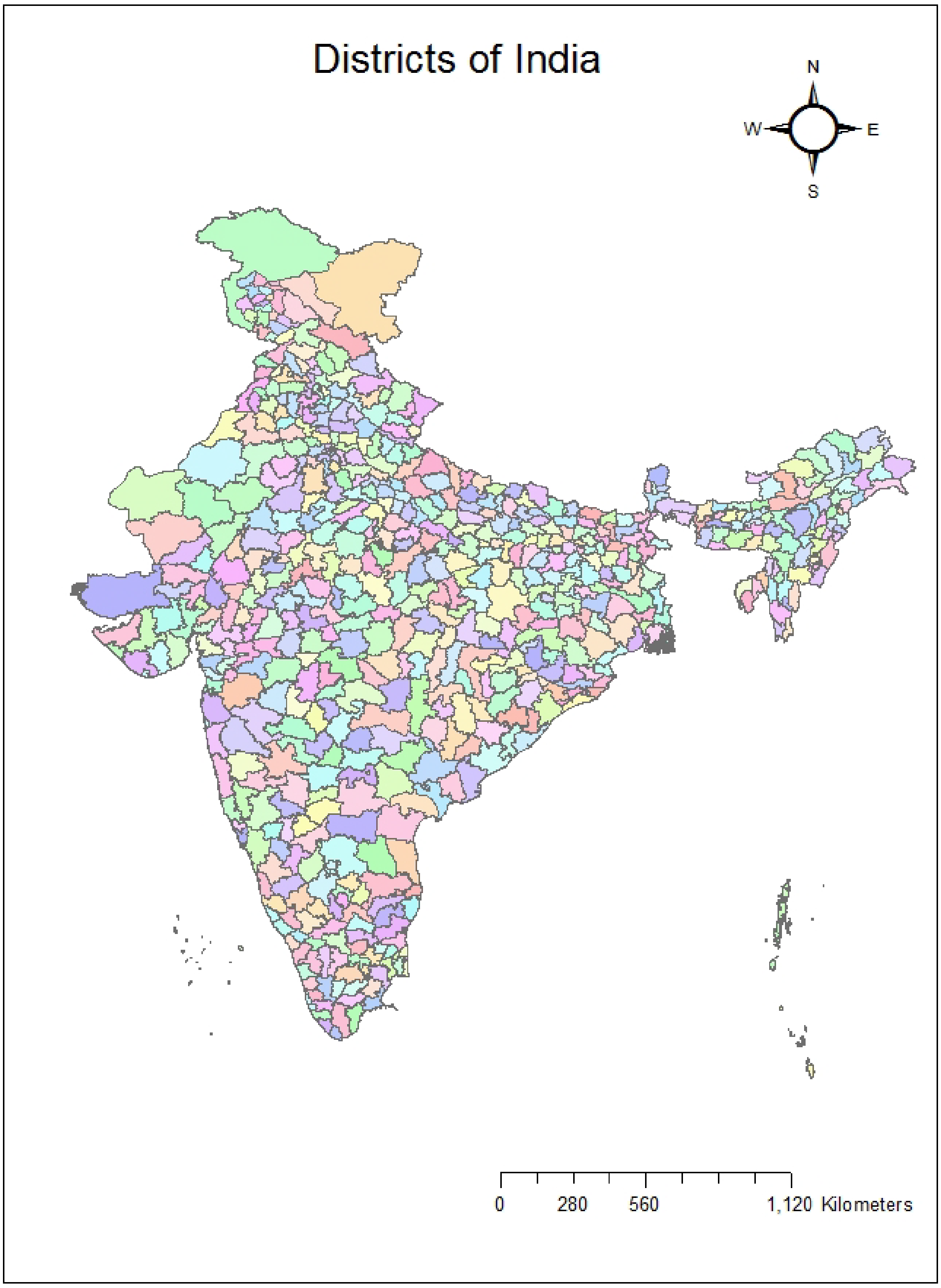


Figure 3.11 District map of India (2011 census)

3.2.10 Evaporation from major/medium/minor reservoirs and other water bodies

Evaporation was considered from the major/medium storage schemes present in the basins. Evaporation from small reservoirs/water bodies has not been considered in the study.

3.3 Approaches and Hydrological Models

Rainfall-runoff models can be classified in terms of the processes represented, the time & space scale used, and the methods of solution to equations are used (Beven, K.J. 1996, 2001, 2002a). The main features for distinguishing the approaches are; the nature of basic algorithms (empirical, conceptual or process-based), whether a stochastic or deterministic approach is taken, and whether the spatial representation is lumped or distributed.

The first feature defines if the model is based on a simple mathematical link between input and output variables of the catchment or it includes the description, even if in a simplified way of the basic processes involved in the runoff formation and development. Generally, when the observations are reliable and adequate, extremely simple statistical or parametric models are used. They vary from the simple regression models to the more recent Artificial Neural Networks models. These models are strongly dependent on the data used for calibration and, due to non-linear behavior of the rainfall-runoff process. Their reliability beyond the range of observations may be questionable. For this reason, conceptual models are generally preferred. The term conceptual denotes also the fully distributed physically based models because, even if they use parameters which are related to physical characteristics of the catchment and operate in a distributed framework, they must use average variables and parameters at grid or element scales greater than the scale of variation of the processes modeled (NRSC, 2009).

Another basic distinction between models is whether stochastic or deterministic representations and inputs are to be used. Most models are deterministic so they generate a single set of output. On the basis of the spatial representation, the hydrological models can be classified into three main categories: lumped models, semi-distributed models, and distributed models. The semi-distributed and distributed models take an explicit account of spatial variability of processes, input, boundary conditions, and/or watershed characteristics. Of course, lack of data prevents such a general formulation of distributed models, i.e., these models cannot be considered fully distributed.

Finally, according to the hydrological processes, hydrological models can be further divided into event-driven models, continuous-process models, or models capable of simulating both short-term and continuous events, and monthly based models. The first are designed to simulate individual rainfall-runoff events and their emphasis is placed on infiltration and surface runoff. The major limit to the use of event type model is the problem of unknown initial soil moisture conditions that cannot be measured and may heavily condition the forecasts in real time. Continuous process models, on the other hand, take explicitly account of all runoff components with provision for soil moisture redistribution between storm events. The daily models are suitable where sufficient field data is available and the study area is not very big and the user is intending to estimate runoff for a particular duration (may be a hydrological year). Monthly models are realistic for long term estimates in river basins and it gives reasonable estimates when we do water resources assessment at national level. These monthly models are process-based and take care of all hydrological processes such as Potential Evapotranspiration, Actual Evapotranspiration, soil moisture, change in groundwater storage, etc.

Various models and its data requirements, scope, limitations are examined. These includes, initial and constant rate model, Modified SCS Curve Number Loss Model**,** Continuous Soil Moisture Accounting (SMA) Model, Green and Ampt Loss Method, NAM Model (rainfall runoff (RR) module of the MIKE11 river modeling system), TOPMODEL, VIC Model (Variable Infiltration Capacity Model)**,** SWAT Model (uses SCS and Green Ampt models for runoff estimation), MIKE SHE, HEC-HMS, and other monthly water balance models (X U CY and Singh V. P., 1998).

Selection of a model mainly depends on the objectives of study, data available, spatial and temporal scale of the study. Each model requires different type of input data, when we are doing hydrological modelling at basin level one has to optimize the model considering the availability of input data. It is obvious that distributed or semi-distributed models are more accurate in runoff estimation compared to lumped models. Land use, soil texture, and digital elevation models are basic topographic input for any distributed hydrological modelling. Some models require extensive data on soil moisture, groundwater condition, etc.

For the country like India estimating daily runoff for many years is very cumbersome task both in quantity and in input data requirements. Monthly models can simulate the runoff nearer to the field reality that can give the overall picture on national water resources. Various monthly models like Thornthwaite and Mather (TM) model, Pitman model, Thomas abcd model, Roberts model, etc. are widely used for runoff estimation. These models were used for estimating runoff at national level in various countries like China, Brazil, USA, Russia, and in other countries. Advantages of these monthly models are, each component of hydrological cycle can be computed separately and accurately. Different algorithms can be chosen for estimating individual components of the hydrological cycle also. Considering the need, and the availability of long-term hydro-meteorological data at national level, it is proposed to use monthly water balance model in the study.

After examining various water balance models, Mather soil water balance model is chosen for the study as it uses distributed modelling approach and widely applied in various countries. This model is almost nearer to the process-based approach in which, potential evapotranspiration, water loss and accumulated water loss in a month, water holding capacity of soils up to root zone depth are considered in calculating actual evapotranspiration and subsequently runoff. Since the evapotranspiration is the major component in the hydrological water balance, a suitable and practically feasible method has to be adopted at basin scale considering the data availability.

3.4 WRA models

The modelling of water resources availability is aimed at calculating the necessary hydrological background information to determine basin yield. The obligatory element of the module is the water balance model corresponding to the surface and the replenishable groundwater.

The changes in land use influencing the quantity of the water resources as well through the following parameters: interception, evapotranspiration, surface runoff, infiltrations were considered through land cover coefficient for vegetation. The models applied for calculating the water balance include information on the land use directly (hydrological parameters are calculated in the model in function of the land use as an input) or indirectly (information on the land use are used for estimating the input parameters of the model).

The model framework is developed for assessment of water resources in all the basins of India using water balance approach comprising relevant elements in the input domain. WRA tool by NRSC, Hyderabad has been selected in harmony with the problems and the available information, providing flexibility in the application.

3.4.1 Establishment of the models

The appropriate models are selected during the conceptualisation phase. Set-up of the model includes (i) geometrical settings, (ii) input of parameters, (iii) preparation and compilation of datasets used for calibration and validation, (iv) calibration and validation. These are well known technical steps of the modelling. Only the calibration and the validation needed some special remarks regarding the main objective of the project.

3.4.2 Calibration and validation of the models

Calibration of the models is essential for the reliability of the assessment. Land cover coefficients for vegetation are to be changed by hit and trial method till the desired output is achieved.

3.5 Broad Methodology

The modeling frame work for the present study (Figure 3.12) involves integration of spatial data sets (DEM, LULC, soil texture, village census) with hydro-meteorological data sets (rainfall, temperature, groundwater flux, reservoir flux and river discharge) in GIS environment to carry out water balance computations at hydrological response unit level. The 30-years water balance outputs were averaged to arrive at long-term average annual basin level water resources.

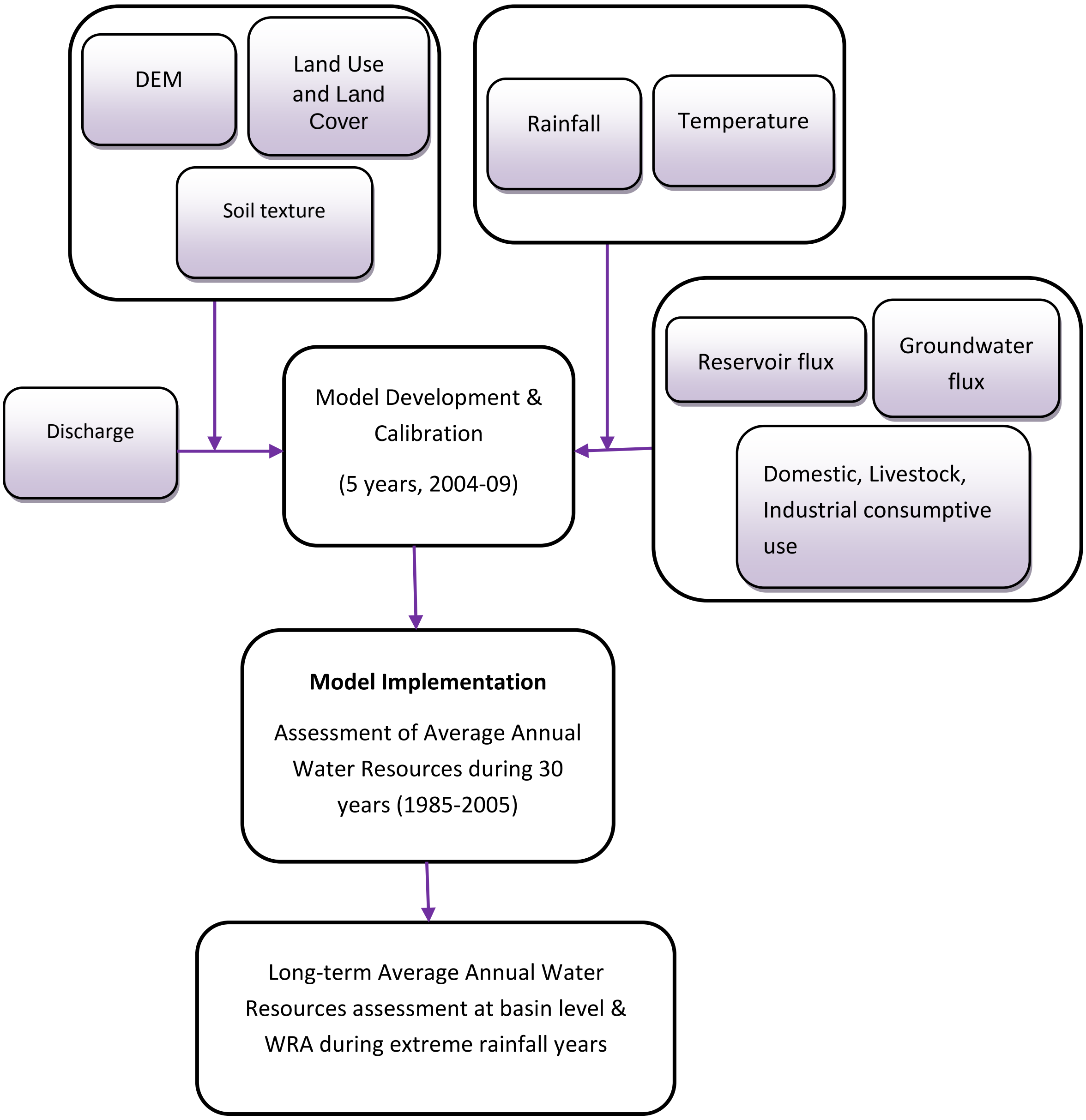


Figure 3.12 Modelling frame work of Water Resources Assessment

The water balance has been used for computing seasonal and geographic patterns of irrigation demand, the soil moisture stresses under which crop and natural vegetation can survive. Water table calculated for a single soil profile or for an entire catchment, refers to the balance between incoming of water by precipitation and outflow of water by evapotranspiration, groundwater recharge and stream flow. Among the several possible methods of calculation, the one introduced by Thornthwaite and Mather (1957) generally has been accepted. This technique uses long term average monthly rainfall, long term average potential evapotranspiration, and soil & vegetation characteristics. The last two factors are combined in the water capacity of the root zone. Computation of ET in this method is mainly based on temperature data only. By using the Eq. 1, a monthly heat index (j) is calculated employing the mean monthly temperatures.

$$j = \left(\frac{t_n}{5}\right)^{1.514} \quad \text{(Eq. 1)}$$

where, j = monthly heat index

t_n = monthly mean temperature, ^{0}c (where n= 1,2,3………12)

Annual heat index (J) is given by the Eq. 2 adding together twelve monthly heat indices.

$$J = \sum_1^{12} j \quad \text{(Eq. 2)}$$

Then, monthly PET for any month is calculated by means of the following Eq. 3:

$$\mathrm{PET} = 16f\left(\frac{10t_n}{J}\right)^a \quad \text{(Eq. 3)}$$

where, a is the cubic function of J

$$a = (675*10^{-9})J^3 - (771*10^{-7})J^2 + (179*10^{-4})J + 0.492 \quad \text{(Eq. 4)}$$

f = factor, to correct for unequal day length between months.

It is necessary to adjust the value of unadjusted 30-day potential evapotranspiration and 12 hours of sunshine per day, modulating by factor (f). For other latitudes f value has to be interpolated from Table - 3.

Table - 3: Values of factor (f)

North Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0^o	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10^o	0.97	0.98	1.01	1.03	1.05	1.06	1.05	1.03	1.08	0.99	0.98	0.96
20^o	0.93	0.96	1.00	1.05	1.09	1.11	1.10	1.07	1.03	0.98	0.93	0.91
30^o	0.87	0.93	1.00	1.08	1.14	1.18	1.16	1.10	1.03	0.96	0.88	0.85
40^o	0.80	0.89	0.99	1.10	1.20	1.25	1.23	1.15	1.04	0.93	0.83	0.78
50^o	0.72	0.84	0.98	1.15	1.28	1.37	1.33	1.21	1.06	0.90	0.76	0.68

Day length factor grid has been prepared in GIS environment. PET has been calculated using temperature grids and day length grids through spatial modelling technique. These spatial PET maps of study basin are prepared and subsequently PET grids of study basin are extracted.

Land Cover Coefficients: The Thornthwaite method doesn't account for vegetative effect which is most useful parameter in water balance estimations (Peter E. Black). Monthly land cover coefficients have been derived to study river basin using satellite remote sensing data and integrated with PET to account to vegetation effect on PET. The Thornthwaite method uses air temperature as an index of the energy available for evapotranspiration, assuming that air temperature is correlated with the integrated effects of net radiation and other controls of evapotranspiration, and that the available energy is shared in fixed proportion between heating the atmosphere and evapotranspiration. This method estimates PET only based on air temperature and do not consider the land cover and vegetation classes. But actually, the ET also depends on whether the soil is covered with or without vegetation and vegetation types (Dolman et al., 2001). Hence, in this study it is proposed to consider the effect of vegetation cover and its type in estimating the PET using the Thornthwaite method by using land cover based coefficients.

$PET_{revised}$ (or $ET_{LC\ (model\ estimated)}$) = PET * Land cover coefficient (Eq. 5)

The land cover coefficient for vegetation (K_c) integrates the effect of characteristics that distinguish field crops from each other. Consequently, different crops will have different K_c. The K_c primarily depends on crop type, crop growth stage, soil evaporation. Uniform K_c during all the months has been considered for the vegetation like forest, scrub land etc. Whereas for agricultural lands, variable coefficients have been taken in different months according to the crop growth stage and type of crop. These coefficients are further calibrated using the field discharge data.

After the calculation of $ET_{LC\ (model\ estimated)}$, the dry and wet seasons should be identified. If the difference between P & $ET_{LC\ (model\ estimated)}$ is positive, it is considered as wet season, otherwise it is dry season. The severity of the dry season increases during the sequence of months with excessive potential evapotranspiration. The accumulated potential water loss (La), which is the cumulative of negative values of (P - $ET_{LC\ (model\ estimated)}$) for the dry season is calculated from the end of the wet season.

Next, the Soil Moisture (SM), which depends upon the soil texture type, root zone depth of vegetation and land use is determined. Then for dry season months amount of water retained in the soil for various La is found from the readily available tables or graphs or by using the empirical formula. Whereas for wet season months, SM can be determined by adding the excess precipitation to the soil moisture value of the previous month until the total storage again reaches the water-holding capacity of the soil.

The soil moisture status for each month with evapotranspiration exceeding precipitation is calculated using Eq. 6:

$$SM = W * e^{\left(\frac{-La}{W}\right)} \qquad \text{(Eq. 6)}$$

where, SM = soil moisture, mm

W = available water, which has been calculated for the different land use class and soil texture, mm

La = accumulated potential water loss, mm

The ability of soil to retain water depends upon the amount of silt and clay present in it; the higher the amount, the greater is the soil moisture content. Available water (W) of each pixel has been calculated based on the land use, root zone depth, and soil textural information. ΔSM in each month is calculated based on W and La in the month. ΔSM is the change in soil moisture in a month to its previous month.

Actual evapotranspiration ($AET_{model\ estimated}$) represents the actual transfer of moisture from the soil and vegetation to the atmosphere.

When P exceeds $ET_{LC\ (model\ estimated)}$, it is assumed that there is sufficient moisture to meet the climatic demands and

$$AET_{model\ estimated} = ET_{LC\ (model\ estimated)} \qquad \text{(Eq. 7)}$$

Even if the soil moisture of root zone is not at its water holding capacity, but P > $ET_{LC\ (model\ estimated)}$, it may be assumed that P will be sufficient to satisfy climatic moisture requirements, i.e. $AET_{model\ estimated} = ET_{LC\ (model\ estimated)}$.

When, P< ET $_{LC\ (model\ estimated)}$, and meteorological demand is partially satisfied from the stored soil water.

$$AET_{model\ estimated} = P + |\Delta SM| \quad \text{(Eq. 8)}$$

In irrigated agricultural land (canal and well irrigation), Estimated Consumptive Irrigation Input (P- $ET_{LC\ (model\ estimated)}$) is added to rainfall to equate AET $_{model\ estimated}$ to ET $_{LC\ (model\ estimated)}$. This assumption is made assuming that irrigation water requirements are fully met. The added Estimated Consumptive Irrigation Input has been subsequently adjusted while computing runoff.

