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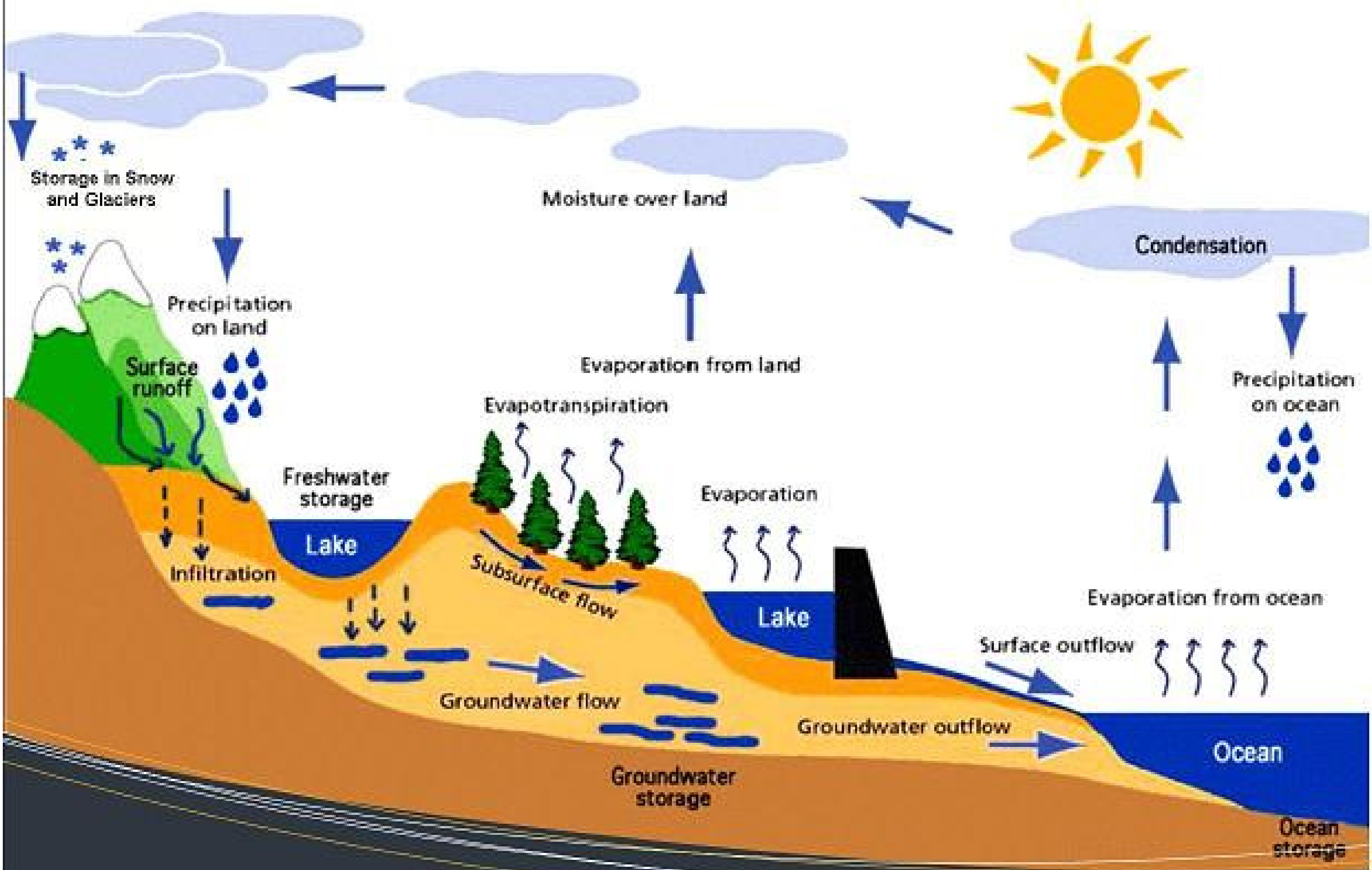
Government of India
Ministry of Water Resources

Preliminary Consolidated Report on Effect of Climate Change on Water Resources



New Delhi
June 2008

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Preliminary Consolidated Report on Effect of Climate Change on Water Resources

Central Water Commission
National Institute of Hydrology

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June 2008

उमेश नारायण पंजियार
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Foreword

The global warming is bound to affect the hydrologic cycle resulting in further intensification of temporal and spatial variations in the water availability.

Though almost all the reports and findings of the studies in this field mention about a definite change in the characteristics of the water availability, in majority of the cases, the projections are qualitative in nature. Therefore, the first and foremost action required is commencement of studies to have a reliable assessment of the impact of climate change on the glaciers and snow melt as well as on the rainfall and their effect on run-off generated into the river system and on contribution to ground water with the help of reliable data.

Central Water Commission and National Institute of Hydrology have initiated action for collection of necessary data and development of suitable hydrologic model and for predicting a reliable estimate of the likely effect of climate change on the availability of water resources. With a view to understand the process in proper perspective, the 'Preliminary Consolidated Report on Effect of Climate Change on Water Resources' summarizing the findings of studies conducted in this field so far has been prepared jointly by the Central Water Commission and National Institute of Hydrology.

I am confident that the report will be very useful in proper understanding of the issues and identifying the most appropriate course of action.

(Umesh Narayan Panjiar)

Preface

Climate change, whether as a natural cyclic variability and/or due to anthropogenic reasons, is affecting and likely to further affect the water resources, which is a vital necessity for existence of life form. The predicted intensification of hydrological cycle would change all of its constituents both in time and space domain. This is a long term phenomenon and the necessity is to understand the intensity of the effects on various aspects of water resources by way of scientific studies backed by the available observed field data. Need is also felt for further improving data collection network with modern collection and storage methods.

Involvement of academicians in the studies with a goal to achieve object oriented implementable results has already been started by way of setting up of Chairs in the four Indian Institute of Technology and two National Institute of Technology by Ministry of Water Resources (MoWR). The National Institute of Hydrology (NIH) has already conducted various studies particularly on glacier-melt and snow-melt aspects in Indus and Ganga basins based on the related field data collected by them and other national agencies, which need to be continued. Studies are required to be conducted for Brahmaputra basin and peninsular India including other basins also by involving related organizations. New institutional arrangements are required to be created by involving various organisations to focus on climate change issues and guide related studies in a co-ordinated & time bound manner so that impending threat can be successfully tackled by adopting appropriate strategies, both in the realm of adaptation and mitigation, for the benefit of the people.