Then, we should identify the months in which moisture deficit (D) occurs. D, that exists only in dry period when P< $ET_{LC\ (model\ estimated)}$, is calculated by Eq. 9.

$$D = ET_{LC\ (model\ estimated)} - AET_{model\ estimated} \quad \text{(Eq. 9)}$$

The amount of excess water that cannot be stored is termed as moisture surplus (S). When storage reaches its capacity, surplus is calculated using the Eq. 10.

$$S = P - (AET_{model\ estimated} + |\Delta SM|) \quad \text{(Eq. 10)}$$

By definition, actual runoff equals to the available annual surplus. However due the lag between the time of precipitation and the time the water actually passes through the gauging station, monthly computed surplus is not the same as monthly runoff. As per Thornthwaite and Mather's suggestion it can be assumed that for large catchments approximately 50% of the surplus water is available for runoff in any month. The rest of the surplus is detained in the subsoil, groundwater, small lakes, and the channels of the basin and is available for runoff during the next month.

Hydrological Response Units Generation: The simulation assigns the entire basin into number of Hydrological Response Units (HRU) based on the land use, soil texture, root zone depth, and command area grids. A Hydrological Response Unit (HRU) is an area within the basin having same soil type and land use, a basic computational unit assumed to be homogeneous in hydrologic response to land cover change. Depending on the number of soil textural classes and land cover classes, a number of HRU are derived within the basin. It is assumed that a particular soil textural class can have particular water holding capacity and a certain vegetation type can have a certain root zone depth. So a combination of soil textural class and vegetation type results in different HRUs. Meteorological data of the concerned HRU is used in runoff calculations.

In addition to the derived HRUs they are further categorized based on the irrigation command area boundaries. The HRUs within the command boundary are assumed to meet all the AET demand considering the major crop season/seasons (i.e. Kharif, Rabi, Zaid and Double/Triple) in the basin. For example, Double/Triple crop assumed to satisfy all the AET demand (i.e. Actual ET = $ET_{LC\ (model\ estimated)}$) whether it is within the command boundary.

In irrigated crop areas (both in canal and tube well irrigated) the water requirements in excess of precipitation are supplemented through irrigation sources. In the present study, all the cropped area within irrigation canal jurisdiction and Double/Triple cropped area were considered as irrigated. In general, these irrigated cropped areas will meet their full water requirements through precipitation and supplementary irrigation. But availability of records of irrigation supplies is difficult to collect because the irrigation sources may vary from surface storage from reservoirs, tanks and groundwater sources such as open wells, deep bore wells etc. Hence, in the present study irrigation supplies are computed from the precipitation and $ET_{LC\ (model\ estimated)}$. It is assumed that under these cropped areas, actual evapotranspiration attains potential evapotranspiration. It means, whenever precipitation (P) falls short of $ET_{LC\ (model\ estimated)}$, the shortage (i.e., $ET_{LC\ (model\ estimated)}$, - P) is met with supplementary irrigation (Estimated Consumptive Irrigation Input). To account for these irrigation supplies, the precipitation under the above mentioned cropped areas is revised as detailed under:

Precipitation (revised), $P_{revised} = P$, when Precipitation>$ET_{LC\ (model\ estimated)}$

$= P + (ET_{LC\ (model\ estimated)} - P)$, when Precipitation<$ET_{LC(model\ estimated)}$

(For Double/Triple cropped area and cropped area within irrigation command jurisdiction)

Model runoff calculations of particular HRU having available water (water holdind capacity) as 90 mm is shown in Table - 4 as an example.

Table – 4: Model Runoff Calculations

	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
Rainfall	200.7	363.4	501.4	195.6	57.1	39.1	1.8	0.1	0.5	0.0	0.1	0.9	1360.7
PET	199.4	139.8	121.1	148.7	147.7	102.6	73.6	63.9	91.6	147.4	240.4	278.6	1754.8
Vegetation factor	1.1	1.2	1.1	0.9	1.1	1.2	1.1	0.9	0.5	0.8	1.1	0.7	
$ET_{LC(model\ estimated)}$	209.4	167.8	133.3	133.9	155.1	123.1	80.9	57.5	45.8	110.6	252.4	195.0	1664.8
$P_{revised}$	209.4	363.4	501.4	195.6	155.1	123.1	80.9	57.5	0.5	0.0	0.1	0.9	1687.9
$P_{revised} - ET_{LC(model\ estimated)}$	0.0	195.6	368.1	61.7	0.0	0.0	0.0	0.0	-45.3	-110.6	-252.3	-194.1	
APWL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-45.3	-155.9	-408.2	-602.3	
Soil moisture	0.1	90.0	90.0	90.0	90.0	90.0	90.0	90.0	54.4	15.9	1.0	0.1	
Change in SM	0.0	89.9	0.0	0.0	0.0	0.0	0.0	0.0	-35.6	-38.5	-14.9	-0.9	
$AET_{model\ estimated}$	209.4	167.8	133.3	133.9	155.1	123.1	80.9	57.5	36.1	38.5	15.0	1.8	1152.4
Deficit	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.7	72.1	237.4	193.2	
Surplus	0.0	105.7	368.1	61.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	535.5
Tot. Avl. for Runoff	0.0	105.7	421.1	272.3	136.2	68.1	34.1	17.0	8.5	4.3	2.2	1.1	
RO(Runoff)	0.0	52.9	210.6	136.2	68.1	34.1	17.0	8.5	4.3	2.2	1.1	0.5	535.5
Detention	0.0	52.9	210.6	136.2	68.1	34.1	17.0	8.5	4.3	2.2	1.1	0.5	

- *Available water (water holding capacity) of the soil (up to root zone depth) = 90 mm,*
- *Calculations are for Double/Triple crop within command area. Third crop (Feb to May) is grown on residual soil moisture without ECII.*

3.5.1 Model calibration and validation

The runoff estimated from each pixel at monthly time step is aggregated within each sub-basin. The monthly surface runoff is further aggregated to annual time step for all the sub-basins. The estimated runoff for each sub-basin is calibrated with observed discharge at annual scale.

If any unknown variable exists in the model, it can be calibrated using the observed/field data during the calibration process. The land cover coefficients are the main variable to be modified. Basically the calibration process is a trial and error method. Land cover coefficients need to be changed during the calibration process till the desired outputs are achieved. After calibrating the model, the runoff calculations have to be revised using the revised coefficients. The schematic diagram of the calibration procedure is shown in the Figure 3.13.

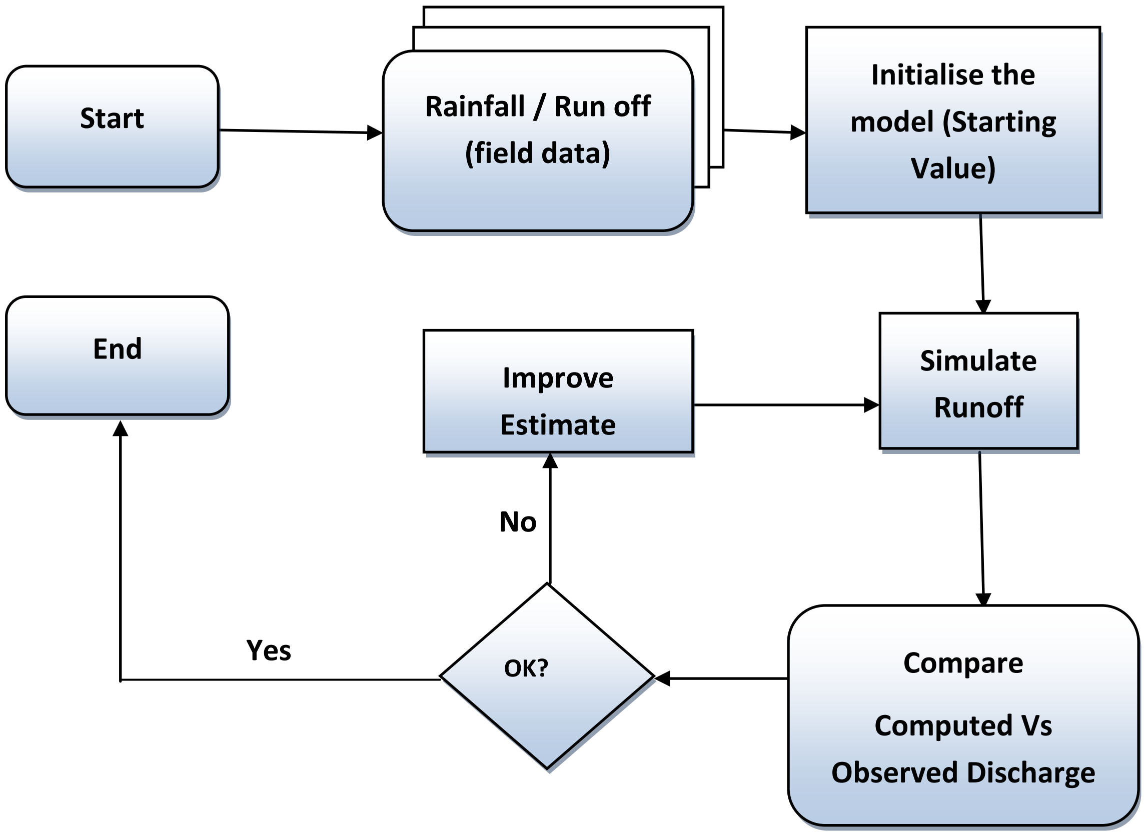


Figure 3.13 Calibration procedure

Once the model is calibrated, it has to be validated with other set of field observations to check the calibrated parameters. In the present study, the model has been calibrated with the hydro-meteorological data of 5 years which includes dry, wet and normal water years. The calibrated model has been validated with the data of all the remaining years. Calibration of the Model is done using the Eq. 11.

$R_{Calibrated/computed} = (R_{Model} - F_{GW} - F_R - F_{DIL}) \approx R_o$ (Eq. 11)

$R_{Calibrated/computed}$ = Calibrated/computed runoff`

R_{Model} = Model estimated runoff (output from Thornthwaite-Mather Model)

F_{GW} = Groundwater Flux (- ve sign for drawdown)

F_R = Reservoir Flux (- ve sign for drawdown)

F_{DIL} = Domestic, Industrial and Livestock consumption

R_o = Observed runoff at gauge sites (CWC's observed data is taken)

3.5.2 Abstractions

Water is abstracted to meet a wide range of uses. Agriculture is responsible for most of the water abstraction from the river and its tributaries, while industry and domestic water supply abstractions are minor. The effect abstraction has on the natural flow regime and the environment is influenced by the amount and timing of the abstraction, the volume that may be returned and where the water is returned after use. Many abstractions are sustainable, but this is not always the case. Abstraction and flow regulation are significant water management issues in the sub-basins and basins. The amount of water abstracted from the basin are given due care along with the water imported from other basins/sub-basins.

3.5.3 Evaporation from Reservoirs and other Water Bodies

Evaporation from reservoirs and other water bodies has been worked out based on the yearly reservoir masks prepared from LULC layers from the year 2004-05 to 2014-15 considering the area of water bodies of more than 1 hectare and excluding flowing water in the river. For the water bodies prior to the year 2004-05 (since LULC layers prior to 2004-05 are not available), water bodies area of respective dams was removed based on the year of completion of the dam.

3.5.3 Water Resources Availability (WRA)

Water resources of the basin comprises runoff in the river at final outlet, upstream effective utilizations for irrigation, domestic, industrial and livestock, groundwater flux and reservoir flux. Thus, it can be expressed as;

$WRA = R_{Calibrated/computed} + ECII + E + F_{GW} + F_R + F_{DIL}$ (Eq. 12)

where,

E = Evaporation losses from the reservoirs (computed)

ECII = Estimated Consumptive Irrigation Input Provided (computed)

Annual water resources availability during the 30 years (1985-86 to 2014-15) has been computed for all sub-basins. Average annual water resources have been further calculated. Rainfall during the last 30 years has been analyzed and the water resources availability during the extreme minimum and maximum rainfall years has been analyzed further.

3.6 Characteristics of Basins

Characteristics in respect of the twenty river basins have been presented in the following paragraphs.

3.6.1 Indus (within India)

The Indus basin spreads over states of Jammu & Kashmir (60.31%), Himachal Pradesh (15.98%), Punjab (15.66%), and part of Rajasthan (4.92%), Haryana (3.09%), besides Union Territory of Chandigarh (0.04%) having an area of 3,17,708 sq.km which is nearly 9.8 percent of the total geographical area (Figure 3.14). The geographical extent of the basin is between 72°28' to 79°39' East longitudes and 29°8' to 36°59' North latitudes of the country. The upper part of the basin, which lies in Jammu & Kashmir and Himachal Pradesh, is dominated by mountain ranges and narrow valleys. In Punjab, Haryana and Rajasthan, the basin consists of vast plains, which are fertile granary of the country. There are 6 major rivers which are flowing in the basin namely, Indus, Jhelum, Chenab, Ravi, Beas and Sutlej. Indus is a trans-boundary river that originates in Tibet, it flows in Jammu & Kashmir region and further goes in Pakistan. Sutlej is also a trans-boundary river originating in Tibet and flows in Himachal Pradesh and Punjab region. There is snowmelt runoff addition in the flow in the summer months of the year.

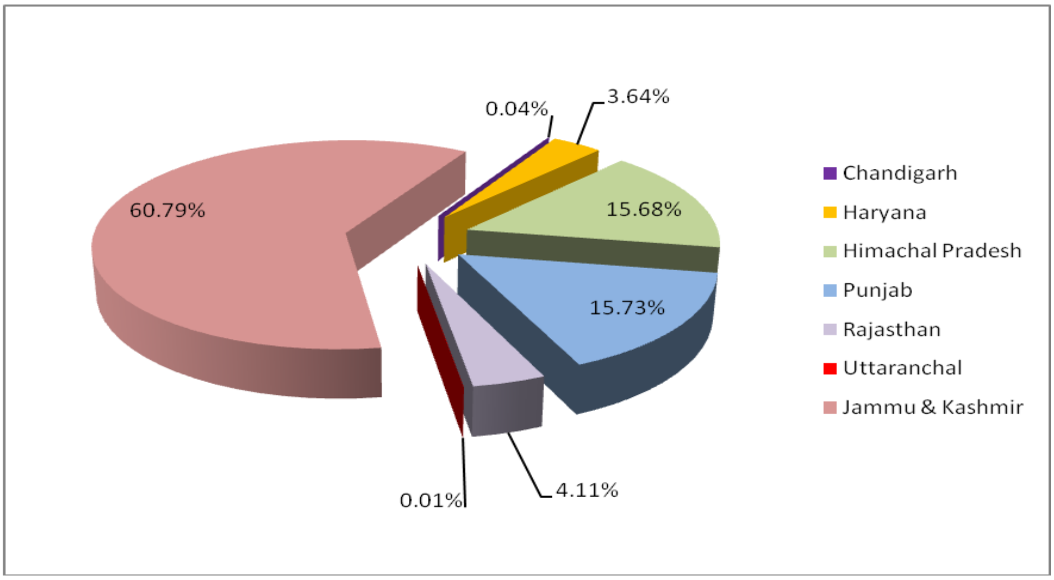


Figure 3.14 Percentage area of Indus basin in various States

Rainfall

The rainfall varies temporally and spatially across the basin. The south-west monsoon brings rains in the summer months while the winter rains are caused by the storms in Jammu & Kashmir. Mean annual rainfall of the study time period is 896 mm for the basin.

During the study period (1985 to 2015) maximum rainfall was recorded as 1315.6 mm in 1995-96 and minimum as 512.6 mm in 2000-01.

Temperature

The Indus basin faces variability in temperature from upper portion of the basin to the lower portion of the basin. The difference may be due to variation in topography of the basin. The temperature goes below 0^oC in the upper part of the Indus basin, whereas the temperature rises above 40^oC in the lower part of the basin.

3.6.2 Ganga-Brahmaputra-Meghna

a) Ganga

The Ganga basin outspreads in India, Tibet (China), Nepal and Bangladesh over an area of 10,86,000 sq.km. In India, it covers states of Uttar Pradesh (28.68%), Madhya Pradesh (21.65%), Rajasthan (11.22%), Bihar(12.86%), West Bengal (8.37%), Uttarakhand (6.38%), Jharkhand (6.04%), Haryana (1.59%), Chhattisgarh (2.20%), Himachal Pradesh (0.71%) and Union Territory of Delhi (0.18%) draining an area of 8,38,803 sq.km which is nearly 26% of the total geographical area Of the country (Figure No 3.15). The basin lies between East longitudes 73°2’ to 89°5’ and North latitudes 21°6’ to 31°21’ having maximum length and width of approximately 1,543 km and 1024 km. The basin is bounded by the Himalayas on the north, the Aravalli on the west, the Vindhyas and Chhotanagpur plateau on the south and the Brahmaputra Ridge on the east. Mean annual rainfall of the study time period is 1007 mm for the basin.

River Ganga rises in the Gangotri glacier in the Himalayas at an elevation of about 7,010 m in the Uttarkashi district of Uttarakhand. At its source, the river is called as the Bhagirathi. It descends down the valley up to Devprayag where after joining another hill stream Alaknanda, it is called Ganga. The total length of river Ganga (measured along the Bhagirathi and the Hooghly) up to its outfall into Bay of Bengal is 2525 km. The principal tributaries joining the river from right are the Yamuna and the Sone. The Ramganga, the Ghaghra, the Gandak, the Kosi and the Mahananda join the river from left. The Chambal and the Betwa are the two other important sub-tributaries. The major part of basin in Indian Territory is covered with agricultural land accounting to 65.57% of the total area and 3.47% of the basin is covered by water bodies.

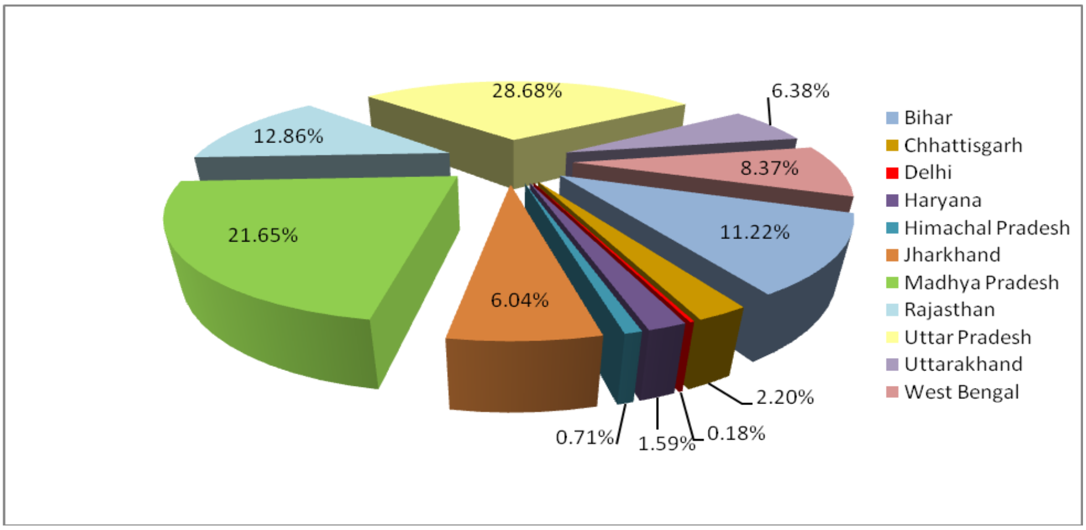


Figure 3.15 Percentage area of Ganga basin in various States

b) Brahmaputra

The Brahmaputra basin spreads over countries of Tibet (China), Bhutan, India and Bangladesh having a total area of 5,80,000 sq.km. In India, it spreads over states of Arunachal Pradesh (42.60%), Assam (36.46%), West Bengal (5.92%), Meghalaya (5.70%), Nagaland (5.63%) and Sikkim (3.69%) and lies between 88°11' to 96°57' East longitudes and 24°44' to 30°3' North latitudes and extends over an area of 1,93,252 sq.km which is nearly 5.9% of the total geographical area of the country (Figure 3.16). It is bounded by the Himalayas on the north, the Patkari range of hills on the east running along the India-Myanmar border, the Assam range of hills on the south and the Himalayas and the ridge separating it from Ganga basin on the west. The Brahmaputra River originates in the north from Kailash ranges of Himalayas at an elevation of 5150 m just south of the lake called Konggyu Tsho and flows for about a total length of 2900 km. In India, it flows for 916 km. The principal tributaries of the river joining from right are the Lohit, the Dibang, the Subansiri, the Jiabharali, the Dhansiri, the Manas, the Torsa, the Sankosh and the Teesta whereas the Burhidihing, the Disang, the Dikhow, the Dhansiri and the Kopili joins it from left. The major part of basin is covered with forest accounting to 55.48% of the total area and 5.79% of the basin is covered by water bodies. Mean annual rainfall of the study time period is 2330 mm for the basin.

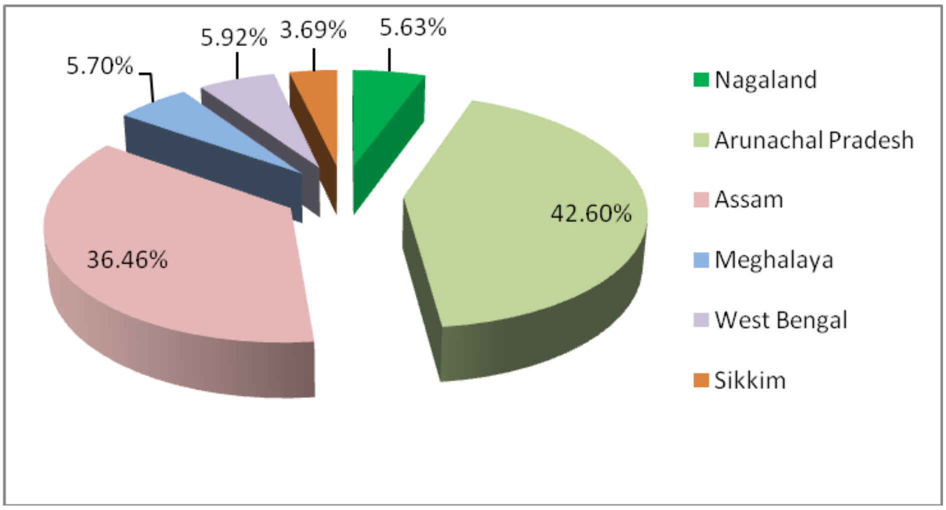


Figure 3.16 Percentage area of Brahmaputra basin in various States

The Teesta basin extends over an area of 9,855 sq.km, which is nearly 0.28% of the total geographical area of the country. The basin lies in the states of Sikkim (72.43%) and West Bengal (27.57%). The Teesta River is a 309 km long river with drainage area of 12,540 sq.km, flowing through India and Bangladesh and finally draining into Bay of Bengal. The Teesta River originates from the Pahunri (or Teesta Kangse) glacier above 7068 m, and flows southward through gorges and rapids in the Sikkim Himalaya. The river then flows past the town of Rangpo where the Rangpo River joins, and where it forms the border between Sikkim and West Bengal up to Teesta Bazaar. Just before the Teesta Bridge, where the roads from Kalimpong and Darjeeling join, the river is met by its main tributary, the Rangeet River. At this point, it changes course southwards flowing into West Bengal. The river then goes merging up with the Brahmaputra River after it bifurcates the city of Jalpaiguri and flows just touching Cooch Behar district at Mekhliganj and moves to Fulchori in Bangladesh. The Teesta River is one of the rivers that has changed over the years. Teesta river area is in the seismically active Zone-IV and has experienced micro-seismic activity. The hydroelectric projects are cascaded over the length of the river, do not store large amounts water, have small reservoirs, and therefore the projects are expected to have very low risk from the reservoir induced seismicity in the area.

The Teesta basin receives major part of its rainfall during the South-West monsoon period. Rainfall is heavy and well distributed during the months from May to early October. July is the wettest month in most of the places. The intensity of rainfall during South-West monsoon season decreases from South to North, while the distribution of winter rainfall is in the opposite order. Some tributaries flowing from Bhutan also contribute to the basin, which have been considered in the present study.

c) Barak & others

The Barak & others basin extends over an area of 86,335 sq.km, which is nearly 1.44% of the total geographical area of the country. The basin covers the states of Meghalaya (24%), Manipur (20%), Mizoram (19%), Tripura (18%), Assam (17%) and Nagaland (2%) (Figure 3.17). The Barak river rises from the Manipur Hills, south of Mao in Senapati District at an elevation of 2,331 m. Then it flows along Nagaland-Manipur border through hilly terrains and enters Assam. It further enters Bangladesh where it is known by the Surma and the Kushiyara and later called the Meghna before receiving combined flow of the Ganga and the Brahmputra. The length of Barak River from its origin up to the border of Assam along the Kushiyara is 564 km. The principal tributaries from right are the Jiri, the Chiri, the Modhura, the Jatinga, the Harang whereas the Dhareshwari, the Singla, the Longai, the Sonai are principal tributary joining from the left.

Rainfall: Rainfall varies both spatially and temporally in Barak & others basin. Annual rainfall of the basin varies from 1975 mm to 3518 mm. The average annual rainfall (1985-2015) in the Barak & others basin is 2,625 mm.

Climate: The Barak & other basins has a tropical climate. The average annual monthly maximum temperature is about 27.9°C and average annual minimum temperature is about 26.5°C in the basin.Temperatures in the bordering region with Bangladesh are higher, whereas in interior location temperature is moderate.

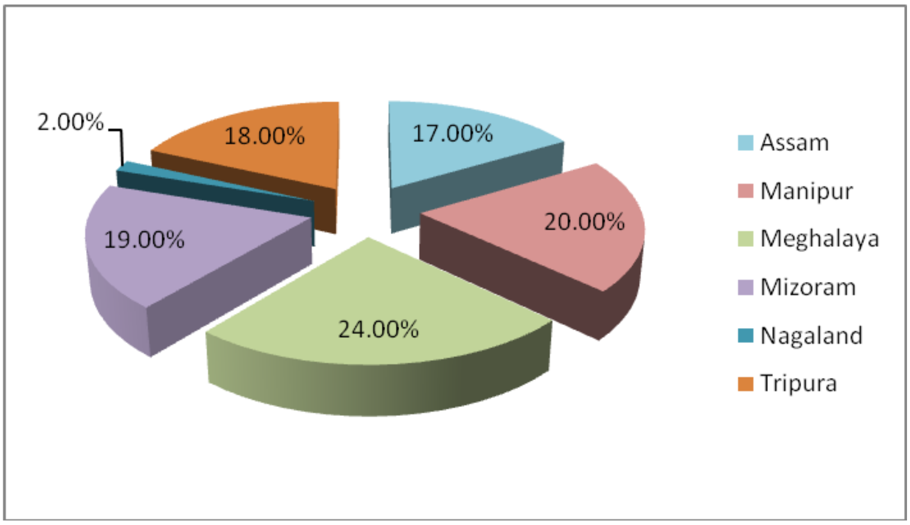


Figure 3.17 Percentage area of Barak & others basin in various States

3.6.3 Godavari

The Godavari basin extends over an area of 3,12,150 sq.km, which is nearly 9.5% of the total geographical area of the country. The basin lies in the states of Maharashtra (48.50%), Andhra Pradesh & Telangana (23.30%), Chhattisgarh (12.50%), Madhya Pradesh (8.6%), Odisha (5.70%), and Karnataka (1.40%) (Figure 3.18).

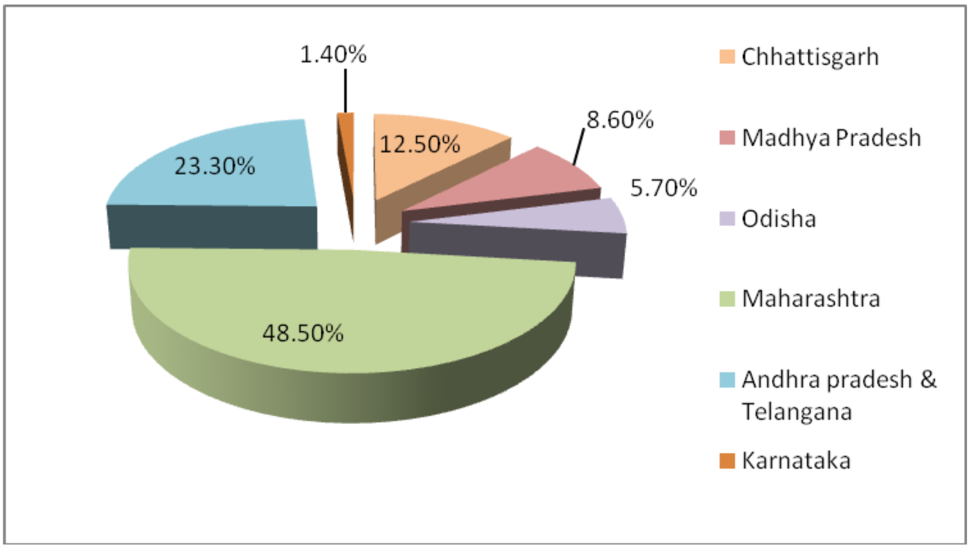


Figure 3.18 Percentage area of Godavari basin in various States

Godavari is a perennial and the second largest river draining in India. Godavari River originates near Trayambakeswar near Nasik, northeast of Mumbai in the state of Maharashtra at an elevation of 1,067 m and flows for a length of about 1,465 km before joining the Bay of Bengal. It flows through the Eastern Ghats and emerges out at Polavaram into the plains. At Dhawaleswaram the river divides into two branches, the Gautami and Vasishta. Between the two lies the Godavari Central Delta. Pranahita, Manjeera, Sabari, Indravati, Maner and Manar are the main tributaries of the Godavari River. The Godavari basin receives major part of its rainfall during the South-West monsoon period. The other rainy seasons are not so well defined and well spread as the South-West monsoon season. Floods are the regular phenomenon in the basin. Bhadrachalam, Kunavaram, and Deltaic portion of the river are more flood-prone.

Rainfall: Rainfall varies both spatially and temporally in Godavari Basin. Annual rainfall of the basin varies from 877 mm to 1,493 mm. The mean annual rainfall (1985-2015) in the Godavari basin is 1,117 mm.

Climate: The Godavari basin has a tropical climate. The temperature varies from 20^{o}C to 35^{o}C in a year which causes lot of monthly variations in the potential evapotranspiration in the basin. Minimum potential evapotranspiration in the basin is 30 to 100 mm during January/February and maximum goes up to 400 mm to 450 mm during April/May months.

3.6.4 Krishna

The Krishna basin extends over an area of 2,59,439 sq.km, which is nearly 7.9% of the total geographical area of the country. Krishna basin lies in the states of Maharashtra (26.60%), Karnataka (43.80%), Telangana (19.80%) and Andhra Pradesh (9.80%) (Figure 3.19). The river Krishna is a perennial river and second largest eastward draining interstate river in Peninsular India. The river rises from the Western Ghats near Jor village of Satara district of Maharashtra at an altitude of 1337 m just north of Mahabaleshwar. The total length of river from origin to its outfall into the Bay of Bengal is 1400 km. Its principal tributaries joining from right are the Ghatprabha, the Malprabha, the Koyna, the Varna, the Panchganga, the Dudhganga and the Tungabhadra whereas the Bhima, the Khagna, the Musi and the Munneru are principal tributaries joining the river from left. The Krishna basin receives major part of its rainfall during the South-West monsoon period. Around 70% of the rainfall takes place during July to September months. The other rainy seasons are not so well defined and well spread as the South-West monsoon season.

Rainfall: Rainfall varies both spatially and temporally in Krishna basin. Annual rainfall of the basin varies from 604 mm to 1,045 mm and the mean annual rainfall (1985-2015) in the Krishna basin is 841 mm. Many times basin receives high rainfall in less duration causing floods in those years.

Climate: The Krishna basin has a tropical climate. The mean monthly maximum and minimum temperature is about 32.1°C and 26.5°C in the basin respectively. Temperatures in the coastal region are moderate but humidity is higher.

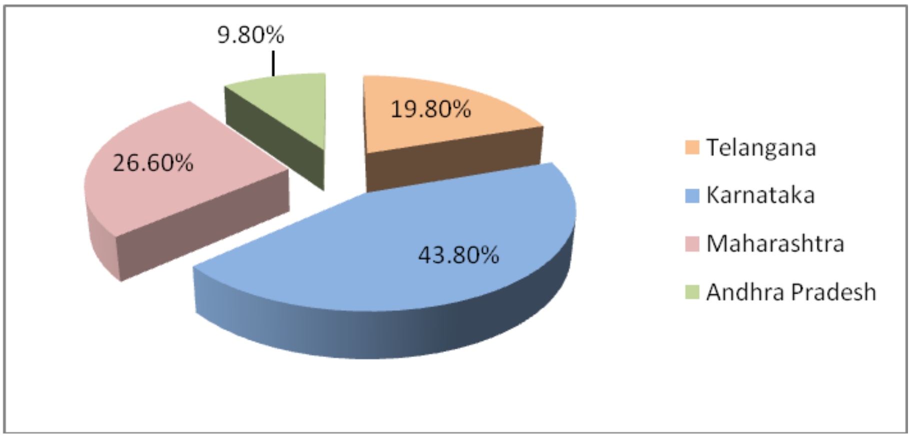


Figure 3.19 Percentage area of Krishna basin in various States

3.6.5 Cauvery

The river Cauvery is biggest river in south India. It rises at Talakaveri on the Brahmagiri range in the Western Ghats in Karnataka at an elevation of about 1,341 m above Mean Sea Level and flows for about 800 km, before its outfall into the Bay of Bengal. The Cauvery river system consists of 21 principal tributaries each with catchment area around 250 sq.km.

The Cauvery basin extends over states of Tamil Nadu (55.28%), Karnataka (41.24%), Kerala (3.26%) and Union Territory of Puducherry (0.22%), draining an area of 85,167 sq.km *(GIS Calculated as per India-WRIS Database)* which is nearly 2.59% of the total geographical area of the country with a maximum length and width of about 560 km and 245 km, respectively. Out of this, 41.24% area lies in Karnataka, 55.28% area in Tamil Nadu, 0.22% in Puducherry and 3.26% in Kerala (Figure 3.20). The total length of the river Cauvery from the head to its outfall into the sea comprises a length of 320 km in Karnataka, 416 km in Tamil Nadu and remaining length of 64 km forms the common boundary between states of Karnataka and Tamil Nadu. Its principal tributaries are Shimsa, Arkavathi, Hemavathi, Kabini, Amravati, Noyil and Bhavani.

Rainfall: The rainfall in the basin varies from region to region. The normal annual rainfall in Kerala region is about 2,400 mm. In the Western Ghats it ranges from 1,700 mm to 3,800 mm. In Karnataka for the Cauvery basin, the average rainfall is between 600 mm to 800 mm resulting into semi-arid condition. In Tamil Nadu, under the Cauvery basin the average rainfall is low ranging from 500 mm to 1000 mm and is semi-arid. In general, the highest rainfall in the Cauvery basin usually occur in July or early August and the mean annual rainfall (1985-2015) is around 949 mm.

Climate: The Cauvery basin has a tropical and sub-tropical climate. The average annual monthly maximum temperature is about 30.56°C and average annual minimum temperature is about 20.21°C in the basin. Temperatures in the coastal region are moderate but humidity is higher.

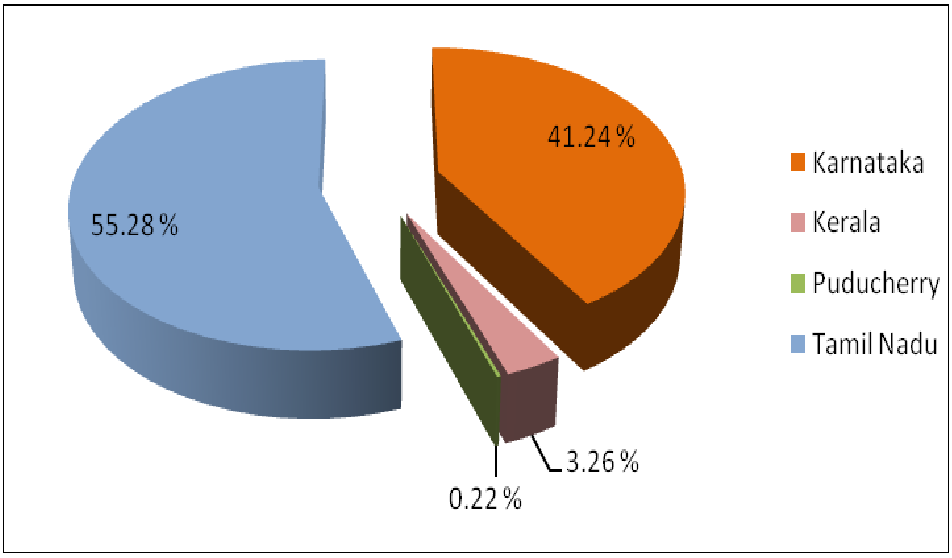


Figure 3.20 Percentage area of Cauvery basin in various States

3.6.6 Subernarekha

The Subernarekha (Including Burhabalang) basin extends over an area of 26,804 sq.km which is nearly 0.82% of the total geographical area of the country. The basin covers the states of Jharkhand (48.87%), Odisha (37.31%) and West Bengal (13.82%) (Figure 3.21). The river Subernarekha is one of the longest east flowing interstate rivers. It originates near Nagri village in Ranchi district of Jharkhand at an elevation of 600 m. The total length of river is about 395 km. The principal tributaries of the river are Kanchi, Kharkai and Karkai. Subernarekha river is situated in the North-East corner of peninsular India. It is bounded on the North-West by the Chhotnagpur Plateau, in the South-West by Brahmani basin, in the South by Burhabalang basin and in the South-East by the Bay of Bengal. The basin is generally influenced by the South-West monsoon, which onsets in the month of June and extends up to October. The mean annual rainfall of the basin is around 1451.5 mm.

Rainfall: Rainfall varies both spatially and temporally in Subernarekha basin. Annual rainfall of the basin varies from 1007 mm to 1810 mm. The mean annual rainfall (1985-2015) in the Subernarekha basin is 1427 mm. Many times basin receives high rainfall in less duration causing floods in those years.

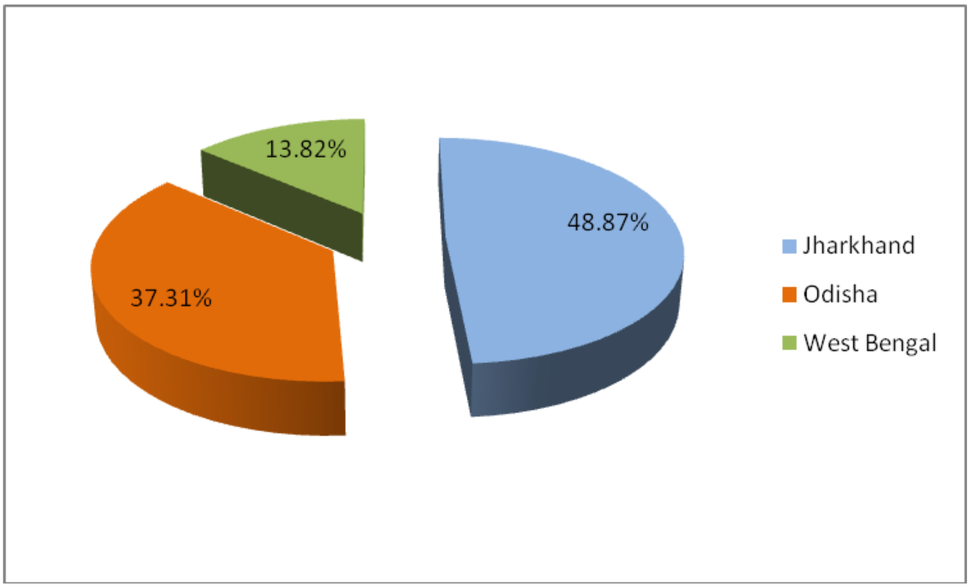


Figure 3.21 Percentage area of Subernarekha basin various States

Climate: The Subernarekha basin has a tropical climate with hot summers and mild winters. Mean monthly maximum and minimum temperature varies from 27°C to 25°C in the basin (2004-05).

3.6.7 Brahmani-Baitarani

The combined Brahmani-Baitarani river basin extends over a geographical area of 53,902 sq.km and the basin is bounded on the north by the Chhotanagpur Plateau, on the west and south by the ridge separating it from Mahanadi basin and on the east by the Bay of Bengal. Through intersection of state administrative boundaries and basin boundary (derived for the present study) state-wise drainage areas are computed. The drainage area of the basin lies in the states of Odisha (33,923 sq.km.), Jharkhand (15,479 sq.km.) and Chhattisgarh (1,367 sq.km.). Out of the total basin area, major part of 66.82% is covered in Odisha, 30.49% in Jharkhand and 2.69% in Chhattisgarh (Figure 3.22). The basin is bounded by 20^{o} 29' 00" to 23^{o} 37' 47" North latitude and 83^{o} 53' 49" to 87^{o} 1' 27" East longitude.

Rainfall

Rainfall varies both spatially and temporally in Brahmani-Baitarani basin. Annual rainfall of the basin varies from 1,108 mm to 1,452 mm. The mean annual rainfall (1985-2015) in the basin is 1,456 mm. Rainfall varies both spatially and temporally in the Brahmani-Baitarani basin.