This "Preliminary Consolidated Report on Effects of Climate Change on Water Resources" is the first step in that direction and has been prepared with a view to summarize the findings of the studies so far and propose a way forward. An effort has been made to consolidate all the efforts carried out so far in this field and serve as a ready reference for further work in the field. The report has been prepared jointly by Central Water Commission (CWC) and National Institute of Hydrology (NIH), MoWR. The efforts of Planning & Development Directorate (P&D), CWC in bringing out this report under the guidance of Shri R. C. Jha, Member (River Management), Shri G. S. Purba, Chief Engineer, P&D Organisation, CWC and Shri A. K. Kharya, Director (P&D) in coordination with Shri R. D. Singh, Director, NIH and Dr. M. L. Arora, Scientist 'B', NIH are put on record. The guidance and directions by Ministry of Water Resources are also gratefully acknowledged.

New Delhi
June, 2008

(A. K. Bajaj)
Chairman, CWC

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Abbreviations and Common terms

Abbreviation	*Full form*
BBMB	Bhakhra Beas Management Board
BSIP	Birbal Sahni Institute of Palaeobotany, Lucknow
CCRS	Center for Climate Research Studies
CCSR	Center for Climate System Research, University of Tokyo, Japan
CDF	Cumulative Distribution Function
CFC	Chlorofluorocarbon
CGWB	Central Ground Water Board, Faridabad
CH_4	Methane
CI	Composite Index
CMT	Cumulative Mean Temperature
CO_2	Carbon dioxide
COMMIT	Committed
COP	Conference of the Parties
CSRE	Centre of Studies in Resource Engineering
CWC	Central Water Commission, New Delhi
DEFRA	Department for Environment, Food and Rural Affairs, UK
DIAT	Defence Institute of Advanced Technology, Pune
DST	Department of Science & Technology, New Delhi
DTR	Diurnal Temperature Range
EFC	Expenditure Finance Committee
EFR	East Flowing Rivers
ENSO	El Nino–Southern Oscillation
EQUINOO	Equatorial Indian Ocean Oscillation
FAO	Food and Agriculture Organisation
FCCC	Framework Convention on Climate Change
FYP	Five Year Plan
GCM	General Circulation Model/ Global Climatic Model
GHG	Green House Gases
GLOF	Glacial Lake Outburst Flood
GoI	Government of India
GPS	Geographical Positioning System
GSI	Geological Survey of India
hm^3 (MCM)	Hectometer (Million Cubic Metre)
IHP	International Hydrology Programme
IISc	Indian Institute of Science, Bangalore
IIT	Indian Institute of Technology
IITM	Indian Institute of Tropical Meteorology, Pune
IMD	India Meteorological Department, New Delhi
INCOH	Indian National Committee on Hydrology
IPCC	Intergovernmental Panel on Climate Change
IRS-LISS	Indian Remote Sensing-Linear Imaging and Self Scanning
JNU	Jawahar Lal Nehru University, New Delhi
km	Kilometre
km^2	Square Kilometre
km^3 (BCM)	Cubic Kilometre (Billion Cubic Metre)
MHa	Million Hectare
MEA	Ministry of External Affairs
MoEF	Ministry of Environment and Forests
MoST	Ministry of Science and Technology
MoWR	Ministry of Water Resources
MSLP	Mean Sea Level Pressure
mm	Millimetre
Mm3	Magnitudes of errors
N_2O	Nitrous Oxide
NATCOM	National Communication
NCAOR	National Centre for Antarctic and Ocean Research, Goa
NCAR	National Centre for Atmospheric Research

Abbreviation	*Full form*
NCEP	National Centre for Environmental Prediction
NIES	National Institute of Environmental Studies, Japan
NIH	National Institute of Hydrology, Roorkee
NIT	National Institute of Technology
NO_2	Nitrogen Oxide
NOAA	National Oceanic and Atmospheric Administration
NRSA	National Remote Sensing Agency, Hyderabad
NWA	National Water Academy, Pune
NWDA	National Water Development Agency, New Delhi
NWP	National Water Policy
O_3	Ozone
PAMC-HG	Programmed Advisory & Monitoring Committee on Himalayan Glaciology
PMF	Probable Maximum Flood
PMO	Prime Ministers' Office
PMP	Probable Maximum Precipitation
PRL	Physical Research Laboratory, Ahmedabad
RBA	Rashtriya Barh Ayog
RBF	Radial Basis Function
RCM	Regional Climatic Model
RGWR	Replenishable Ground Water Resources
RVM	Relevance Vector Machine
SAC	Space Application Centre
SAR	Synthetic Aperture Radar
SASE	Snow and Avalanche Study Establishment, Manali
SCA	Snow Covered Area
SOI	Survey of India, Dehradun
SMF	Snow Melt Factor
SPF	Standard Project Flood
SPI	Standardized Precipitation Index
SPS	Standard Project Storm
SRES	Special Report on Emission Scenarios
SSC	Suspended Sediment Concentration
SSL	Suspended Sediment Load
SVM	Support Vector Machine
UBC	University of British Columbia
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational Scientific and Cultural Organisation
UNFCCC	United Nations Framework Convention on Climate Change
UPRSAC	Uttar Pradesh Remote Sensing Application Centre, Lucknow
WCIRP	World Climate Impacts Assessment and Response Strategies Programme
WCP	World Climate Programme
WFR	West Flowing Rivers
WGS-80	World Geodetic System-80
WIHG	Wadia Institute of Himalayan Geology, Dehradun
WRIS	Water Resources Information System
WMO	World Meteorological Organization

Executive Summary

Prime Minister's Council on Climate Change, in its first meeting held on 13-07-07 decided that "Institutions should be mandated by MoWR to initiate studies for major river basins of rivers whose waters come from snow melt". Accordingly, MoWR chalked out an Action Plan of activities to take up related studies through its organizations ie. CWC, NIH and Brahmaputra Board. Preparation of a "Preliminary Consolidated Report on Effect of Climate Change on Water Resources" has been decided as one of the activities of the Action Plan. In the Report an attempt has been made to give a brief account of the available studies on possible impacts of climate change on India's water resources, change in India's water needs, climate of India, river basins of the country, present water resources and future demand and supply, impacts of projected climate change and variability, and associated hydrological events and likely vulnerability of regional water resources to climate change. Identification of key risks, research needs and prioritization of adaptation responses has also been discussed.