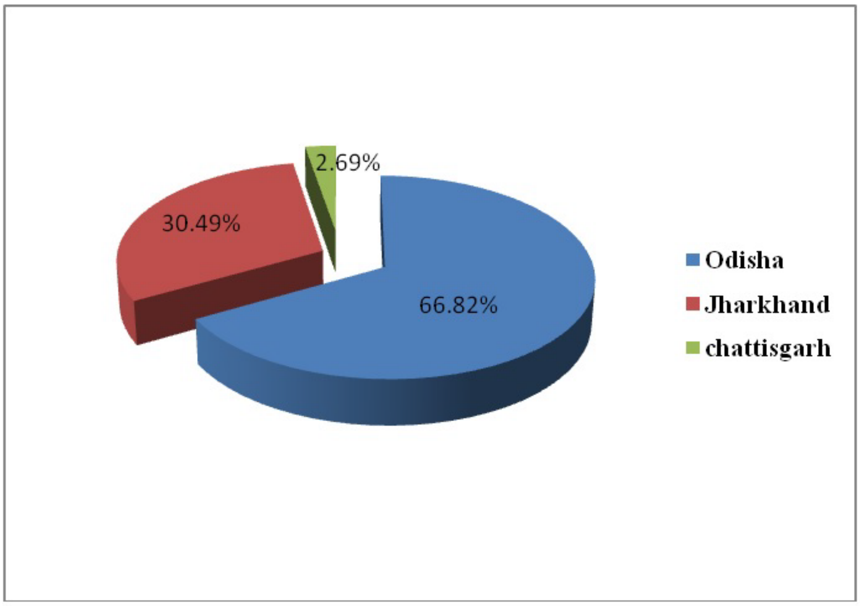


Figure 3.22 Percentage area of Brahmani - Baitarani basin in various States

Climate

In Brahmani-Baitarani basin, maximum temperature rises to 47°C during summer while the minimum during winter may be as low as 4°C. Temperatures in the coastal region are moderate but humidity is higher.

3.6.8 Mahanadi

The Mahanadi basin extends over states of Chhattisgarh (52.94%) and Odisha (46.33%) and comparatively smaller portions of Jharkhand (0.46%), Maharashtra (0.18%) and Madhya Pradesh (0.09%), draining an area of 1,44,905 sq.km which is nearly 4.4% of the total geographical area of the country (Figure 3.23). The geographical extent of the basin lies between 80°28' and 86°43' East longitudes and 19°8' and 23°32' North latitudes. The basin has maximum length and width of 587 km and 400 km. It is bounded by the Central India hills on the north, by the Eastern Ghats on the south and east and by the Maikala range on the west. The Mahanadi is one of the major rivers of the country and among the peninsular rivers, in water potential and flood producing capacity, it ranks second to the Godavari. It originates from a pool, 6 km from Farsiya village of Dhamtari district of Chhattisgarh. The total length of the river from origin to its outfall into the Bay of Bengal is 851 km. The Seonath, the Hasdeo, the Mand and the Ib joins Mahanadi from left whereas the Ong, the Tel and the Jonk joins it from right. Six other small streams between the Mahanadi and the Rushikulya draining directly into the Chilka Lake also forms the part of the basin. The major part of basin is covered with agricultural land accounting to 54.27% of the total area and 4.45% of the basin is covered by water bodies. The Mahanadi basin receives major part of its rainfall during the South-West monsoon period. Around 70% of the rainfall takes place during July to September months. The other rainy seasons are not so well defined and well spread as the South-West monsoon season.

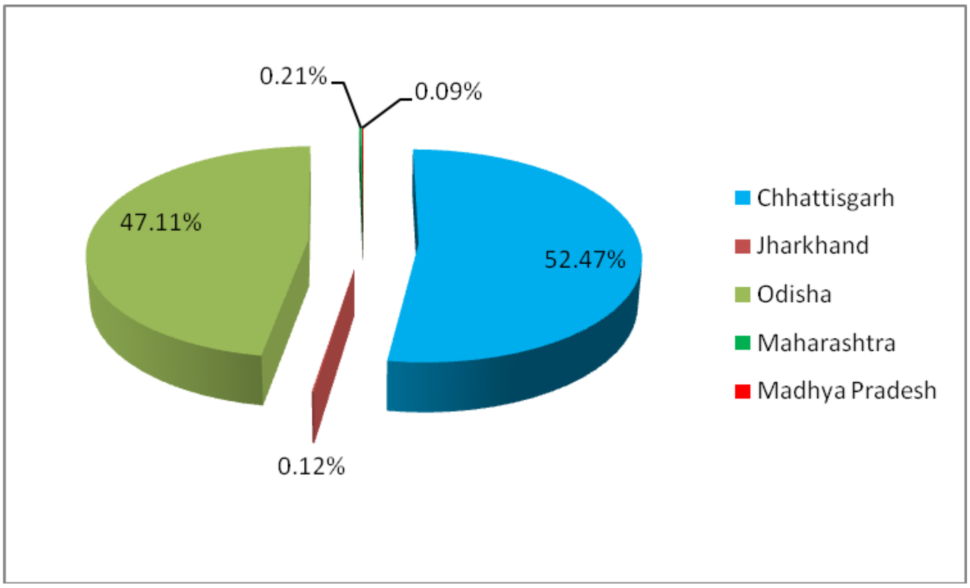


Figure 3.23 Percentage area of Mahanadi basin in various States

Rainfall: Rainfall varies both spatially and temporally in Mahanadi Basin. Annual rainfall of the basin varies from 923 mm to 1905 mm. The average annual rainfall (1985-2015) in the Mahanadi basin is 1317 mm .

Climate: The Mahanadi basin has a sub-tropical climate. The mean monthly maximum and minimum temperature is about 29°C and 21°C in the basin respectively. Temperatures in the coastal region are moderate but humidity is higher.

3.6.9 Pennar

The Pennar River (also known as Uttara Pinakini) is one of the major East Flowing Rivers in southern India. It rises in the Chenna Kasava hill of the Nandidurg range in Karnataka, flows in the North Westerly direction through Kolar and Tumkur districts of Karnataka and enters Andhra Pradesh in the Hindupurtaluk of Anantapur district, runs eastwards before draining into the Bay of Bengal near Nellore. The Somasila is major project in the catchment area of the river basin. Located in peninsular India, the Pennar basin extends over states of Andhra Pradesh and Karnataka having an area of 54,905 sq.km which is nearly 1.67% of the total geographical area of the country with maximum length and width of 433 km and 266 km (Figure 3.24). The basin lies between 77°1' to 80°10' East longitudes and 13°18' to 15°49' North latitudes. The fan shaped basin is bounded by the Erramala range on the north, the Nallamala and Velikonda ranges of the Eastern Ghats on the east, the Nandidurg hills on the south and the narrow ridge separating it from the Vedavati valley of the Krishna basin on the west. The other hill ranges in the basin to the south of the river are the Seshachalam and Paliconda ranges.

The total length of the river from origin to its outfall in the Bay of Bengal is 597 km. The principal tributaries of the river joining from left are the Jayamangali, the Kunderu and the Sagileru whereas the Chitravathi, the Papagni and the Cheyyeru join it from right.

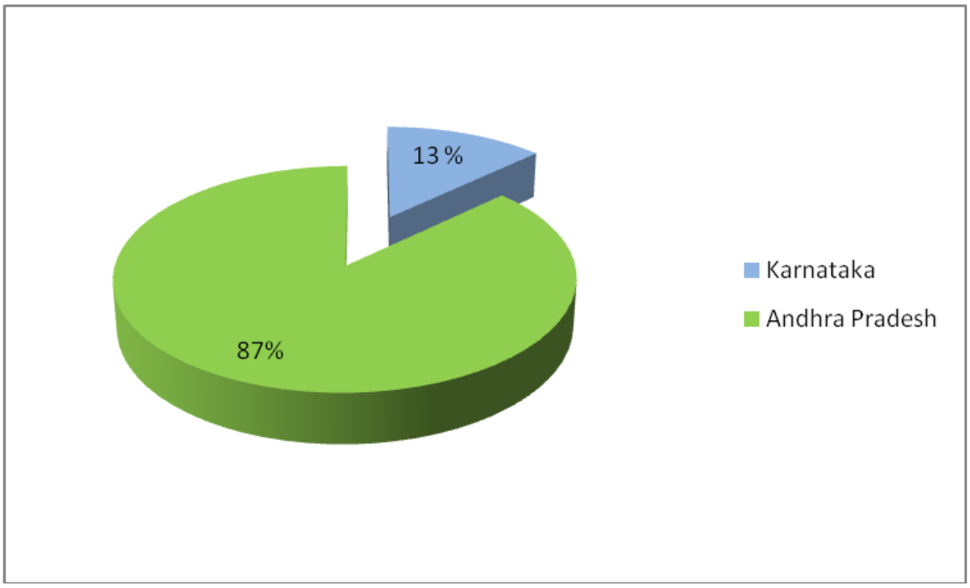


Figure 3.24 Percentage area of Pennar basin in various States

Rainfall: The entire basin lies largely in a semi-arid region with low rainfall. The annual average rainfall is highest in Nellore region in the Eastern end of the basin. A large part of the basin lying in the region of Karnataka and Anantapur, Kurnool and Cuddapah districts of Andhra Pradesh receives rainfall ranging from 400-800 mm. Parts of Nellore district, adjacent to the sea-coast receive some rain from the retreating monsoon also. Mean annual rainfall of the study time period is 716 mm for the basin.

Climate: As far as the temperature is concerned, the annual average maximum, minimum and mean temperature for the basin for the years from 1969 to 2004 is found to be 32.71°C, 21.63°C and 27.17°C respectively.

3.6.10 Mahi

The Mahi basin extends over an area of 39,566 sq.km. (which includes the independent Dhadhar basin having as area of 4,131 sq.km), and is nearly 1.2% of the total geographical area of the country. The basin lies in the states of Rajasthan (42.05%), Gujarat (39.91%), and Madhya Pradesh (18.04%) (Figure 3.25). River Mahi is the major inter-state west flowing river of India. The river is rising from the northern slopes of the Vindhyas near the village of Sardarpur in the Dhar district of Madhya Pradesh at an elevation of about 500 m and draining in to the gulf of Khambhat. Before falling in to Arabian Sea through the Gulf of Khambhat in Kheda district of Gujarat, the river flows about 538 km through Madhya Pradesh, Rajasthan and Gujarat states. The major tributaries of river are Som, Anas and Panam. The Mahi basin receives major part of its rainfall during South-West monsoon, that to in the months of July and August. The other rainy seasons are not so well defined and well spread as the South-West monsoon season. Mean annual rainfall of the study time period is 811 mm for the basin.

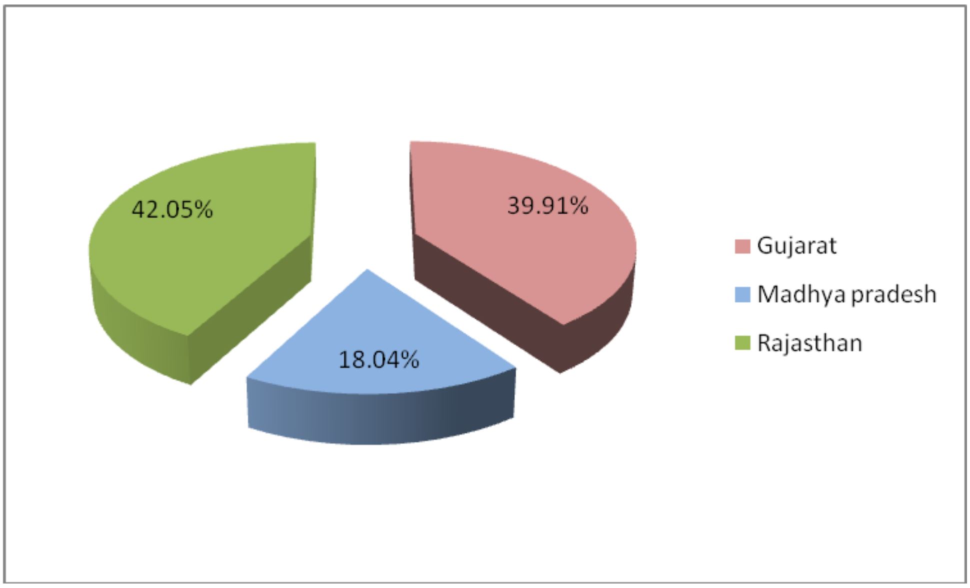


Figure 3.25 Percentage area of Mahi basin in various States

Rainfall: Rainfall varies both spatially and temporally in Mahi basin. The mean rainfall of these 30 years is found to be 811 mm. When spatial variations are considered, some areas receive 405 mm and some other areas receive 1,366 mm annual rainfall for year 2004-05. Major part of the basin receives an annual rainfall of 500 mm to 1,000 mm.

Climate: The mean annual temperature in Mahi basin varied from 25.00^{o}C to 27.44^{o}C in 2004-05.

3.6.11 Sabarmati

The Sabarmati River is one of the major west flowing inter-state rivers in India draining into the Gulf of Khambhat. The Sabarmati river originates in the Aravalli hills at latitude 240^{0} 40’ North and longitude 73^{o} 20’ East in the State of Rajasthan at an elevation of 762 m above Mean Sea

Level. The basin is bounded by Aravalli hills in the North and north-east, ridge separating it from Minor streams which are flowing into the Rann of Kutch in the west and Gulf of Khambhat in the south. The total catchment area of the Sabarmati basin extends over an area of 31,901 sq.km and is nearly 0.97% of the total geographical area of the country. The basin lies in the states of Rajasthan and Gujarat and have a drainage area of 4126.2 sq.km (12.93%) and 27,775 sq.km (87.07%) respectively (Figure 3.26). Before falling in to Arabian Sea through the Gulf of Khambhat in Kheda district of Gujarat, the river flows about 371 km through Rajasthan (48 km) and Gujarat states (323 km). The major tributaries of the Sabarmati are Sei, Wakal, Harnav, Hathmati and Watrak. The Sabarmati basin receives major part of its rainfall during South-West monsoon, in the months of July and August. The other rainy seasons are not so well defined and well spread as the South-West monsoon season. Mean annual rainfall of the study time period is 727 mm for the basin.

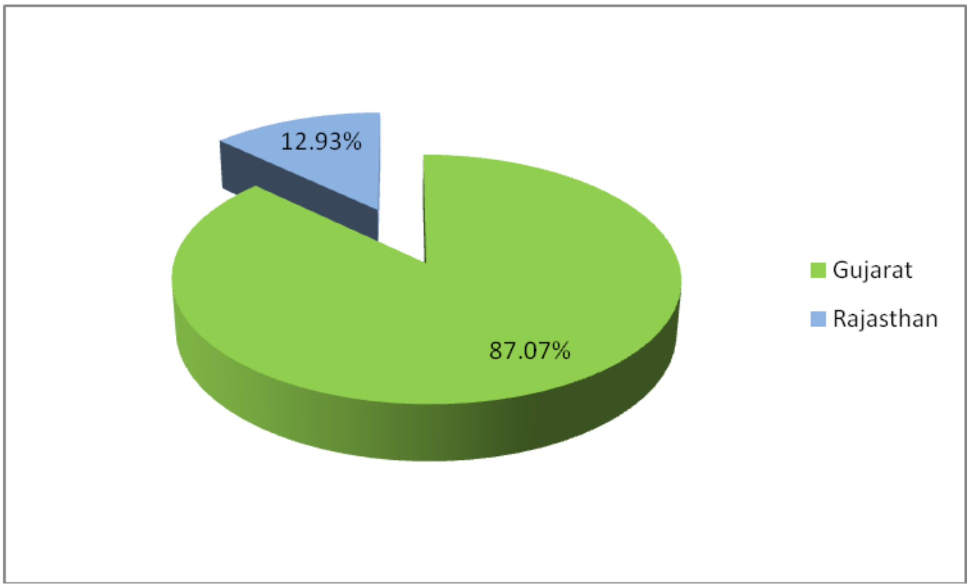


Figure 3.26 Percentage area of Sabarmati basin in various States

3.6.12 Narmada

The Narmada basin extends over an area of 97,162 sq.km, which is nearly 2.96% of the total geographical area of the country. The basin lies in the states of Madhya Pradesh (86.9%), Gujarat (11.60%) and Maharashtra (1.50%) (Figure 3.27). The Narmada originates from a Kund (spring) at an elevation of 1057 m at Amarkantak in the Maikal hill in Shahdol district of Madhya Pradesh and flows through Madhya Pradesh, Maharashtra and Gujarat between Vindhya and Satpura hill ranges before falling into the Gulf of Cambay in the Arabian Sea, about 10 km north of Bharuch, Gujarat. The total length of this west flowing river from its origin to its outfall into the Arabian Sea is 1312 km. For the first 1079 km, it flows in Madhya

Pradesh and thereafter forms the common boundary between Madhya Pradesh and Maharashtra for 35 km, and Maharashtra and Gujarat for 39 km. In Gujarat State it stretches for 159 km. There are 41 important tributaries to the Narmada. Significant among them are Burhner, Banjar, Hiran, Tawa, Chhota Tawa, Orsang and Kundi which are major tributaries having catchment area more than 3500 sq.km. The remaining tributaries are having catchment area ranging from 500 to 2500 sq.km. The Narmada basin receives major part of its rainfall during the South-West monsoon period. The other rainy seasons are not so well defined and well spread as the South-West monsoon season. Mean annual rainfall of the study time period is 1,045 mm for the basin.

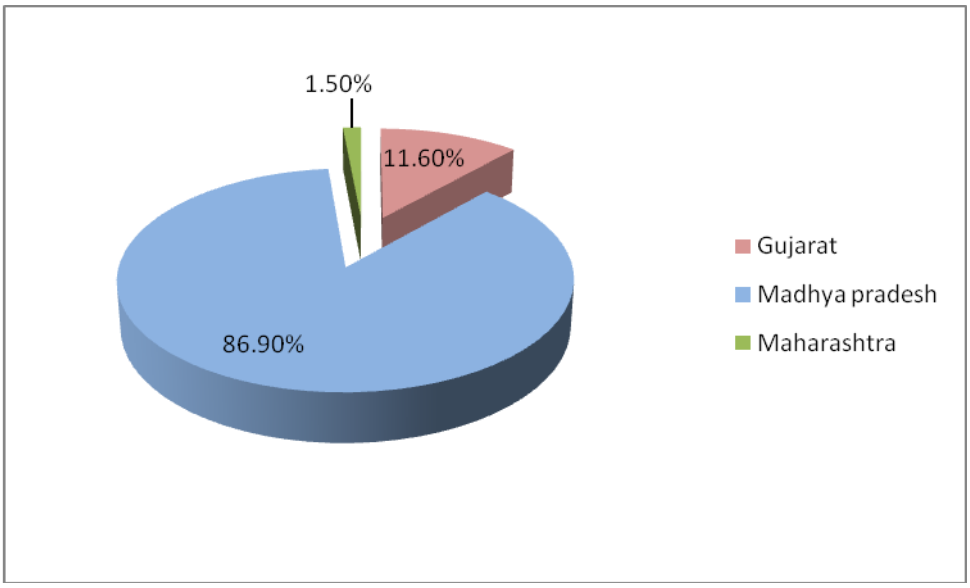


Figure 3.27 Percentage area of Narmada basin in various States

3.6.13 Tapi

The Tapi basin extends over states of Maharashtra (77.38%), Madhya Pradesh (14.21%) and Gujarat (8.41%) and having an area of 65,806 sq.km of 65805 sq. km which is nearly 2% of the total geographical area of the country, with a maximum length and width of 534 and 196 km (Figure 3.28). It lies between 72°33' to 78°17' East longitudes and 20°9' to 21°50' North latitudes. Situated in the Deccan plateau, the basin is bounded by the Satpura range on the north, the Mahadev hills on the east, the Ajanta Range and the Satmala hills on the south and the Arabian Sea on the west. The hilly region of the basin is well forested while the plains are broad and fertile areas suitable for cultivation. The Tapi is the second largest westward draining river of the Peninsula. It originates near Multai reserve forest in Betul district of Madhya Pradesh at an elevation of 752 m. The total length of the river from origin to outfall into the Arabian Sea is 724 km and its important tributaries are the Suki, the Gomai, the

Arunavati and the Aner which joins it from right, and those joining from left are the Vaghur, the Amravati, the Buray, the Panjhra, the Bori, the Girna, the Purna, the Mona and the Sipna. The major part of basin is covered with agriculture accounting to 66.19% of the total area. 2.99% of the basin is covered by water bodies. Mean annual rainfall of the study time period is 839 mm for the basin.