The Report has been structured in eight chapters which include (i) Introduction, (ii) Water resources of India, (iii) Global scenario, (iv) Initiatives taken by MoWR/GoI, (v) Trends of climate change in India, (vi) Impacts of climate change on water resources for selected Basins, (vii) Adaptation strategies and (viii) Future directions.

Chapter 1 has been mainly devoted to the background information related to definition of climate change being referred by IPCC & UNFCCC and considered in this Report; Greenhouse effect and global warming; Warming of Indian sub-continent; GCM/RCM and climate predictions; Climate prediction for India; Climate change and water resources; Importance of Glaciers in climate change studies; and Impacts of climate change have been briefed. An analysis of temperature data of all over India shows an increase of 0.42^0 C, 0.92^0 C and 0.09^0 C in annual mean temperature, mean maximum temperature and mean minimum temperature respectively in last 100 years. However, the trends are varying on regional basis. It has been observed that the changes in temperature in India/Indian-Subcontinent over last century are broadly consistent with global trend of increase in temperature.

Scenarios of future climate change are usually developed using the GCMs with different scenarios of GHG emissions. For generating future climate scenarios on regional basis there are downscaling models called RCMs which use output of GCMs. However, RCMs do not give basin level scenarios.

Glaciers are considered as proxy records of climate change. The Himalayan region, called the "*Water Tower of Asia*", supports 9575 glaciers in India having an area of about 18000 km^2 and a volume of about 1300 km^3. The main river basins fed by glaciers are the Indus, the Ganga and the Brahmaputra. During lean season, river flows in these basins depend on the glacier melt which is vital for all kind of human and environmental activities. The temperature rise is going to affect natural process of Glaciation and de-glaciation and thus the human and environmental activities.

Chapter 2 deals with Surface water resources including River basins in India & Surface water storage; Groundwater resources covering Groundwater resources availability and utilisation scenarios & Stage of Groundwater Development; and Glacier resources of Indian Himalaya. Out of the total precipitation, including snowfall, of around 4000 km^3 in the country, the availability from surface water and replenishable groundwater is estimated as 1869 km^3. Due to various constraints of topography, uneven distribution of resource over space and time, it has been estimated that only about 1123 km^3 including 690 km^3 from surface water and 433 km^3 from groundwater resources can be put to beneficial use. River basin is considered the basic hydrologic unit for planning and development of water resources. There are 12 major river basins and 46 medium river basins in the country. All the major river basins and many medium river basins are inter-state in nature which cover about 81% of the geographical area of the country.

Extreme conditions exist in the country – there are floods followed by droughts. About 40 mha of area is flood-prone which constitute 12% of total geographical area of the country. Droughts are also experienced due to deficient rainfall. It has been found that 51 mha area is drought prone which constitute 16% of total geographical area.

A total storage capacity of 225.14 km^3 has been created in India and expected storage capacity through completed, on-going and contemplated Projects would be 390.34 km^3 against total utilisable surface water resources availability of 690.31 km^3 in the river basins of the country.

The stage of groundwater development in the country is 58%. Growing demand of water in agriculture, industrial and domestic sectors, has brought problems of over-exploitation of the groundwater resource, continuously declining groundwater levels, sea water ingress in coastal areas, and groundwater pollution in different parts of the country.

Global Scenario has been briefed in **Chapter 3**. There are various agencies which are working on Climate Change issues on global scale which include IPCC, UNFCCC, UNDP, WMO, UNESCO, World Bank etc. IPCC has since brought out its fourth report on the issue and reported rising trend in concentration of GHGs leading to global warming of varying degrees across the globe and further rising has been predicted. It has been predicted that Climate Change would impact hydrological cycle in a big way globally however, its impacts on regional or basin level are yet to be studied. Many of the countries including USA, European Union, China, Japan etc. have already started works/studies for understanding the impacts at local level and discussions have begun for adaptation/ mitigation measures.

Chapter 4 summarizes the initiatives taken by MoWR, GoI in respect of impacts of climate change on water resources. For studying impacts on water resources in India, MoWR has already started its activities and finalized an Action Plan which culminates in the organization of an International sympozium in May 2012. The Plan envisages development of appropriate model for three major basins viz. Indus, Ganga and Brahmaputra and one of the peninsular rivers for prediction of the flow series under varying climate conditions. A Standing Committee has also been constituted for "Assesment of Impacts of Climate Change on Water Resources" under the Chairman, CWC which looks after the overall coordination and direction on the subject with the related organizations.

Recognizing the need of more interaction between academic research and applied engineering and technology, MoWR has decided for establishment of Chair Professors in six academic Institutes including four IITs at Roorkee, Kanpur, Kharagpur & Guwahati and two NITs at Patna & Srinagar. IIT Roorkee and NIT Srinagar will mainly work on Indus basin, IIT Kanpur and NIT Patna will mainly work on Ganga basin and IIT Kharagpur and IIT Guwahati will mainly work on Brahmaputra basin.

NWA/CWC and NIH have organized National workshop and Brain stroming session respectively on the related subjects and come out with relevant recommendations which are detailed under para 4.3 "Knowledge sharing" of the Report. Related scintific stuides have also been compiled and published as "Jalvigyan Sameeksha" (Hydrology Review), and in the form of State of the Art Report by NIH. Various Organizations and Academic Institutes which are engaged in various facets of the Impacts on Water Resources have been listed under para 4.5 "Initiative taken/Studies conducted by different Organizations". CWC is establishing six new sites for snow and other weather parameters observations in the catchments of Yamuna, Ganga, Chenab and Beas basins in addition to modernization of the existing sites in XI FYP.

Trends of Climate Change in India mainly covering the aspects of Future scenario of temperature, Collaborative Programme of MoEF & DEFRA, and Regional projections of climate change over India have been briefed in section 'Temperature' of the **Chapter 5**. Sub-section 'Rainfall' talks about

Future scenario of rainfall, Study by IITM and Study by IISc. Study on trends of River Flows carried out by CWC alongwith its limitations and Observations of GSI have also been covered in different sub-sections. The Needs for further research on the related aspects of temperature, rainfall and river flows have been indicated.