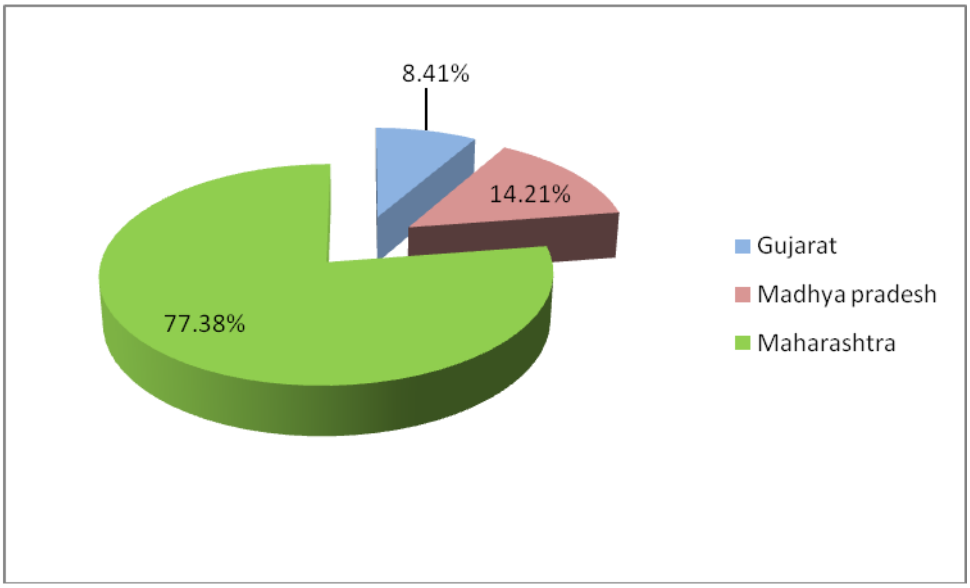


Figure 3.28 Percentage area of Tapi basin in various States

3.6.14 West Flowing Rivers from Tapi to Tadri

The composite basin extends over an area of 58,360 sq.km, which is nearly 1.77 % of the total geographical area of the country. The basin lies in the states of Maharashtra (57.01%), Karnataka (18.99%), Gujarat (16.94%), Dadar & Nagar Haveli (0.84%) and Goa (6.22%) (Figure 3.29). Being a coastal basin, the various rivers of basin do not meet into one major stream; rather they flow independently and drain directly into the Arabian Sea. The independent rivers in the basin are Purna, Ambika, Damanganga, Vaitarna, Ulhas, Amba, Savitri, Vashishti, Kajvi, Vaghotan, Gad, Mandavi, Kalinadi, Gangavali (Bedti) and Tadri. Mean annual rainfall of the study time period is 2,661 mm for the basin.

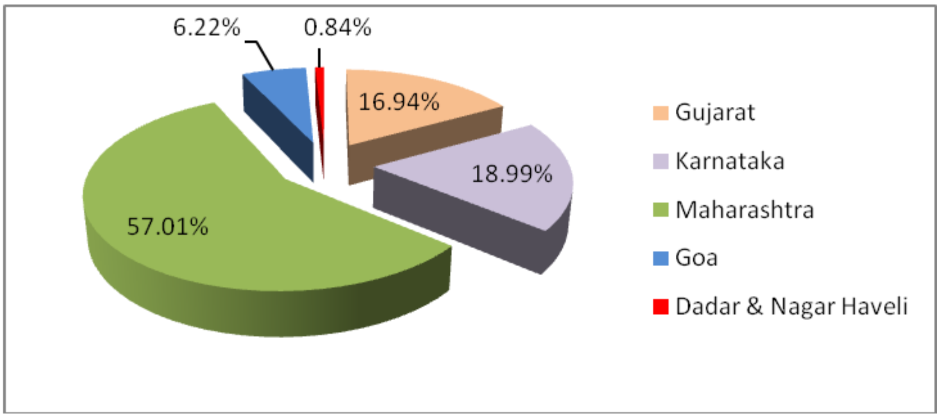


Figure 3.29 Percentage area of WFR from Tapi to Tadri basin in various States

3.6.15 West Flowing Rivers from Tadri to Kanyakumari

The composite basin extends over the states of Kerala (63%), Karnataka (28%), Tamil Nadu (8%), and Union Territory of Puducherry (1%) (Figure 3.30). It has an area of 54,231 sq.km which is 1.66% of total geographical area of the country, with a maximum length and width of 777 km and 135 km respectively. The basin is divided into nine sub-basins namely Gurpur, Netravati, Valapatanam, Chaliyar, Bharathapuzha, Periyar, Pamba, Kallada, and Others (ungauged portion of composite basin). There are 54-river systems in the basin. The total river length is about 98,395 km. The major independent rivers (directly draining into Arabian Sea) in the basin having length more than 150 km are Bharathapuzha, Periyar, and Pamba. The basin falls into three Agro-Climatic Zones and three Agro-Ecological Zones. As per LULC statistics (2014-15), major part (52.80%) of the basin is covered with agricultural land. Forest cover in the basin is about 37.90% of the total basin area. The basin is bounded by Sahyadri hills on the north, the Western Ghats on the east, Indian Ocean on the south, and the Arabian Sea on the west. The mean annual rainfall in the composite basin during 1985-2015 is 2854 mm. The sub-basins namely Chaliyar, Bharathapuzha, Periyar, and Kallada have lesser rainfall as compared to sub-basins like Gurpur,Netravati, Valapatanam, Pamba, and others. Mean annual rainfall of the study time period is 2773 mm for the basin.

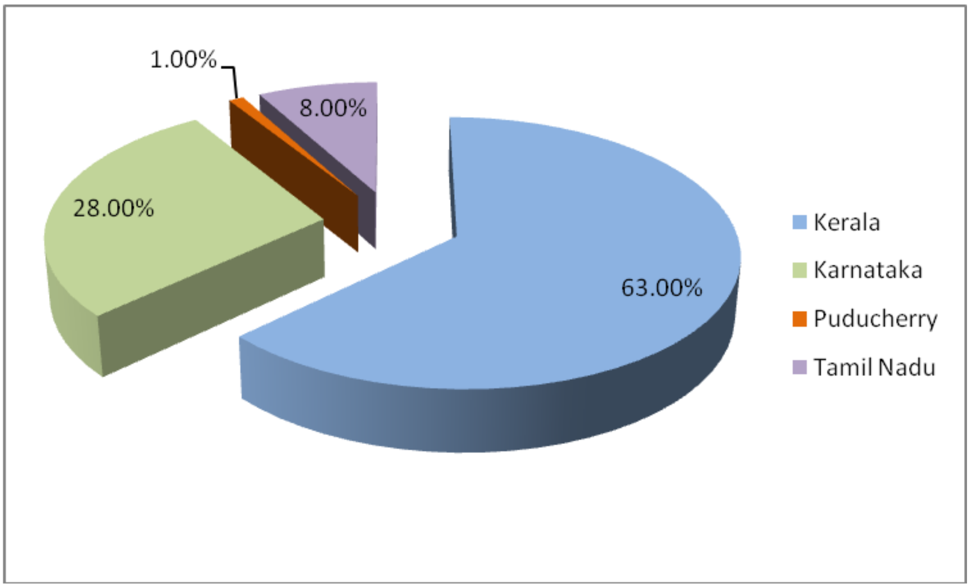


Figure 3.30 Percentage area of WFR from Tadri to Kanyakumari basin in various States

3.6.16 East Flowing Rivers between Mahanadi and Pennar

The composite basin extends over an area of 82,073 sq.km. and is nearly 2.50% of the total geographical area of the country. The basin lies in the states of Andhra Pradesh (71.00%), Odisha (28.00%), and Telangana (1.00%) and stretches between 78°40' to 85°1' East longitudes and 14°34' to 20°22' North latitudes (Figure 3.31). It is bounded by the Eastern Ghats on the north and west, Nallamala Range and Andhra plains on the south and the Bay of Bengal on the east. This composite basin comprises of three river systems. The river systems between Mahanadi and Godavari covers an area of 49,685 sq.km and the river systems between Krishna and Pennar extends over an area of 24,669 sq.km. In addition, there is also a small area between Godavari and Krishna drained mainly by the small stream of Palleru. This minor portion of the basin has an area of about 12,289 sq.km. The independent rivers (directly draining into Bay of Bengal) in the basin from north to south are the Rushikulya, the Bahuda, the Vamsadhara, the Nagavali, the Sarada, the Varaha, the Tandava, the Eluru, the Gundlakamma, the Musi, the Paleru and the Manneru. The major part of basin is covered with agricultural land accounting to 59.85% of the total area and 3.66% of the basin is covered by water bodies.

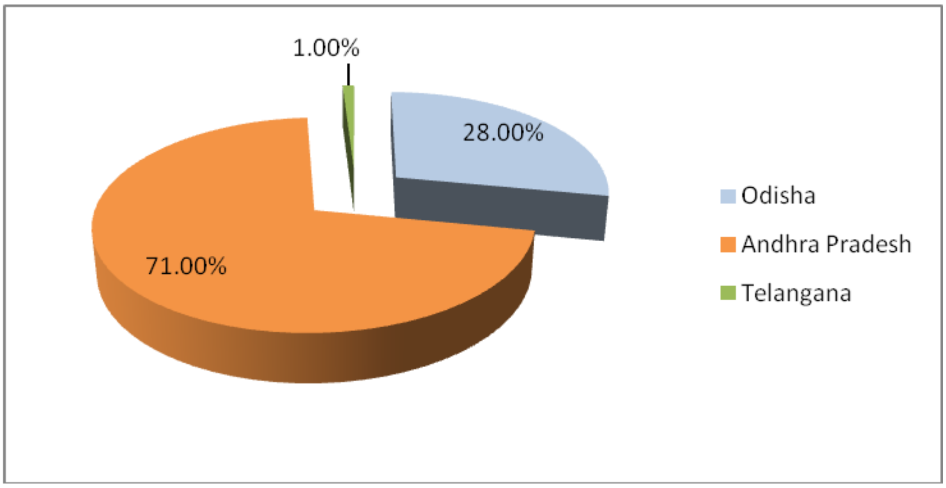


Figure 3.31 Percentage area of EFR between Mahanadi and Pennar basin in various States

Rainfall: The mean annual rainfall (1985-2015) in the composite basin is 1,144 mm. The South-West monsoon sets in by the middle of June and withdraws by the first week of October. About 90% of total rainfall is received during the monsoon months of which 50% is received during July and August.

Climate: The composite basin has a sub-tropical climate. The average annual monthly maximum temperature is about 29°C and average annual minimum temperature is about 21°C in the basin. Temperatures in the coastal region are moderate but humidity is higher.

3.6.17 East Flowing Rivers between Pennar and Kanyakumari

The composite basin comprises the river systems between Pennar and Kanyakumari having an area of 1,01,657 sq.km. The basin lies in the states of Tamil Nadu (77.45%), Andhra Pradesh (15.83%), Karnataka (6.37%), Puducherry (0.29%) and Kerala (0.06%) (Figure 3.32). The independent rivers (directly draining into Bay of Bengal) are the Kandleru, the Swarnamukhi, the Arani, the Korttalaiyar, the Cooum, the Adyar, the Palar, the Gingee, the Ponnaiyar, the Vellar, the Varshalei, the Vaigai, the Gundar, the Vaippar and the Tambraparni. The basin comprises four sub-basins viz. Vaippar and others sub-basin, the Palar and other sub-basin, Pamba and others sub-basin and Ponnaiyar and other sub-basin.

Pennar to Cauvery part of this basin is bounded on the north, west and south by the various ranges of the Eastern Ghats. These are the Velikonda Range, the Nagari Hills, the Javadi Hills, the Shevaroy Hills, the Chitteri Hills, the Kalrayan Hills, the Kollaimalai Hills, the Pachai Malai Hills etc., and on the east by the Bay of Bengal. This basin area has a maximum length of about 290 km and a maximum width of about 360 km.

Cauvery to Kanyakumari basin area is bounded by the Varushanad hills, the Andippatti hills, the Cardamom hills and Palani hills on the west, the Indian Ocean on the south, the Palk-Strait, Palk Bay and the Gulf of Mannar on the east and the ridge, which separates it from the Cauvery basin on the north. Shape of the area is irregular; it has a maximum length of 236 km in the northwest-southeast direction and a maximum width of 275 km in the northeast-South-West direction. Mean annual rainfall of the study time period is 960 mm for the basin.

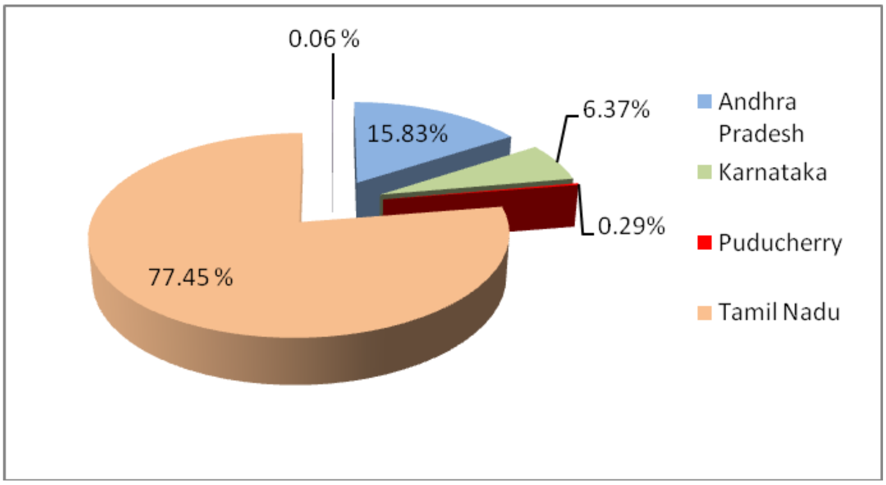


Figure 3.32 Percentage area of EFR from Pennar and Kanyakumari basin in various States

3.6.18 West Flowing Rivers of Kutch & Saurashtra including Luni

The composite basin extends over large areas in Rajasthan (39%) and Gujarat (61%) and covers whole of Diu having an area of 1,92,112 sq.km with maximum length and width of 865 km and 445 km (Figure 3.33). It lies between 67°52' to 75°19' East longitudes and 20°53' to 26°57' North latitudes. The basin is bounded by Aravalli range and Gujarat plains on the east, Rajasthan desert on north, and the Arabian Sea on the south and the west. Luni is the major river system of the basin and it originates from western slopes of the Aravalli ranges at an elevation of 772 m in Ajmer district of Rajasthan. The total length of the river is 511 km and it drains a total area of 32,879 sq.km. The river flows up to Rann of Kutch forming a delta where the water spreads out and does not contribute any runoff. The main tributaries of Luni joining from left are the Lilri, the Guhiya, the Bandi (Hemawas), the Sukri, the Jawai, the Khari Bandi, the Sukri Bandi and the Sagi whereas the Jojri joins it from right. Other independent rivers of the basin are the Shetrunji, the Bhadar, the Machhu, the Rupen, the Saraswati and the Banas. The Shetrunji drains into the Gulf of Khambhat, the Bhadar outfalls into Arabian Sea, and the Machhu, the Rupen, the Saraswati and the Banas drains into Little Rann of Kutch. The major part of basin is covered with agriculture accounting to 65.06% of the total area and only 5.25% of the basin is covered by water bodies. Mean annual rainfall of the study time period is 479 mm for the basin.

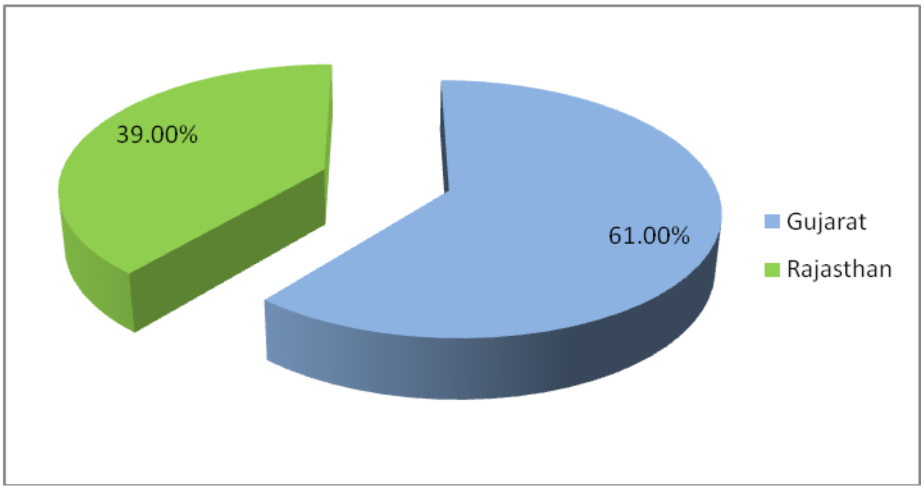


Figure 3.33 Percentage area of WFR of Kutch & Saurashtra including Luni basin in various States

3.6.19 Area of inland drainage in Rajasthan Desert

The composite basin extends over states of Haryana (13.21%) and Rajasthan (86.78%) and lies between 69°13' to 77°15' East longitudes and 25°31' to 29°44' north latitudes (Figure 3.34). The basin is having an area of 1,44,836 sq.km. It is bounded by the Punjab plains on the north and east, Aravalli range on the south and Thar Desert on the west. Small rivers draining into the basin are the Kantu, the Kakni, the Ghugri and the Sukri. The major part of basin is covered with agricultural land accounting to 64.15% of the total area and 0.4% of the basin is covered by water bodies. Mean annual rainfall is 302 mm (1985-2015) for the basin.

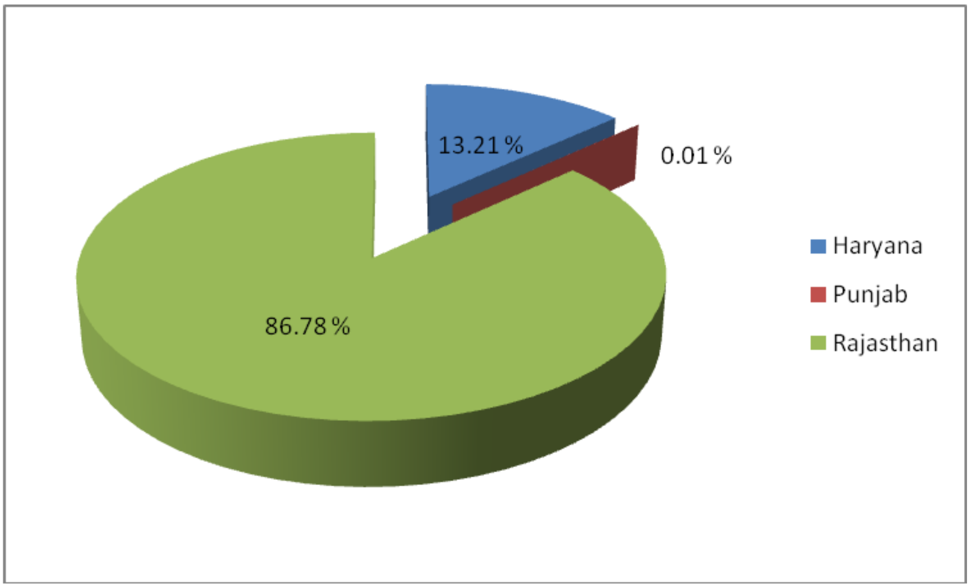


Figure 3.34 Percentage area of inland drainage in Rajasthan Desert

3.6.20 Minor rivers draining into Myanmar (Burma) and Bangladesh

The composite basin extends over states of Manipur (40%), Mizoram (39%), Nagaland (15%) and Tripura (6%) having a total area of nearly 31,382 sq.km and its geographical extent is between 91°33’ to 94°52’ East longitudes and 21°45’ to 26°40’ North latitudes (Figure 3.35). The basin is bounded by Purvanchal range in the north and the west and Bay of Bengal in the east and the south. The Imphal is the main river of the basin and it rises near Kangpokpi in Senapati district of Manipur and receives the Iril from the south and the Thoubal from the east. It also receives the Khuga from the south-west and is known as Manipur River below its confluence. The Chakpi River joins Imphal from the opposite direction 3 km below Shuganu and the combined water flows southward through a narrow gorge to fall into the Chindwin river of Burma. The major part of basin is covered with forest accounting to 71.64% of the total area and only 1.66% of the basin is covered by water bodies. Mean annual rainfall of the study time period is 1812 mm for the basin.

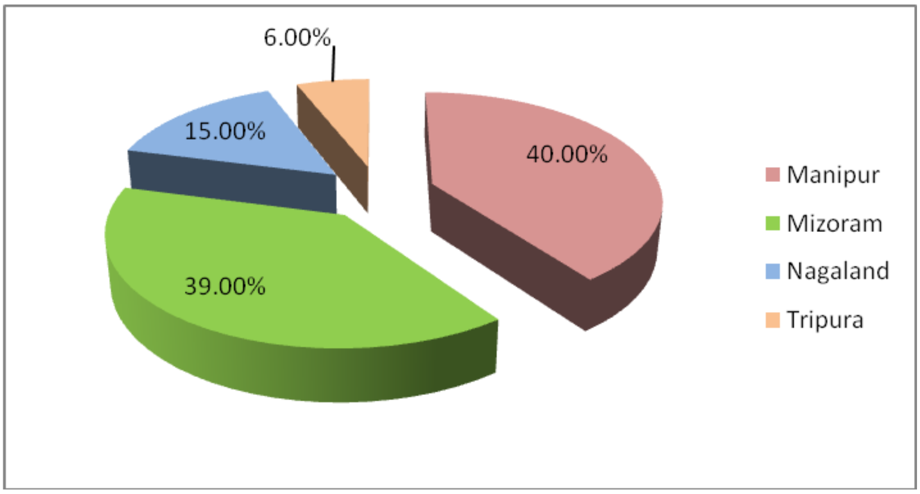


Figure 3.35 Percentage area of Minor rivers draining into Myanmar (Burma) and Bangladesh basin in various States

CHAPTER 4

WATER RESOURCES ESTIMATION

[This chapter summarizes extensive studies of the water resource availability of the twenty basins. The details of basin study can be found from individual reports available in separate volumes, Volume - I and Volume - II.]

4.1 General

Water resource estimation in the river basins of India has been carried out by water balance method over 30-year period of time (1985-2015). The main objective of the study has been to assess the current status and trends in water resource availability to strengthen water management, decision-making, by improving the validity of visions, scenarios and strategies. The basic water balance study was based on conservation of water mass in which within a specific area over a specific period of time, water inflows are equal to water outflows, plus or minus any change of storage within the area of interest. Putting more simply, the water entering an area has to leave the area or be stored within the area.

The discharge is estimated using the procedure as mentioned in methodology Section 3.5 of this report. The runoff that is estimated from each pixel at monthly time step is aggregated within each sub-basin. The monthly surface discharge was further aggregated to annual time step for all the sub-basins. The estimated discharge for each sub-basin is calibrated with observed discharge at annual scale. The model estimated discharge is calibrated against the observed discharge at G&D sites of CWC.

Water resources availability in a basin comprises the model runoff, Estimated Consumptive Irrigation Input (excess water in addition to rainfall), evaporation from reservoirs, and reservoir & groundwater fluxes.

The study of water balance modelling for reassessment of water availability of Indian basins has provided with a comprehensive understanding of the water flow system and water resources in the basins/sub-basins under consideration. Water resources availability during the study period has been computed and presented in the Table - 5. Figures 4.1 and 4.2 show the basin-wise water availability in India.

The average annual water resource of the basins is **1913.60 BCM**.

The assessment made by the first Irrigation Commission (1901-03) for all the river systems in India (as it was then but excluding Burma, Assam and East Bengal) was 1,443 km^3).

The assessment made in 1949 based on Khosla's formula was 1,673 km^3.

According to the study made by the Central Water and Power Commission during 1954-66 based on statistical analysis of flow data and on rainfall-runoff relationships as discussed in para 2.3, the water resources potential of 'the various river systems amounted to 1,881 km^3.

The CWC Publication No. 30/88 on "Water Resources of India" (1988) gives a compilation of the results of the assessment studies in respect of the twenty river basins as were available at that time with corrections for ground water abstractions, as discussed in para 2.4. According to this compilation, the water resources potential for the entire country worked out to 1,880 km^3.

Table - 5: Water Resources Availability of Indian Basins

Sl. No.	Basins	Catchment Area (sq.km)	Average Rainfall in Water Year (1985-2015) (BCM)	Water Resources Availability (BCM)	
				Average	(75% dependable)
1	2	3	4	5	6
1)	Indus (within India)	3,17,708	330	45.53	37.15
2)	Ganga- Brahmaputra-Meghna				
	a) Ganga	8,38,803	914	509.52#	471.76
	b) Brahmaputra	1,93,252	495	441.68@	385
	c) Barak & others	86,335	134	86.67	68.58
3)	Godavari	3,12,150	365	117.74	87.67
4)	Krishna	2,59,439	226	89.04	71.43
5)	Cauvery	85,167	81	27.67	22.62
6)	Subarnarekha	26,804	40	15.05	12.00
7)	Brahmani-Baitarani	53,902	83	35.65	25.00
8)	Mahanadi	1,44,905	200	73.00	49.00
9)	Pennar	54,905	40	11.02	5.95
10)	Mahi	39,566	35	14.96	9.14
11)	Sabarmati	31,901	25	12.96	8.92
12)	Narmada	96,659.79	108	58.21	45.24
13)	Tapi	65,805.80	59	26.24	21.23
14)	West Flowing Rivers from Tapi to Tadri	58,360	161	118.35	106.81

1	2	3	4	5	6
15)	West Flowing Rivers from Tadri to Kanyakumari	54,231	151	119.06	106.13
16)	East Flowing Rivers between Mahanadi and Pennar	82,073	97	26.41	17.41
17)	East Flowing Rivers between Pennar and Kanyakumari	1,01,657	98	26.74	18.21
18)	West Flowing Rivers of Kutch & Saurahtra including Luni	1,92,112	100	26.93	14.59
19)	Area of inland drainage in Rajasthan Desert	1,44,835.9	49	Negligible	Negligible
20)	Minor rivers draining into Myanmar (Burma) and Bangladesh	31,382	61	31.17	26.56
	Total	32,71,953*	3880	**1913.60****	

 # Without contribution from Nepal (17.24 BCM). Considering contribution from Nepal, Water Resources Availability in Ganga basin is 526.76 BCM comprising components viz. 197.22 BCM in Upper Ganga, 192.60 BCM in Lower Ganga and 136.94 BCM in Yamuna sub-basins.

@ Without contribution from Bhutan (63.50 BCM). Water Resources Availability in Brahmaputra basin i.e. 441.60 BCM comprises components viz. 418.67 BCM in Brahmaputra and 22.93 BCM in Teesta.

** Excluding area of Indus above border, Lakshadweep Island and Andaman and Nicobar group of islands.*
*** Excluding contribution from Nepal (17.24 BCM) and Bhutan (63.5 BCM).*

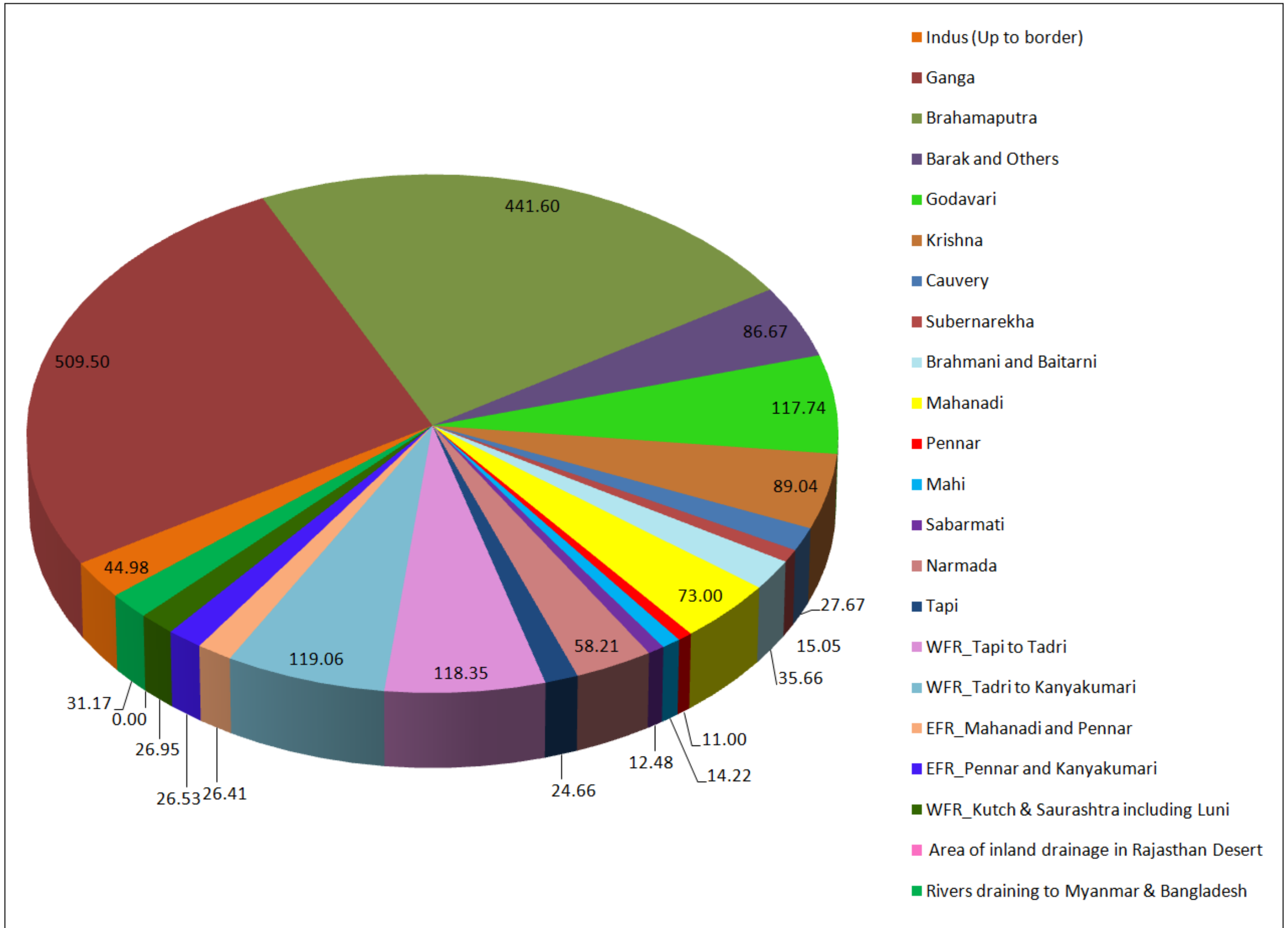


Figure 4.1 Water availability in various river basins of India

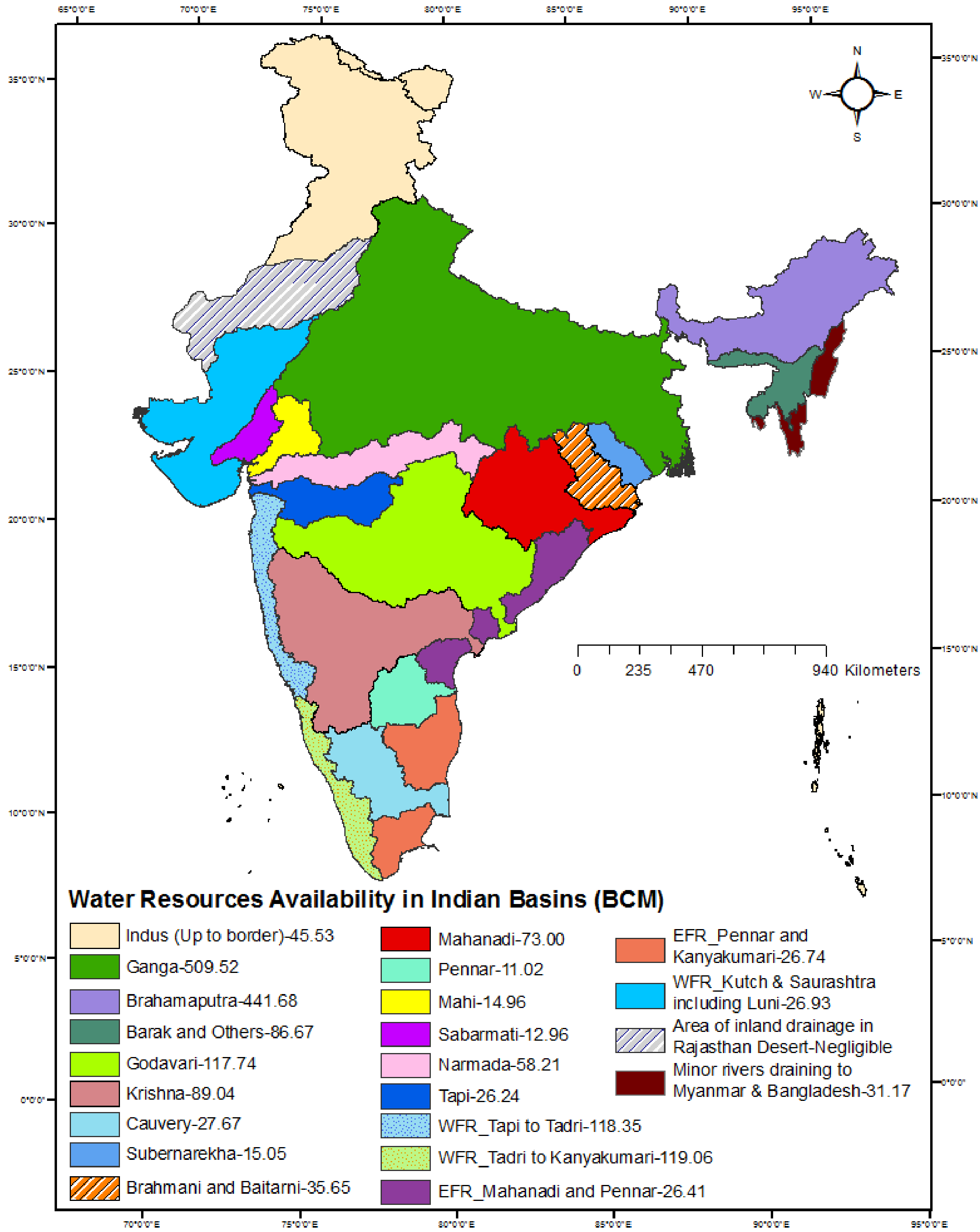


Figure 4.2 Map of basin-wise water availability in India

4.2 Discussions on the results of the study

The average annual water availability of the basins during the study period (1985-2015) is estimated as 1913.60 BCM where as the water potential assessed during the 1993 study is 1869.35 BCM excluding Teesta basin. The comparative figures of rainfall during the period 1955-2015 have been presented in Table - 6. The maximum and minimum rainfall during the present study period have been estimated as 1,255 mm (4,412 BCM, year 1990-91) and 889 mm (3,125 BCM, year 2002-03) respectively. The mean annual rainfall during the period of present study (1985-2015) is 3,880 BCM (1,105 mm) as compared to 3945 BCM (1,123 mm, period 1955-1984) and 3853 BCM (1,096 mm, period 1965-1984); the comparison is presented in Figures 4.3 and 4.4 respectively.

Table - 6: Comparative figures of rainfall during the period 1955-2015

Sl. No.	Basins	Average Rainfall in Water Year (1955-1984)		Average Rainfall in Water Year (1965-1984)		Average Rainfall in Water Year (1985-2015)	
		mm	BCM	mm	BCM	mm	BCM
1)	Indus (within India)	762	303	752	299	895	356
2)	Ganga- Brahmaputra-Meghna						
	a) Ganga	1069	978	1035	947	1007	914
	b) Brahmaputra	2589	551	2635	561	2330	495
	c) Barak & others	2462	126	2593	133	2625	134
3)	Godavari	1122	365	1062	346	1117	365
4)	Krishna	842	225	797	213	841	226
5)	Cauvery	957	82	948	81	949	81
6)	Subarnarekha	1412	40	1408	40	1427	40
7)	Brahmani-Baitarani	1407	80	1369	78	1456	83
8)	Mahanadi	1311	200	1237	189	1317	200
9)	Pennar	684	38	675	38	716	40
10)	Mahi	840	36	839	36	811	35
11)	Sabarmati	726	25	711	24	727	25
12)	Narmada	1133	117	1104	114	1045	108
13)	Tapi	876	61	838	58	839	59
14)	West Flowing Rivers from Tapi to Tadri	2664	161	2548	154	2661	161

15)	West Flowing Rivers from Tadri to Kanyakumari	3059	166	2929	159	2773	151
16)	East Flowing Rivers between Mahanadi and Pennar	1081	91	1035	88	1144	97
17)	East Flowing Rivers between Pennar and Kanyakumari	928	95	938	96	960	98
18)	West Flowing Rivers of Kutch & Saurashtra including Luni	482	100	465	96	479	100
19)	Area of inland drainage in Rajastahan Desert	317	51	305	49	302	49
20)	Minor rivers draining into Myanmar (Burma) and Bangladesh	1680	57	1733	58	1812	61
	Total	1123	3945	1096	3853	1105	3880

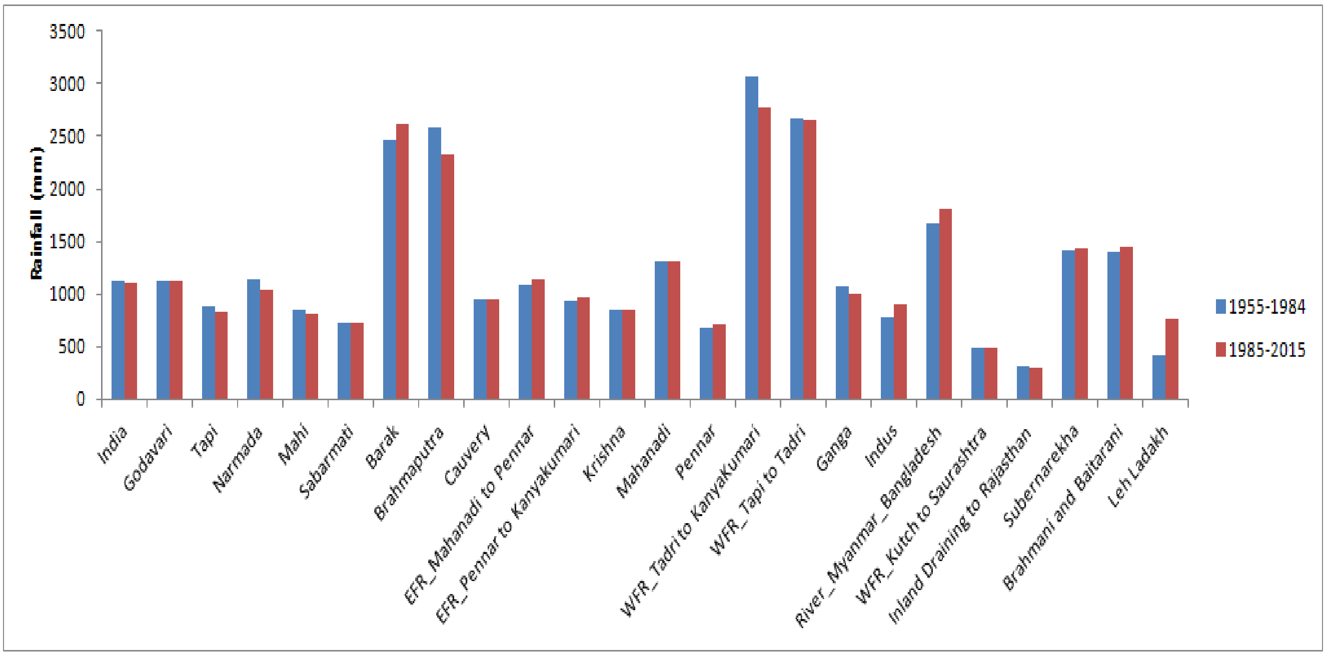


Figure: 4.3 Comparison of Rainfall (in BCM) between (1955-1984) and (1985-2015)

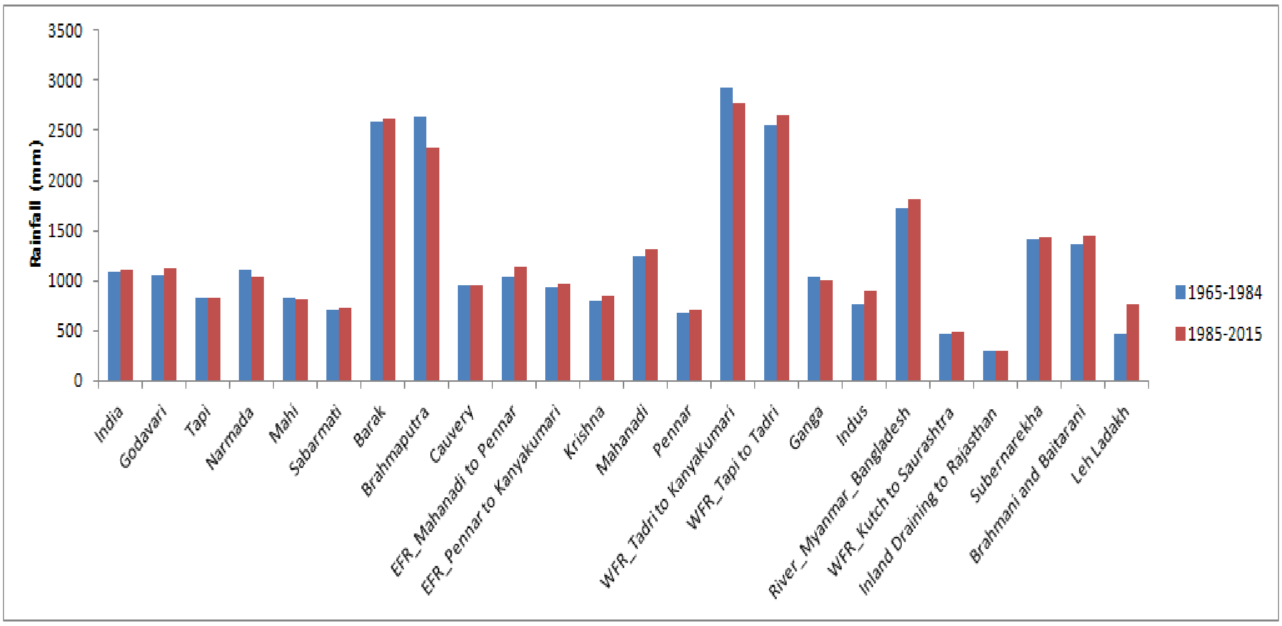


Figure: 4.4 Comparison of Rainfall (in BCM) between (1965-1984) and (1985-2015)

The total catchment area considered for the present study is 32,33,561 sq.km (excluding the areas of Indus above border, Lakshadweep Island and Andaman and Nicobar group of islands), whereas the area considered for the 1993 study is 32,30,368 sq.km.