In **Chapter 6** a stock has been taken of “Basin-wise Impacts of Climate Change on Water Resources” particulalrly of Indus, Ganga and Brahmaputra basins incorporating Water Resources availability, development in context of Irrigation, hydropower, flood management and qualitative aspects and reported glacier retreat position. Various studies conducted by Research Institutes incluidng NIH specifically on glaciology and various scenario generation according to the likely climatic conditions have been compiled. A discussion on the areas already covered for studies and probable areas to be taken up have been included for each basin.

It would be slightly preposterous to discuss about adaptation or mitigation strategies as the relaible understanding of the various impacts due to likely climate change at basin level are yet to develop. However, considering the likely impacts as projected at global or regional level, some thought has been given on adaptation strategies, in **Chapter 7**, which include Assessment of water resources, Hydrological design practices and dam safety, Operation policies for water resources projects, Flood management strategies, Drought management strategies, Temporal & spatial assessment of water for Irrigation, Land use & cropping pattern, Coastal zone management strategies. However, the proposed adaptation measures would continue to change and evolve further as the results of the needed studies come in the future.

The possible future directions on various related issues have also been brought out in **Chapter 8**. These include Data collection; Scientific studies; Networking of the Institutions; Watch on impacts on other sectors; River basin-wise studies; Mitigation measures; River basin organisation; Flood management; Involvement of academicians and capacity building; and Awareness programme etc.

1. Introduction

1.1 What is climate change

Climate in a narrow sense is defined as "average weather", or more rigorously, as the statistical description in terms of mean and variability of relevant quantities of weather parameters over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by WMO. These parameters are most often surface variables such as temperature, precipitation and wind. Climate change in IPCC usage refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that of UNFCCC which defines climate change as, "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". Climate change is not only a major global environmental problem, but also an issue of great concern to a developing country like India.

In this Report no distinction has been made between climate change induced because of human activities or natural variability. Some natural factors are changes in the Sun's intensity; the Earth's orbit; Ocean circulation; Volcanic eruptions etc. Similarly, Human Factors include changes in the land use pattern, burning fossil fuel and release of GHG.

1.2 Greenhouse effect and global warming

The earth's atmosphere - the layer of air that surrounds the earth - contains many gases. Short-wave radiation from the sun passes through the earth's atmosphere. Partly this radiation is reflected back into space, absorbed by the atmosphere and remainder reaches the earth's surface, where it is either reflected or absorbed. In turn the earth's surface, emits long-wave radiation toward space. The GHG available in the atmosphere, which principally include CO_2, NO_2, CH_4, CFCs and O_3, absorb some of this long-wave radiation emitted by the Earth's surface and re-radiate it back to the surface. Thus GHG modify the heat balance of the Earth by retaining long-wave radiation that would otherwise be dispersed through the Earth's atmosphere to space. This effect is known as the greenhouse effect. Evidently, GHG have an important role in controlling the temperature of the earth and an increase in their concentration in the atmosphere would increase the temperature of the Earth. In addition, presence of excess quantities of CFCs affects the protective ozone layer which deflects the harmful short wave rays. The IPCC observed that global average air temperature near earth's surface rose to $0.74 \pm 0.18\ ^0C$ in the last century. A schematic diagram showing components of the global climate system their process and interactions and some aspects that may change are shown in Figure - 1.

1.3 Warming of Indian sub-continent

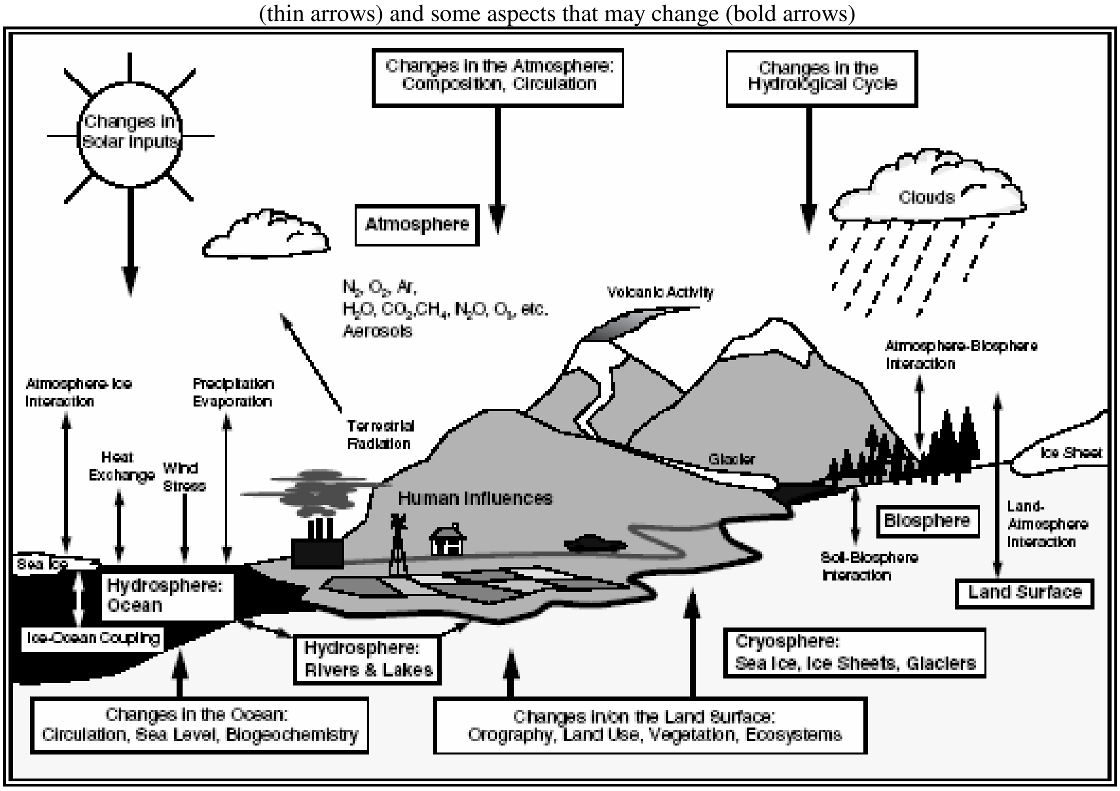
Studies have been carried out by NIH to analyze the trends of variation in temperature over India/Indian Sub-continent and the results have been compared with global trend. An analysis of temperature data of 125 stations distributed all over India shows an increase of 0.42^0 C, 0.92^0 C and 0.09^0 C in annual mean temperature, mean maximum temperature and mean minimum temperature respectively over the last 100 years. However, the trends are varying on regional basis. It has been observed that the changes in temperature in India/Indian-Subcontinent over last century are broadly consistent with global trend of increase in temperature.