In Table - 7 are given comparative figures of the water availability of the twenty basins as assessed in 1993 and as asessed now**.** There is reduction in water availability in basins viz. Indus (27.78 BCM), Ganga (15.5 BCM) and Brahmaputra (95.56 BCM). In rest of the basins, there is increase in water availability (avg. increase being 7.4 BCM) having largest increase in Barak and Others (38.31 BCM) and WFR from Tapi to Tadri (31.14 BCM).

There are variations in water availability in individual basins, but overall change being only an increase of 44.25 BCM. However, if contribution of Teesta Basin (22.93 BCM) is added to the 1993 study, the difference between the two studies is reduced to 21.32 BCM only. Therefore, it may be concluded that the present study corroborates the 1993 study. However, since the present study is based on the most advanced methodology, it generates more confidence in the results achieved.

Table - 7: Comparative figures of water availability assessed earlier and asasessed now

		1993 study		2017 (Present) study		
	Basins	Catchment Area (sq.km)	Average Water Potential (BCM)	Catchment Area (sq.km)	Average Rainfall in Water Year (1985-2015) (BCM)	Average Water Availability (BCM)
1	2	3	5	6	7	8
1)	Indus (within India)	3,21,289	73.31	3,17,708	330	45.53
2)	Ganga- Brahmaputra- Meghna					
	a) Ganga	8,61,452	525.02	8,38,803	914	509.52
	b) Brahmaputra	1,94,413	537.24	1,93,252	495	441.68
	c) Barak & Others	41,723	48.36	86,335	134	86.67
3)	Godavari	3,12,812	110.54	3,12,150	365	117.74
4)	Krishna	2,58,950	78.12	2,59,439	226	89.04
5)	Cauvery	81,155	21.36	85,167	81	27.67
6)	Subarnarekha	29,196	12.37	26,804	40	15.05
7)	Brahmani-Baitarani	51,822	28.48	53,902	83	35.65
8)	Mahanadi	1,41,589	66.88	1,44,905	200	73.00
9)	Pennar	55,213	6.32	54,905	40	11.02

1	2	3	5	6	7	8
10)	Mahi	34,842	11.02	39,566	35	14.96
11)	Sabarmati	21,674	3.81	31,901	25	12.96
12)	Narmada	98,796	45.64	96,659.79	108	58.21
13)	Tapi	65,145	14.88	65,805.80	59	26.24
14)	West Flowing Rivers from Tapi to Tadri	55,940	87.41	58,360	161	118.35
15)	West Flowing Rivers from Tadri to Kanyakumari	56,177	113.53	54,231	151	119.06
16)	East Flowing Rivers between Mahanadi and Pennar	86,643	22.52	82,073	97	26.41
17)	East Flowing Rivers between Pennar and Kanyakumari	1,00,139	16.46	1,01,657	98	26.74
18)	West Flowing Rivers of Kutch & Saurashtra including Luni	3,21,851	15.10	1,92,112	100	26.93
19)	Area of inland drainage in Rajasthan Desert	1,44,836	Negligible	1,44,835.90	49	Negligible
20)	Minor rivers draining into Myanmar (Burma) and Bangladesh	36,302	31.00	31,382	61	31.17
	Total	32,30,368	1869.35	32,71,953	**3,880***	**1,913.60**

**Including 27 BCM of Leh Ladakh.*

The basin-wise discussions on the results of the present study along with their comparison with 1993 study have been presented in the following paragraphs.

4.2.1 Indus

During 1993 study no separate assessment was made for estimating water resources of the Indus basin. Water resources of the basin were taken as 73.31 BCM, as recorded in earlier study done by Indus Commission in 1960. Therefore, present study and 1993 study cannot be compared as such.

4.2.2 a) Ganga

During 1993 study, no separate assessment was made for estimating water resources of the Ganga basin. The potential of 502.02 BCM was reproduced in the 1993 report from CWC publication N0/88 “Water Resources of India”, April 1988. Earlier, the erstwhile Ganga Basin Water Studies Organisation of CWC carried out the assessment of water resources potential and had presented the details of the study in their report of 1986. The assessment was based on the actual observed flow data available at several locations for durations ranging from 5 years to 20-25 years. Simple rainfall-runoff regression analysis and multi-site data generation were resorted to wherever the observed flow data were found to be inadequate.

On the other hand, present study takes into consideration 28-30 years data and the methodology for assessment is totally different. Also, there is reduction in average rainfall during the period from 1965-1984 (947 BCM) to 1985-2015 (914 BCM). Temperature values for hilly regions are inconsistent, as informed by M/s DELTARES. They are using same data for carrying out study 'Strategic Basin Planning of Ganga River Basin in India'.

4.2.2 b) Brahmaputra

During 1993 study, no separate assessment was made for estimating water resources of the Brahmaputra basin. The Brahmaputra Board in their report of 1987 on “Master Plan of Brahmaputra Basin: Part 1 Main Stem” has reported the average annual flow at Jogighopa (Pancharatna) on Brahmaputra as 537.067 BCM. Jogighopa is located 85 km upstream of the point at which river crosses India-Bangladesh border. The average annual flow was worked out on the basis of observed flows in the years 1955-57 and 1971-77 (8 years), which was insufficient for estimating water potential. The rainfall during the present study (1985-2015) is about 495 BCM compared to 551 BCM rainfall during 1955-1984. There is a down departure of 56 BCM in the present study as compared to the previous study. The present study encompasses the rainfall from two sources, IMD and Global Ensemble Forecast System (GEFS) gridded rainfall. Besides, there are upstream interventions in the basin outside the Indian territory, which has reduced the non-monsoon flows in the river.

4.2.2 c) Barak & others

In 1993 estimate, water resources up to Badarpurghat (Catchment area = 25070 sq.km) were directly taken from report on Master Plan for Barak sub basin-1988 submitted by Brahmaputra Board. The total catchment area of Barak in India was considered as 41723 sq.km. For rest of the region (Meghalaya and Tripura) no direct estimate was available. A proportionate approach was adopted to estimate the water resources of the remaining basin area. Accordingly, the potential was estimated as 48.36 BCM. However an area of 47,440.1 sq.km has been estimated in the present study. In Meghalaya and Tripura region, catchment areas are steeper than Badarpurghat catchment area. Average rainfall run-off co-efficient is higher for Meghalya and Tripura region than Badarpurghat catchment area. The earlier study ignored the higher average rainfall of Meghalaya and Tripura area, which led to under estimation of water resources of Barak and other river basin. Average rainfall in Meghalaya region is 2.2 times more than average rainfall of Badarpurghat catchment area.

4.2.3 Godavari

The previous CWC (1993) estimate of available water resources of the basin was 110.54 BCM while in present study (1985 to 2015) it is 117.74 BCM.

Observed flow data at Polavaram was for the period from 1967-68 to 1984-85 (14 years) and the same was taken into account for arriving at potential of the basin in the 1993 study. The basin rainfall during the period 1965 to 1984 is about 346 BCM as against rainfall of 365 BCM during the period 1985 to 2015 **(**present study duration). Hence, the mean annual rainfall for the basin in the present study period i.e., for the period 1985-2015 is about 19 BCM more than the mean annual rainfall during the period 1965-84. A comparison of water resources assessment of Godavari basin has been presented in Table 8.

Table - 8: Comparison of Water Resources Assessment of Godavari basin

Details	(1965-1984)	Present Study (1985-2015)
Average Basin Rainfall (BCM)	346	365
Water Availability (BCM)	110.54	117.74
Percentage of available water to rainfall	31.90	32.25

4.2.4 Krishna

The previous CWC (1993) estimate of available water resources of the basin was 78.12 BCM while in present study (1985 to 2015) it is 89.04 BCM (Table - 9). Observed discharges are taken into account for arriving at the natural flow at Vijayawada in the 1993 study while in present study calibrated runoff is taken into account after accounting for all other abstractions. The comparison shows significantly the water utilisation for irrigation, exploitation of groundwater has gone up over the last 30 years, while decrease in flow at Vijayawada signifies the coming up of various storage projects during the last 30 years in the basin.

Table - 9: Comparison of water resources assessment of Krishna basin

Details	(1993 study period)	Present Study (1985-2015)
Average Basin Rainfall (BCM)	212	226
Water availability (BCM)	78.12	89.04
Percentage of available water to rainfall	36.84	39.40

The following points emerged from the comparision of the present study with previous estimate of CWC in 1993:

- The mean annual rainfall during 1985-2015 is 6.60% more than the mean annual rainfall during the period 1971-85 (for which observed river flows were considered).
- In 1993 estimate, area proportionate approach was adopted to estimate water resources of delta area. While using this approach, the delta area was estimated at 7,581 sq.km as against 3,047 sq.km estimated in the present study. Also catchment area up to Vijayawada was considered as 2,51,369 sq.km against the present value of 2,56,392 sq.km (which is based on geo-spatial data sets). However, as per 1993 estimate, the total area of Krishna basin considered was 2,58,950 sq.km while in the present study it is 2,59,439 sq.km (based on the geospatial data sets) i.e. more than 489 sq.km.

4.2.5 Cauvery

During 1993 study, no separate assessment was made for estimating water resources of the Cauvery basin. The assessment of the potential was carried out in 1972 by the Cauvery Fact Finding Committee constituted by the Government of India. The assessment study was based on the observed flow data for 38 years (1934-35 to 1971-72). The assessment made was at Lower Anicut across Coleroon, a branch of Cauvery in the Delta. An area of near 8,000 sq.km in the delta was not accounted for in this assessment. The potential at Lower Anicut was taken as the potential for the entire basin. The mean annual rainfall during 1985-2015 is 15.25% less than the mean annual rainfall during the period from 1934-35 to 1971-72 for which observed river flows were considered. Percentage ratio of available water to rainfall is more reasonable in the present study (34%) as compared with 1993 study (22.8%).

As discussed above, an area of near 8000 sq.km in the delta was not accounted for in the 1993 report. The potential at Lower Anicut has been taken as the potential for the entire basin. Whereas in the present assessment, the whole catchment area of the Cauvery basin is considered for the assessment. As per 1993 estimate, the total area of Cauvery basin considered was 81,155 sq.km, while in the present study it is 85,167 sq.km (based on the geospatial data sets), an overall increase of 4012 sq.km area.

4.2.6 Subernarekha

The previous CWC (1993) estimate of available water resources of the total basin was 12.37 BCM while in present study (1985 to 2015) available water resources of the total basin is 15.05 BCM (Table 10).

Table - 10 Comparison of water resources assessment of Subernarekha basin

Details	(1971-72 to 1986-87) 1993 study period	Present Study (1985-2015)
Average Basin Rainfall (BCM)	41	38.91
Water availability (BCM)	12.37	15.05
Percentage of available water to rainfall	30.17	38.67

4.2.7 Brahmani - Baitarani

The previous CWC (1993) estimate of available water resources of the total basin was 28.48 BCM while in present study (1985 to 2015) available water resources of the total basin is 35.65 BCM. (Table -11)

Table - 11 Comparison of Water Resource Assessment of Brahmani-Baitarani basin

Details	Brahmani-Baitarani Basin	
	(1964-65 to 1984-85) 1993 study period	Present Study (1985-2015)
Average basin Rainfall (BCM)	79	83
Water Availability (BCM)	28.48	35.65
Percentage of available water to Rainfall	36.05	42.96

The comparison of the present estimate with previous estimate of CWC of 1993 reveals that:

- The mean annual rainfall during 1985-2015 is 5.06% more than the mean annual rainfall during the period 1964-65 to 1984-85 (for which observed river flow records were available).
- In 1993 estimate, the river discharge data was available only at Jenapur on Brahmani river and at Birdi on Baitarani river. Discharge data at the outlet of the composite basin was not available. Hence, area proportionate approach was adopted to estimate composite delta water resources. While using this approach, the composite delta area was estimated at 3,595 sq.km as against the delta area estimated from present study as 7,887 sq.km (which is based on geo-spatial data sets). As a result of this, the water resources estimate of composite delta was 2.05 BCM during 1993 as against present estimate of 9.37 BCM. However, total catchment areas during 1993 study and present study have been 51,822 sq. km and 53,902 sq. km respectively, an overall increase of 2,080 sq.km.

4.2.8 Mahanadi

During 1993 study, no separate assessment was made for estimating water resources of the Mahanadi basin. The 1993 report considered an area of 1,41,589 sq.km whereas present assessment is done for an area of 1,44,905 sq.km. An increase of 5.8% rainfall is noted between 1965-84 (189 BCM) and 1985-2015 (200 BCM).

4.2.9 Pennar

The previous CWC (1993) estimate of available water resources of the total basin was 6.312 BCM while in present study (1985 to 2015) available water resources of the total basin is 11.00 BCM (Table 12).

Table - 12 Comparison of water resources assessment of Pennar basin

Details	(1944-45 to 1983-84) 1993 study period	Present Study (1985-2015)
Average Basin Rainfall (BCM)	37	40
Water availability (BCM)	6.32	11.02
Percentage of available water to rainfall	17	27.55

The comparison of the present estimate with previous estimate of CWC of 1993 reveals that:

- In the 1993 study, observed discharges is taken into account for arriving the natural flow at Sangam Anicut (Catchment area =50,253 sq.km) and interpolated for the whole Pennar basin (Catchment Area = 55,213 sq.km) whereas in the present study, calibrated runoffs have been calculated up to Nellore (Catchment Area = 54,201.4 sq.km) and the remaining delta portion (703.98 sq.km) remains uncalibrated. Thus the whole basin (CA=54,905.38 sq. km) is taken into account. Mean annual rainfall during 1985-2015 (40 BCM) is more than that during 1944-45 to 1983-84.
- In the 1993 study, evaporation from the reservoirs and domestic, livestock and industrial demand is assumed as nil but those values are considered and calculated in the present study.
- The quantity of water imported from the neighbouring Krishna basin via Tunghabadra HLC and Srisailam Projects are considered in the present study which was not present in the earlier studies.

4.2.10 Mahi

The previous CWC (1993) estimate of available water resources of the total basin was 11.02 BCM while in present study (1985 to 2015) available water resources of the total basin is 14.96 BCM (Table - 13). Observed discharges were taken into account for arriving the natural flow at Khanpur in the 1993 study after accounting all other abstractions.

Table - 13 Comparison of water resources assessment of Mahi basin

Details	(1979-80 to 1984-85) 1993 study period	Present Study (1985-2015)
Average basin rainfall (BCM)	34	35
Water Availability (BCM)	11.02	14.96
Percentage of available water to rainfall	32.41	42.74

The comparison of the present estimate with previous estimate of CWC of 1993 reveals that:

- In 1993 assessment, rainfall-runoff regression modelling has been resorted to in order to extend the flow record to period of 20 years because the flow record available at Khanpur site which is terminal station for Mahi river basin is only for a period of six (6) years. For present study, total 30 years flow data is available for model calibration purpose.
- The mean annual rainfall during 1985-2015 (35 BCM) which is 2.94 % more than the mean annual rainfall during the period 1979-1985 (34 BCM).
- In 1993 assessment, area proportionate approach was adopted to estimate water resources of downstream area of Khanpur site. While using this approach, the downstream area was estimated at 2,335 sq.km as against 6,580.6 sq.km in the present study. Catchment area up to Khanpur was considered as 32,507 sq.km against the present value of 32,985 sq.km (which is based on geo-spatial data sets). However, as per 1993 estimate, the total area of Mahi basin was considered as 34,842 sq.km while in the present study it is 39,565.6 sq.km (based on the geospatial data sets), an increase of 4723.6 sq.km.

4.2.11 Sabarmati

The previous CWC (1993) estimate of available water resources of the total basin was 3.81 BCM while in present study (1985 to 2015) available water resources of the total basin is 12.96 BCM (Table - 14). Observed discharges were taken into account for arriving the natural flow at Ahmedabad in the 1993 study after accounting all other abstractions.

Table - 14 Comparison of water resources assessment of Sabarmati basin

Details	(1972-73 to 1984-85) 1993 study period	Present Study (1985-2015)
Average Basin Rainfall (BCM)	26	25
Water Availability (BCM)	3.81	12.96
Percentage of available water to rainfall	14.65	51.84

- As per 1993 estimate, the total catchment area of Sabarmati Basin was considered as 21,674 sq.km while in the present study it is 31,901 sq.km (based on the geospatial data sets). The increase of area is about 10, 227.2 sq. km.
- In 1993 assessment, there was only one G&D site at Dharoi having a catchment area of only 5,433 sq.km. The flow data was available for the period 1972-73 to 1984-85 (13 years). The other gauging site was available at Ahmedabad (catchment area = 10,186.78 sq.km) being maintained by State Government. This was shifted twice and the data available was for the period of 1960-61 to 1964-65, 1969-70 to 1984-85. There was gap from 1965-66 to 1968-69 for which the missing data was filled up using rainfall-runoff regression analysis. The Ahmedabad site was used for reassessment. The proportionate approach was adopted to estimate water resources of downstream area of Ahmedabad site.

4.2.12 Narmada

During 1993 study, no separate assessment was made for estimating water resources of the Narmada basin. The potential of Narmada basin was worked out on the basis of catchment area proportion from the potential assessed at Garudeswar (catchment area = 89,345 sq.km) as given in the report with its decision, 1979 of Narmada Water Disputes Tribunal. The total catchment area considered for Narmada basin in 1993 study and present study is 98,796 sq. km and 96,659.79 sq. km respectively.

4.2.13 Tapi

The previous CWC (1993) estimate of available water resources of the total basin was 14.88 BCM while in present study (1985 to 2015) available water resources of the total basin is 26.24 BCM (Table - 15). Observed discharges is taken into account for arriving the natural flow at Ghala in the 1993 study after accounting all other abstractions.

Table - 15 Comparison of water resources assessment of Tapi basin

Details	(1978-79 to 1986-87) 1993 study period	Present Study (1985-2015)
Average basin rainfall (BCM)	54	59
Water Availability (BCM)	14.88	26.24
Percentage of available water to rainfall	27.55	44.47

The comparison of the present estimate with previous estimate of CWC of 1993 reveals that:

- The total catchment area considered for Tapi basin in 1993 study and present study is 65,145 sq.km and 65805.8 sq.km respectively.
- The mean annual rainfall during 1985-2015 is 9.25% more than the mean annual rainfall during the period 1978-79 to 1986-87.
- In 1993 assessment, rainfall-runoff regression modelling has been resorted to in order to extend the flow record to period of 22 years because the flow record available at Ghala site which is terminal station for Tapi river basin is only for a period of 7 years. For present study, total 30 years flow data is available for model calibration purpose.

4.2.14 West Flowing Rivers from Tapi to Tadri

The previous CWC (1993) estimate of available water resources of the total basin was 87.41 BCM while in present study (1985 to 2015) available water resources of the total basin is 118.35 BCM (Table - 16).