1.4 GCM/RCM and climate predictions

Scenarios of future climate change are usually developed using the GCMs with different scenarios of GHG emissions. GCMs are complex 3-dimensional models of the land, atmosphere and oceans. GCMs are invaluable tools for identifying climatic sensitivities and changes in global climate characteristics, the major problem of the current generation of

GCMs is the limitation of their spatial resolution. A single grid of GCM may encompass hundreds of square kilometers and include mountainous and desert terrain, oceans and land areas. Usually, the output of GCMs is given for a scale much larger than that of even a large watershed. There are more than 200 GCMs available which have been developed by different agencies. Input data requirement for the these GCMs are generally same but the output results vary and sometimes with slight variation in input parameters (which may be due to different data collection agencies) the results are contradictory giving confusing future climate scenarios. Despite recent improvements in modeling of the climate dynamics with complex and large-scale models, use of GCMs is still limited in evaluating regional details of climatic changes. For generating future climate scenarios on regional basis there are downscaling models called RCMs which use output of GCMs. However, RCMs do not give basin level scenarios.

Figure - 1 Schematic view of the components of the global climate system (bold) their process and interactions (thin arrows) and some aspects that may change (bold arrows)



1.5 Climate prediction for India

Studies related to the impacts of climate change on various components of the hydrological cycle may be classified broadly into two categories: (i) studies using GCM/RCMs directly to predict impact of climate change scenarios (ii) studies using hydrological models with assumed plausible hypothetical climatic inputs.

IITM is active in studying long-term climate change from observed and proxy data as well as model diagnostics and assessment of climatic impacts, with a particular focus on the Indian summer monsoon. IITM used the Hadley Centre Regional Climate Models (RCMs) for the Indian subcontinent to model the potential impacts of climate change.

The RCMs have shown significant improvements over the global models in depicting the surface climate over the Indian region, enabling the development of climate change scenarios with substantially more regional detail. High-resolution climate change scenarios have been generated for different states of India. Some of the major findings concerning water resources are:

- The rainfall scenarios are dependent on climate scenarios.
- There are substantial spatial differences in the projected rain fall changes. The maximum expected increase in rainfall (10 to 30%) is for central India.
- There is no clear evidence of any substantial change in the year-to-year variability of rainfall over the next century.
- Surface air temperature shows comparable increasing trends by as much as 3 to 4° C towards the end of the 21st century.
- The warming is widespread over the country, and relatively more pronounced over northern parts of India.

1.6 Climate change and water resources

Temperature drives the hydrological cycle, influencing hydrological processes in a direct or indirect way. A warmer climate may lead to intensification of the hydrological cycle, resulting in higher rates of evaporation and increase of liquid precipitation. These processes, in association with a shifting pattern of precipitation, may affect the spatial and temporal distribution of runoff, soil moisture, groundwater reserves etc. and may increase the frequency of droughts and floods. Figure - 2 shows a conceptual model of the effect of GHG and global warming on the hydrologic cycle and phenomena associated with climate extreme. The future climatic change, though, will have its impact globally but likely to be felt severely in developing countries with agrarian economies, such as India. Surging population, increasing industrialization and associated demands for freshwater, food and energy would be areas of concern in the changing climate scenarios. Increase in extreme climatic events will be of great consequence owing to the high vulnerability of the region to these changes.

1.7 Importance of Glaciers in climate change studies

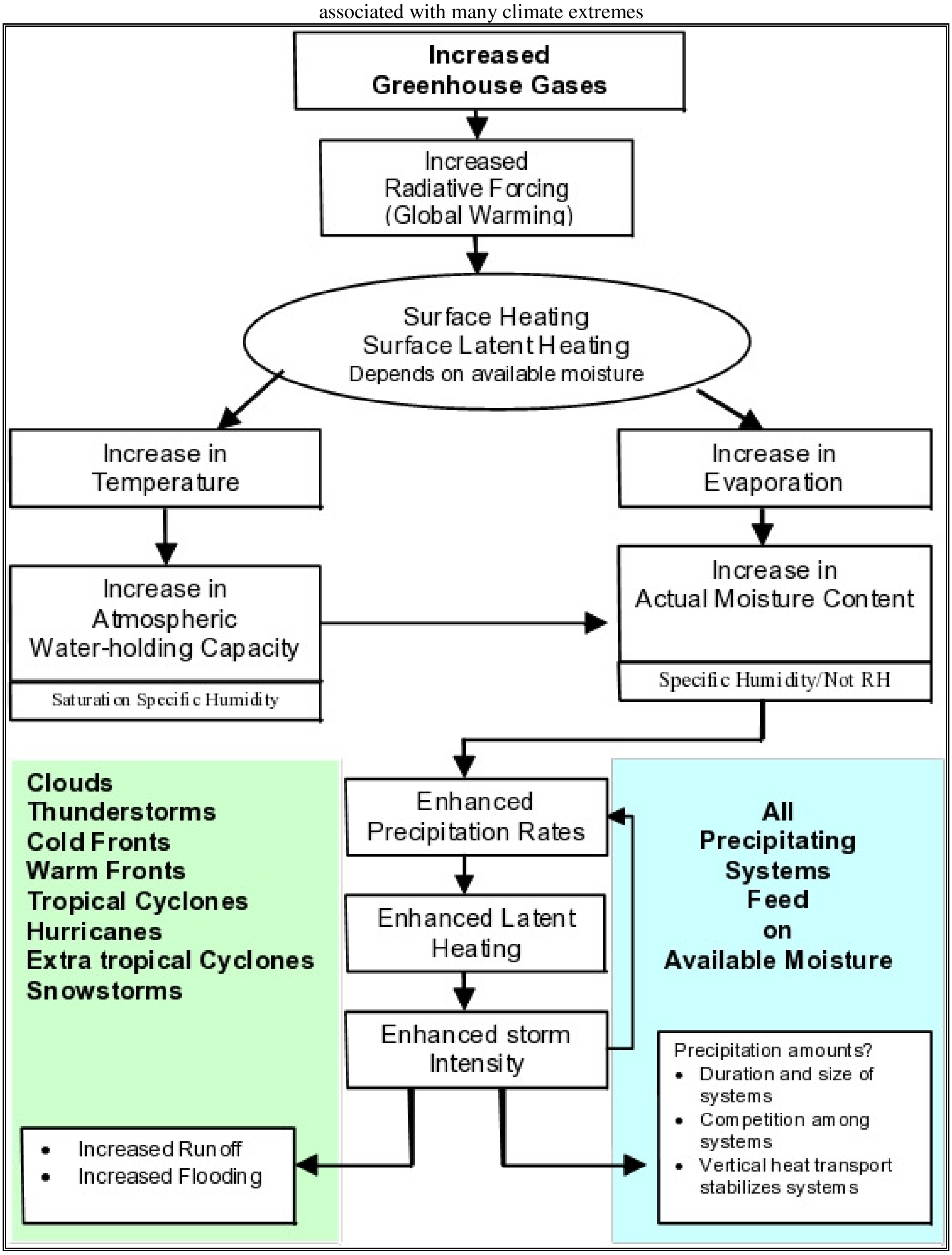
Glaciers and ice sheets are considered as proxy records of climate change. Sensitivity of the glaciers and their wide-spread distribution in space makes them most suitable as proxy records of climate change. The trails left by the advancing/retreating glaciers viz. erosional terraces, glacial deposits, etc. also make them the best available indicators of climatic variations in the past and can form the basis for connecting the dis-continuous time series of glacier fluctuations. Glacier advance and retreat are both a consequence and cause of the climate change. Glaciation and de-glaciation is a continuous natural process.