Table – 16 Comparison of water resources assessment of WFR from Tapi to Tadri

Details	(1971-72 to 1986-87) 1993 study period	Present Study (1985-2015)
Average Basin Rainfall (BCM)	152	161
Water Availability (BCM)	87.411	118.35
Percentage of available water to rainfall	57.50	73.50

The comparison of the present estimate with previous estimate of CWC of 1993 reveals that:

- In 1993 estimate, the total basin area of WFR from Tapi to Tadri considered was 55,940 sq.km while in the present study it is 58,360 sq.km (based on the geospatial data sets), an increase of 2,420 sq.km.
- The mean annual rainfall during 1985-2015 is 5.92% more than the mean annual rainfall during the period 1971-72 to 1986-87.
- In the present study, rainfall has been used as primary input. As per 1993 report, this basin has as many as 45 minor river systems of which only two rivers had observed flow record for 16 years. In the basin containing west flowing rivers from Tadri to Kanyakumari, observed flow records were available for five rivers for periods ranging from 12 to 16 years. Analysing the flows in the seven river systems, a relationship between average annual catchment rainfall and runoff was developed. Using this relationship and knowing the rainfall, the average annual runoff in the other ungauged river systems was estimated.

4.2.15 West Flowing Rivers from Tadri to Kanyakumari

The previous CWC (1993) estimate of available water resources of the total basin was 113.5 BCM while in present study (1985 to 2015) available water resources of the total basin is 119.06 BCM. A comparison has been presented in Table - 17.

Table - 17 Comparison of water resources assessment of WFR from Tadri to Kanyakumari

Details	(1964-65 to 1984-85) 1993 study period	Present Study (1985-2015)
Average Basin Rainfall (BCM)	158	151
Water availability (BCM)	113.50	119.06
Percentage of available water to rainfall	71.83	78.85

The comparison of the present estimate with previous estimate of CWC of 1993 reveals that:

- As per 1993 report, this basin has 54 minor river systems of which five rivers had observed flow records for 12 to 16 years. As explained above these flow records along with the flow records for two river systems in the basin containing west flowing rivers from Tapi to tadri were analysed and a relationship was developed between average annual catchment rainfall and runoff. Using this relationship and knowing the catchment rainfall, the runoff in the remaining river systems was estimated.

- The water availability of different sub-basins was estimated based on the observed flow data of different periods. The increase in the water availability of 5.56 BCM (4.8%) is considerably small.

4.2.16 East Flowing Rivers (EFR) between Mahanadi and Pennar

The previous CWC (1993) estimate of available water resources of the total basin was 22.52 BCM while in present study (1985 to 2015) available water resources of the total basin is 26.41 BCM. A comparison has been presented in Table - 18.

Observed discharges is taken into account for arriving the natural flow at Khanpur in the 1993 study while in present study, calibrated runoff is taken into account after accounting all other abstractions.

Table - 18 Comparison of water resources assessment of EFR between Mahanadi and Pennar

Details	(1973-74 to 1986-87) 1993 study period	Present Study (1985-2015)
Average Basin Rainfall (BCM)	90	97
Water availability (BCM)	22.52	26.41
Percentage of available water to rainfall	25.00	27.23

The comparison of the present estimate with previous estimate of CWC of 1993 reveals that:

- The mean annual rainfall during 1985-2015 is 7 BCM (7.77%) more than that during the period 1973-74 to 1986-87.
- The upstream abstractions for irrigation, industrial and domestic uses along with losses due to evaporation from the existing reservoirs were obtained from Irrigation Department in 1993 study. However, in present study irrigation support and evaporations losses from reservoirs and water bodies up to 1 hectare are obtained from WRA tool (model) itself, which is using geospatial data sets.

4.2.17 East Flowing rivers between Pennar and Kanyakumari

The previous CWC (1993) estimate of available water resources of the total basin was 16.46 BCM while in present study (1985 to 2015) it is 26.74 BCM. A comparison has been presented in Table - 19.

Table - 19 Comparison of water resources assessment of EFR between Pennar and Kanyakumari

Details	(1972-73 to 1987-88) 1993 study period	Present Study (1985-2015)
Average Basin Rainfall (BCM)	92	98
Water availability (BCM)	16.46	26.74
Percentage of available water to rainfall	17.88	27.28

The comparison of the present estimate with previous estimate of CWC of 1993 reveals that:

- The mean annual rainfall during 1985-2015 is 6 BCM (6.52%) more than that during the period 1972-73 to 1987-88.
- In the 1993 study, observed discharges is taken into account for arriving the natural flow at Vilupuram (catchment area = 12,900 sq.km) on Ponnaiyar river for northern part (catchment area = 65,049 sq.km) and at Paramakudi on Vaigai for southern part and extrapolated for the whole East flowing river basin (catchment area = 1,00,139 sq.km).
- Whereas in the present study, calibrated discharges are calculated at 4 different locations on 4 different rivers in the basin i.e. Chengalpet (on river Palar), Vilupuram (on river Ponnaiyar), Paramakudi (on river Vaigai) and Murappanad (on river Tambraparani) and the remaining portion remains uncalibrated (but the water availability is computed for the whole basin with calibrated input coefficients). Thus the whole basin (catchment area = 1,01,657 sq.km) is taken into account for assessment of water availability.

4.2.18 West Flowing Rivers of Kutch & Saurashtra including Luni

The reassessment study of this composite basin was not performed in 1993. The results from the CWC Publication No. 30/88 “Water Resources of India”, 1988 were reproduced in the 1993 report, where in the methodology adopted in 1988 studies has not been mentioned. There is increase in the rainfall in the basin in last 30 years. Rainfall of 399.66 mm during the period from 1985-86 to 1994-95, 431.35 mm during the period from 1995-96 to 2004-05 and 607.31 mm during the period from 2005-06 to 2014-15 have been observed. The basin area considered for the present study is 1,92,112 sq.km as compared to 321, 851 sq.km taken in 1993 study. In addition, there is an increase in command area in parts of basin due to construction of Saradar Sarovar (Narmada) Project for augmenting irrigation facilities.

4.2.19 Minor rivers draining into Myanmar (Burma) and Bangladesh

The previous CWC (1993) estimate of available water resources of the total basin is 31.00 BCM, whereas in present study (1985-2015), it is 31.17 BCM (Table - 20).

Table - 20 Comparison of water resources assessment of Minor Rivers Draining Into Myanmar (Burma) and Bangladesh

Details	(1971-72 to 1984-85) 1993 study period	Present Study (1985-2015)
Average Basin Rainfall (BCM)	61	61
Water availability (BCM)	31	31.17
Percentage of available water to rainfall	50.81	51.10

The following points need to be considered while comparing the present estimate with previous estimate of CWC:

- As per 1993 estimate, the total basin area for Minor Rivers draining to Myanmar (Burma) and Bangladesh was considered as 36,302 sq.km while in the present study it is 31,382 sq.km (based on the geospatial data sets).

4.3 Possible reasons for deviation of the present and CWC 1993 study

The possible reasons for deviation of the present study in comparison with the previous 1993 reassessment study are depicted in the Table - 21.

Table - 21: Possible reasons for deviation of the present study from the CWC, 1993 study

Sl. No.	CWC 1993 Reassessment Study	Current Reassessment study
1 A	All basins were not studied during 1993 study 1) 12 studied basins : 505 BCM 2) 8 not studied basins : 1364 BCM	All basins are studied for the concurrent period i.e. 1985-2015
1 B	Indus, Ganga, Brahmaputra-Meghna, Narmada, Mahanadi, Cauvery, Area of inland drainage in Rajasthan Desert, WFR of Kutch & Saurashtra including Luni were not studied.	
1C	Sum of average water availability for studies during different years was taken, which is not mathematically correct.	
2	Teesta basin was not studied	Teesta basin has been studied (22.93 BCM)
3	Observed discharges at terminal G&D sites were considered, which, in itself, may not be free from errors	Proper calibration and validation exercises were undertaken in the present study on discharges
4	No rainfall component was used in the studies	Rainfall grid (as obtained from IMD and GEFS) have been used for entire India
5A	Utilization data was mostly obtained from States and wherever not available, assumptions were made	The consumptive use in irrigation has been assessed using scientific methods and GIS database for LULC, Soil-texture, crop/vegetation parameters, temperature, and command area boundaries
5B	Utilizations from minor projects were seldom available	
6	Return flow of 10% assumption in irrigation is a crude assumption	Instead of utilisation minus return flows (both are approximate), directly the consumptive use was assessed
7	Groundwater data for year 1967-68 and 1983-84 used and interpolated for other years.	Groundwater flux data (as obtained from CGWB) for entire India was used

4.4 Estimation of 75% dependable flows

The average annual virgin flow at the terminal point of a river is generally reckoned as the potential of the river basin. However, in the planning of water resources projects, flows at varying dependabilities are taken into consideration. For instance, for irrigation projects 75% dependable flows, and for hydel power projects 95% dependable flows are considered, since irrigation projects are designed for 75% success and hydel projects for 95% success. Irrigation is the major consumer of water in our country. Nearly 85% of the total demand for water is for irrigation. It is, therefore, felt that it would be beneficial if 75% dependable flows for the river basins are also worked out and included in the report. The results of the study are indicated In Table - 5.

4.5 Uncertainty and Confidence Interval in Average Annual Water Availability

Changes in key climate variables, namely, temperature, precipitation, and humidity, may have significant long term implications for the quality and quantity of water. Two major water balance components of water yield and actual evapo-transpiration that are highly influenced by the weather conditions dictated by temperature and allied parameters. Impacts of climate change and climate variability on the water resources are likely to affect irrigated agriculture, installed power capacity, environmental flows in the dry season, and higher flows during the wet season.

Considering a statistical analysis of the 30 year water availability series (base and future), at a 0.1 level of significance, the confidence interval could be estimated that comprised the average annual water availability. The greater the range of this interval, the greater also the uncertainty related to the average annual water availability. The range of confidence interval is increased, with a greater percentage, indicating greater variability between the series and, consequently, greater uncertainties in estimating the availability. The average annual water availability during considering a 90% confidence interval was between 1885 BCM and 1961 BCM (range of 48.25 BCM). The Confidence Intervals of all the basins are presented in Table - 22. When dividing the standard deviation by the mean value, the Coefficients of Variation (CV) were obtained for the series, for each year. It could be seen that during the period (1985–2015), the average CV is 0.08. The result indicates marginal increase in the variability of average annual water availability.

As to the uncertainties concerning the hydrological behaviour and, consequently, water availability, having as a reference the results and discussions presented, it is concluded that uncertainties regarding hydrological behaviour between 1984-85 and 2014-15 were greater than in the base period. The main factor that contributed to this result was the increase in the mean itself and in the standard deviation of average annual WRA. Besides these, in the future, time dependency will present a more marked contribution to the composition of annual WRA.

Table - 22: Confidence interval in average annual water availability

Sl No	Basins	Mean WRA (BCM)	Confidence Level (90%)	WRA at 90% Confidence Interval (BCM)
1	Godavari	117.74	12.08	117.74±12.08
2	Krishna	89.04	5.84	89.04±5.84
3	Cauvery	27.67	1.67	27.67±1.67
4	Subernarekha	15.05	1.41	15.05±1.41
5	Brahmani-Baitarani	35.66	2.91	35.66±2.91
6	Mahanadi	73.00	7.42	73.00±7.42
7	Pennar	11.02	1.98	11.02±1.98
8	EFR between Mahanadi & Pennar	26.41	3.28	26.41±3.28
9	EFR between Pennar & Kanyakumari basin	26.74	3.22	26.74±3.22
10	Minor Rivers draining to Myanmar (Burma) and Bangladesh	31.17	2.66	31.17±2.66
11	Indus	45.64	2.87	45.64±2.87
12	Ganga	509.50	18.93	509.50±18.93
13	Brahmaputra	441.68	16.29	441.68±16.29
14	Barak and Others	86.67	6.56	86.67±6.56
15	Mahi	13.12	1.84	13.12±1.84
16	Sabarmati	12.96	1.95	12.96±1.95
17	Narmada	58.21	5.81	58.21±5.81
18	Tapi	25.58	2.48	25.58±2.48
19	WFR Tapi to Tadri	118.55	6.04	118.55±6.04
20	WFR Tadri to Kanyakumari	119.06	6.17	119.06±6.17
21	WFR of Kutch & Saurashtra including Luni	27.10	2.66	27.10±2.66
	All the basins as a whole	1913.60	48.25	1913.60±48.25

4.6 Assumptions and Limitations of the study

The assumptions and limitations of the study are as follows.

i) The model is setup at annual time-step, monthly calibrations are not carried out.

ii) Considering the availability of meteorological data in spatial environment, Thornthwaite-Mather method with suitable land cover coefficients is considered for PET calculations.

iii) The water utilization due to irrigation has been estimated through the use of Mather method and other suitable literature in absence of the withdrawal data uniformly throughout the basin.

iv) Land Use and Land Cover (LULC) maps of the period for the period 2004-05 to 2014-15 only are used for runoff calculation in the study. For runoff computations prior to 2004-05, land use maps of 2004-05 to 2014-15 are adopted based on the mean annual rainfall of the year under consideration.

v) Kharif crop outside of the command area boundary is assumed as rain-fed. Kharif only crop within command boundary, Double/Tripple crops and Zaid crop are considered as irrigated, either by surface or groundwater.

vi) In irrigated agriculture land $AET_{model\ estimated}$ is calculated by assuming that 100% water requirements are met from the rainfall and irrigation supplies together (AET = PET condition).

vii) Based on district-wise groundwater flux, component for each sub-basins are worked out.

4.7 Way forward

a) The accuracy of the reassessment of water resources potential of the river basins made on the basis of the discharge measured on the river depends directly upon the reliability of the discharge observation and the data on abstractions in the upstream. Improved estimates of abstraction would enhance the results of import or export from the basin, vis-a-vis reducing uncertainty.

b) The major consumption of water in most of the river basins is by irrigation. The domestic demand is estimated taking into account the district boundaries of the year 2001 and 2011. Population statistics for intervening period and for the period beyond census years were calculated using geometric progression method. Domestic demand considered as 70 LPCD for rural, 140 LPCD for urban population and Livestock demand at 30 LPCD. Consumption at 15% of this demand is considered in the study. Since industrial demand statistics were not available, the same is assumed as 50% of the domestic demand for each year. It is very essential that diversions for irrigation from major, medium and minor projects are recorded regularly and brought out as yearly booklets similar to rainfall records.

c) More efforts are needed for developing and improving the hydrological observation network and making the data available through the common infrastructure using standardized formats. More gauging stations should be established at the terminal gauging sites of all the basins including composite basins of West Flowing Rivers and East Flowing Rivers, since the existing gauging stations are considered inadequate.

d) There is also a need to modernise the equipment used for gauge and discharge measurements in the existing gauging stations in all the basins.

e) The groundwater flux data prepared by CGWB was used in this study for estimating yearly groundwater fluxes. Basin-wise figures are worked out by area proportionate basis from the district-wise groundwater flux figures. The sum of all districts in sub-basin gives the total groundwater flux for a sub-basin. It would be more convenient if groundwater studies are carried out basin or sub-basin wise.

f) Precipitation is monitored from a variety of platforms including space-borne, ground, and ocean-based platforms. Improved estimates of precipitation and inter-comparisons of these observations are crucial to validating the measurements and providing confidence for each measurement technique.

g) Means should be devised for overcoming the limitations of the present study and implement in the future study of reassessment of basin water availability.

h) It is also suggested to take up studies on improving methodological aspects such as: estimation of fine resolution spatial rainfall estimates, spatial ET/water use estimates, snow-melt runoff contributions, accounting spatial and temporal variability in irrigation water use, groundwater abstraction/recharge, sub-basin level water availability and comparative studies with different hydrological models for water assessment. These studies will lead to improved parameterization and reliable estimates of water availability.

i) The water availability at different stretches/sub-basin/points along the river needs to be quantified through further studies.

j) Utilizable water potential needs to be assessed. The reasons need to be identified for utilization at the vicinity of point of surplus water, for rain-fed agriculture areas, water harvesting and conservation.

4.8 Conclusions

India is not a water deficit country, but due to severe neglect and lack of monitoring of water resources development projects, several regions in the country experience water stress from time to time. Further neglect in this sector will lead to water scarcity in future. It is, therefore, necessary to prevent this crisis by making best use of the available technologies and resources to conserve the existing water resources, convert them into utilisable form and make efficient use of them for agriculture, industrial production and human consumption. Imposing regulatory measures to prevent the misuse of water and introducing rewards and punishment to encourage judicious use of water, will be helpful to conserve water. Finally, awareness and orientation of all the water users to change their lifestyle to conserve water can help the country to tide over the water crisis in the future. The challenge is manageable provided we have favourable policies and mechanisms to persuade our people to change their lifestyle.

The intertwined issues of water availability in the basins are best addressed in concert for basin management solutions. In concordance, the study is expected to eventually promote new and more comprehensive efforts mobilized in the sub-basin and envisioned that as the basin approach is fully implemented, the sub-basin will become more integrated and will provide priorities articulated in greater detail. This study is not only a hydrological modelling framework for periodic assessment of water resources, but also for realisation of impact of climate change on water resources availibility.

In conclusion, this report presents a roadmap of potential water availability and solution options and means of implementation that can be adopted to foster progress in improving water management. Such options go well beyond the merely technical to include legal and institutional frameworks, financing opportunities, building knowledge and capacity, mitigating human and environmental health risk, and fostering social acceptance. As the challenges vary from place to place around the country, it is incumbent upon stakeholders and decision-makers in each region, state, basin and community to identify the most appropriate mix of options for their particular situation.

REFERENCES

1. Anisimov, O., Bolonishnikova, J., Calver, A., Farquharson, F., Lipponen, A., Mahykano, B.O., Meijerink, A.M.J., Oke, A., Okpara, J.N., Richardson, D., Shelley, L., Strelchenko, Y., Vasak, S., Vermooten, S., and Vrba, J., 2012, Technical material for Water Resources Assessment.

2. Australian Water Resources Assessment 2012, Bureau of Meteorology, Govt. of Australia.

3. Beven, K.J. (1996), A discussion of distributed hydrological modeling. In *Distributed Hydrological Modeling* (eds). M.B. Abott and J.c Refsgaard. Kluwer Academic Press: Netherlands. Pp. 278 - 255.

4. Beven, K.J. (2001), Rainfall-runoff modeling: A Primer. Wiley: West Sussex. Pp. 217- 254.

5. Beven, K.J. (2002a), Towards an alternative blueprint for a physically-based digitally simulated hydrologic response modelling system, Hydrol. Process., 16(2), pp.189-206.

6. Dolman, A. J., A. J. Hall, M. L. Kavvas, T. Oki, and J. W. Pomeroy, (Eds.), (2001), Soil-Vegetation-Atmosphere Transfer Schemes and Large-Scale Hydrological Models. IAHS Publ. No 270, pp.372.

7. Durga Rao, K. H. V., Venkateshwar Rao, V., Dadhwal, V. K., (2014), Improvement to the Thornthwaite Method to Study the Discharge at a Basin Scale Using Temporal Remote Sensing Data. International Journal of Water Resources Management, 28: pp.1567-1578.

8. FAO (2002), Crop Evapotranspiration Guidelines for computing crop water requirement. Irrigation and Drainage Paper No. 56.

9. Handbook for the Assessment of Catchment Water Demand and Use Department of International Development, UK, 2003.

10. IPCC, 2013: Climate Change (2013), The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, New York, USA, pp.1535.

11. McCabe, G.J. and Markstrom, S.L., (2007), A monthly water-balance model driven by a graphical user interface: U.S. Geological Survey Open-File report 2007-1088, 6p.

12. Milorad Miloradov and Prvoslav Marjanovic, Guidelines for conducting Water Resources Assessment , UNESCO, 1998.

13. NCIWRD, (1999), Integrated Water Resources Development, A plan for the action, Report of the national commission for Integrated Water resources development, Volume 1, Ministry of Water Resources, Government of India.

14. NRSC, 2009, Water Resources Assessment the National Perspective- A Technical Guide for Research and Practice, NRSC- -TR98.

15. NRSC, 2013, Assessment of water resources at basin scale using space inputs – A pilot study in Godavari and Brahmani-Baitarani basins, NRSC-TR369.

16. Peter E Black, Revising the Thornthwaite and Mather Water Balance, http://www.watershedhydrology.com/pdf/T&M%20Revisited.pdf

17. Rajeevan M., and Jyote Bhate, (2008), A high resolution daily gridded rainfall data set (1971-2005) for meso-scale meteorological studies, National Climate Centre Report, India Meteorological Department, Pune.

18. Rosegrant et al. (2002), World Water and Food to 2025: Dealing with Scarcity, IFPRI Publications, Chapter 9., pp.198-207.

19. Thronthwaite, C.W. and Mather, J.R. (1957), Instructions and tables for computing potential evapotranspiration and water balance, Laboratory of Climatology, Publication No. 10, Centerton, NJ.

20. Water Resources Assessment: Handbook for review of National Capabilities; WMO and UNSECO, June 1997

21. X U CY and Singh V. P. (1998), A Review on Monthly Water Balance Models for Water Resources Investigations. Water Resources Management 12: pp. 31–50.

***