The Himalayan region, called the "*Water Tower of Asia*", supports 9575 glaciers in India having an area of about 18000 km^2 and a volume of about 1300 km^3. The main river basins fed by glaciers are the Indus, which rises near Mansarovar in Tibet; the Ganga that originates from Gangotri glacier in Uttarakhand; and the Brahmaputra, which also starts its journey from Mansarovar in Tibet but eastwards. During lean season, river flows in these basins largely depend on the glacier melt which is vital for all kind of human and environmental activities. The temperature rise is going to affect the natural process of glaciation and de-glaciation and thus the human and environmental activities.

1.8 Impacts of climate change

The projections indicate that the warming would vary from region to region, accompanied by increases and decreases in precipitation. In addition, there would be changes in the variability of climate, and changes in the frequency and intensity of some extreme climatic phenomenon. Flood magnitude and frequency are likely to increase in most regions, and low flows are likely to decrease in many regions. However, there have been very few studies addressing the issue directly, largely due to difficulties in defining credible scenarios for changes in flood producing climatic events. Therefore, as may be observed from the findings reported in para 1.6, studies using hydrological models with assumed plausible hypothetical climatic inputs would be useful for assessing impacts of climate change on water resources.

Figure - 2 Conceptual model of the effect of GHG and global warming on the hydrologic cycle and phenomena associated with many climate extremes



Water resources will come under increasing pressure in the Indian subcontinent due to the changing climate. An attempt has been made here to give a brief account of the possible impacts of climate change on India's water resources, change in India's water needs, climate of India, river basins of the country, present water resources and future demand and supply, impacts of projected climate change and variability, and associated hydrological events and vulnerability of regional water resources to climate change. Identification of key risks, research needs and prioritization of adaptation responses have also been discussed.

2. Water Resources of India

2.1 Surface water resources

Out of the total precipitation, including snowfall, of around 4000 km^3 in the country, the availability from surface water and replenishable groundwater is estimated as 1869 km^3. Due to various constraints of topography, uneven distribution of resource over space and time, it has been estimated that only about 1123 km^3 including 690 km^3 from surface water and 433 km^3 from groundwater resources can be put to beneficial use. Table - 1 shows the water resources of the country at a glance. Many Indian rivers are perennial, though few are seasonal. This is because precipitation over a large part of India is concentrated in the monsoon season during June to September/October. Precipitation varies from 100 mm in the western parts of Rajasthan to over 11000 mm at Cherrapunji in Meghalaya. Rivers do not, however, remain at a high stage throughout the monsoon season. It is only a spell of heavy rains, which may last for a period of several hours to few days that generates large run-off in the catchments.

Table - 1 Water resources of India

Estimated annual precipitation (including snowfall)	4000 km^3
Average annual potential in rivers	1869 km^3
Estimated utilisable water	1123 km^3
(i) Surface	690 km^3
(ii) Ground	433 km^3
Water demand ≈ utilization (for year 2000)	634 km^3
(i) Domestic	42 km^3
(ii) Irrigation	541 km^3
(iii) Industry, energy & others	51 km^3

Extreme conditions exist in the country – there are floods followed by droughts. Due to excess rainwater, floods occur in certain parts. It has been estimated by RBA that 40 mha of area is flood-prone which constitute 12% of total geographical area of the country. Droughts are also experienced due to deficient rainfall. It has been found that 51 mha area is drought prone which constitute 16% of total geographical area.

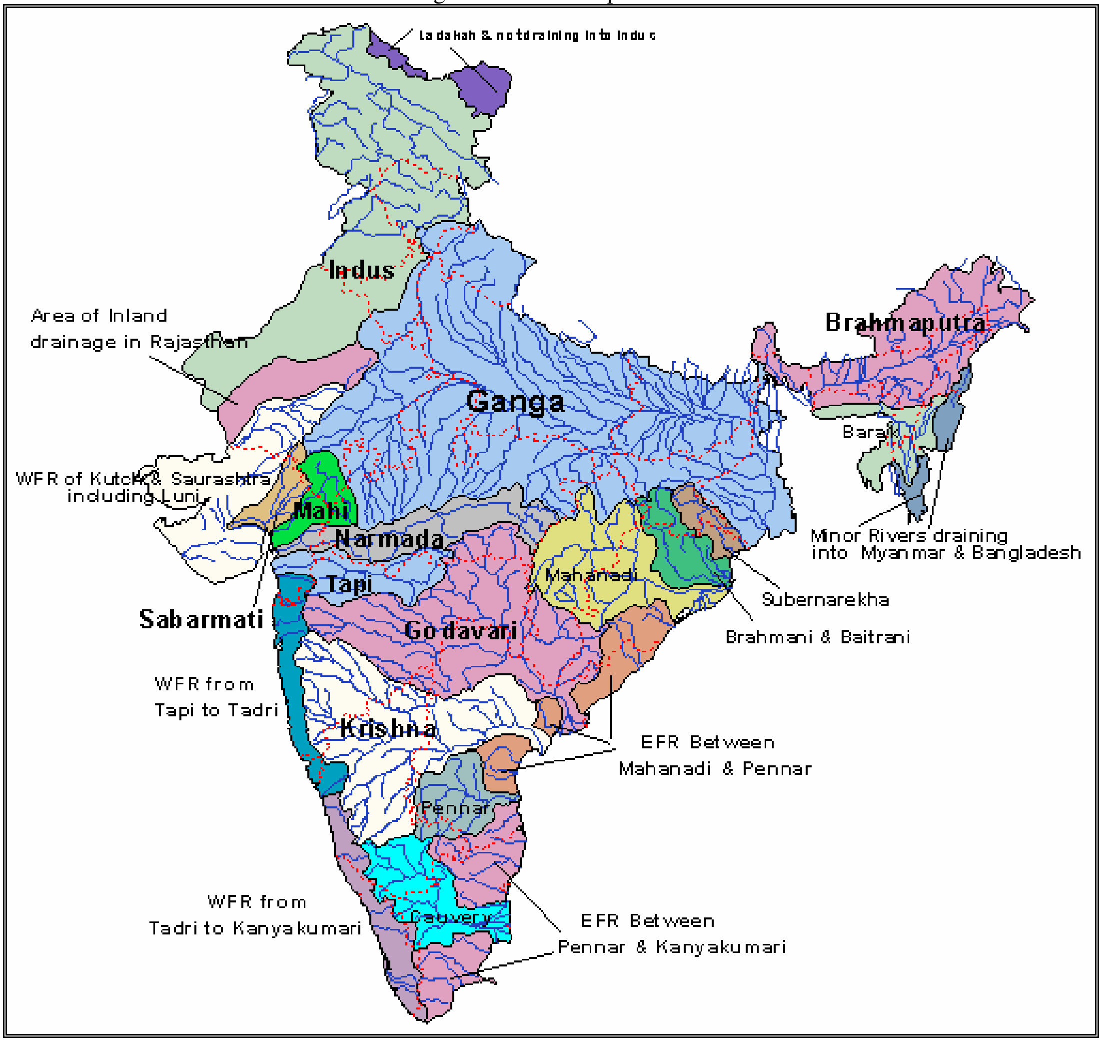
The population of the country has increased from 361 million in 1951 to 1130 million in July 2007. Accordingly, the per capita availability of water for the country as a whole has decreased from 5177 m^3/year in 1951 to 1654 m^3/year in 2007. Due to spatial variation of rainfall, the per capita water availability also varies from basin to basin. The distribution of water resources potential in the country shows that the average per capita water availability in Brahmaputra & Barak basin was about 14057 m^3/year whereas it was 308 m^3/year in Sabarmati basin in year 2000.

2.1.1. River basins in India

River basin is considered the basic hydrologic unit for planning and development of water resources. There are 12 major river basins with catchment area of 20000 km^2 and above. The total catchment area of these rivers is 25.3 lakh km^2. The major river basin is the Ganga-Brahamputra-Meghna system, which is the largest with catchment area of about 11.0 lakh km^2 (more than 43% of the catchment area of all the major rivers in the country). The other major river basins with catchment area more than one lakh km^2 are Indus, Mahanadi, Godavari and Krishna. There are 46 medium river basins with catchment area between 2000 and 20000 km^2. The total catchment area of medium river basins is about 2.5 lakh km^2. All major river basins and many medium river basins are inter-state in nature which cover about 81% of the geographical area of the country.

For the purpose of planning and development, in addition to 12 major river basins, eight composite river basins combining suitably together all the remaining medium and small river systems have been considered. Thus the entire country has been divided into twenty river basins as shown in the Figure - 3.

Figure - 3 Basin Map of India



The details of water resources potential of these river basins are given in Table - 2 below:

Table - 2 Water resources of Major river basins of the country

River Basin	*Catchment area (km^2)*	*Average annual potential (km^3)*	*Utilisable surface water resources (km^3)*
Indus (up to Border)	321289 (1165500)	73.31	46.00
a) Ganga	861452 (1186000)	525.02	250.00
b) Brahmaputra c) Barak and others	194413 (580000) + 41723	585.60	24.00
Godavari	312812	110.54	76.30
Krishna	258948	78.12	58.00
Cauvery	81155	21.36	19.00
Subernarekha	29196	12.37	6.81
Brahmani & Baitarni	51822	28.48	18.30
Mahanadi	141589	66.88	49.99
Pennar	55213	6.32	6.86
Mahi	34842	11.02	3.10
Sabarmati	21674	3.81	1.93
Narmada	98796	45.64	34.50
Tapi	65145	14.88	14.50

River Basin	Catchment area (km^2)	Average annual potential (km^3)	Utilisable surface water resources (km^3)
WFR from Tapi to Tadri	55940	87.41	11.94
WFR from Tadri to Kanyakumari	56177	113.53	24.27
EFR between Mahanadi & Pennar	86643	22.52	13.11
EFR between Pennar & Kanyakumari	100139	16.46	16.73
WFR of Kutch & Saurashtra including Luni	321851	15.10	14.98
Area of Inland drainage in Rajasthan	-	Negligible	Not applicable
Minor Rivers draining into Myanmar & Bangladesh	36202	31.00	Not applicable
Total		**1869.35**	**690.31**

2.1.2. Surface water storage

As per latest information furnished by the State Governments, total storage capacity of 218.90 km^3 has been created in India by the Projects having a live storage capacity of 10 hm^3 and more. The projects under construction will add up another 63.90 km^3 as given in the Table - 3 below. An additional live storage capacity of 6.24 km^3 is estimated to be created through medium projects each having a capacity of less than 10 hm^3 thus making a total live storage capacity of 225.14 km^3 in completed Projects. Therefore expected storage capacity through completed, on-going and contemplated Projects would be 390.34 km^3 against total utilisable surface water resources availability of 690.31 km^3 in the river basins of the country. The Krishna basin leads in term of storage capacity (41.80 km^3) followed by Godavari basin (25.12 km^3) and Narmada basin (16.98 km^3).

Table - 3 Basin-wise status of water storage development

River Basin	Live Storage Capacities of Projects (km^3)					% of grand total of live storage capacities with respect to	
	Completed	Under construction	Total	Under consideration	Grand Total (4) + (5)	average annual potential	utilisable surface water resources
1	2	3	4	5	6	7	8
Indus (up to Border)	16.29	0.28	16.57	2.58	19.14	26.12	41.62
a) Ganga	42.06	18.60	60.66	30.08	90.74	17.28	36.30
b) Brahmaputra, Barak and others	2.33	9.35	11.68	41.26	52.94	9.04	220.60
Godavari	25.12	6.21	31.33	5.84	37.17	33.63	48.72
Krishna	41.80	7.74	49.55	1.13	50.68	64.87	87.37
Cauvery	8.60	0.27	8.87	0.26	9.13	42.74	48.05
Subernarekha	0.67	1.65	2.32	1.38	3.70	29.94	54.37
Brahmani & Baitarni	4.65	0.88	5.52	8.72	14.24	50.02	77.84
Mahanadi	12.33	1.87	14.21	10.09	24.30	36.34	48.61
Pennar	2.65	2.17	4.82	0.00	4.82	76.32	70.26
Mahi	4.72	0.26	4.98	0.01	5.00	45.33	161.16
Sabarmati	1.31	0.06	1.37	0.10	1.47	38.51	76.00
Narmada	16.98	6.63	23.60	0.47	24.07	52.74	69.77
Tapi	9.41	0.85	10.26	0.29	10.54	70.86	72.71
WFR from Tapi to Tadri	11.27	3.46	14.73	0.08	14.81	16.95	124.07
WFR from Tadri to Kanyakumari	10.24	1.32	11.55	1.45	13.01	11.46	53.59
EFR between Mahanadi & Pennar	1.60	1.42	3.03	0.95	3.97	17.64	30.30
EFR between Pennar &	1.84	0.07	1.91	0.00	1.91	11.59	11.40

River Basin	*Live Storage Capacities of Projects (km^3)*					*% of grand total of live storage capacities with respect to*	
	Completed	*Under construction*	*Total*	*Under consideration*	*Grand Total (4) + (5)*	*average annual potential*	*utilisable surface water resources*
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Kanyakumari							
WFR of Kutch & Saurashtra including Luni	4.73	0.80	5.52	2.85	8.37	55.46	55.90
Area of Inland drainage in Rajasthan	-	-	-	-	-	-	-
Minor Rivers draining into Myanmar & Bangladesh	0.31	-	0.31	-	0.31	1.01	-
Total	**218.90**	**63.90**	**282.80**	**107.54**	**390.34**	**20.88**	**61.93**

Pennar basin leads (76.32%) in terms of storage capacity created, under construction and under considertion as percentage of average annual flow followed by Tapi basin (70.86%) which even otherwise has requirement for higher storage capacity as it covers the semi desert areas of Madhya Pradesh, Maharashtra & Gujarat. The West Flowing Rivers of Kutch, Shaurashtra including Luni, Krishna, Narmada and Brahmani & Baitarni basins exceed 50% capacity of their respective average annual potential. The storage percentage is, however, less than 25% in few basins and in some big basins like Brahmaputra, Barak and others the percentage is as low as 9.04%. A illustrasion showing percentage of storage created; storage created + under construction; and storage created + under construction + under consideration in various basins with respect to average annual flow of different basins has been shown in Figure - 4 and similalrly with respect to utilisable surface water resources has been shown in Figure - 5.

Figure - 4 % of storage created; storage created + under construction; and storage created + under construction + under consideration with respect to average annual flow

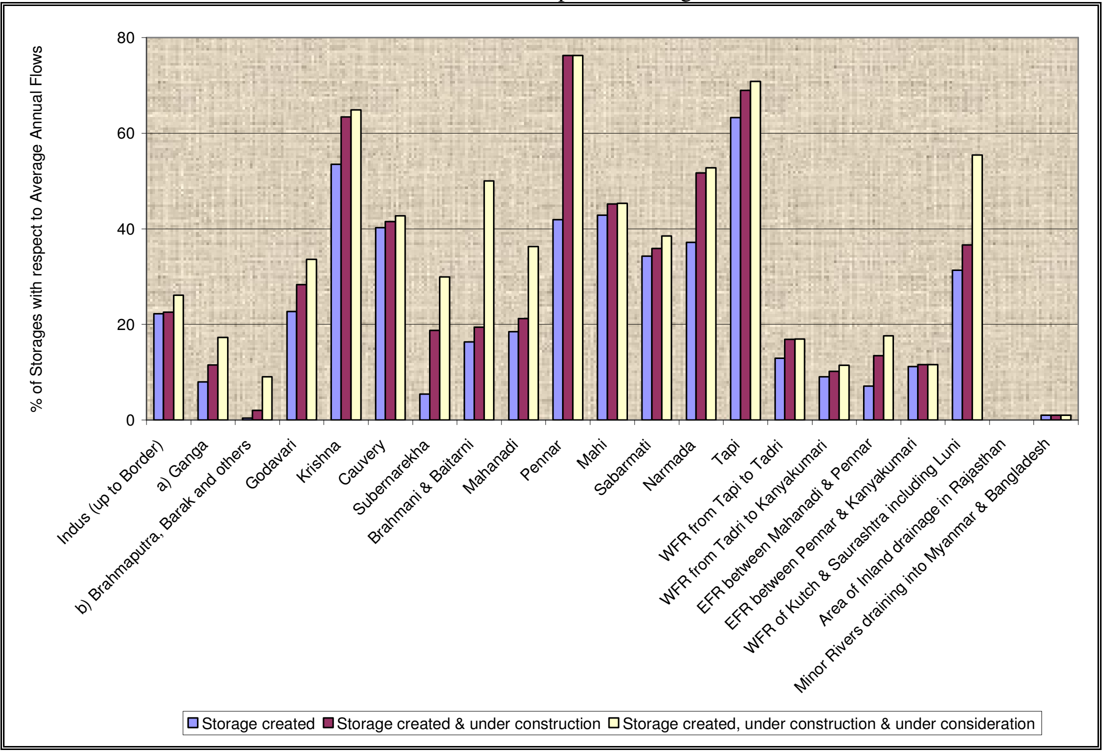
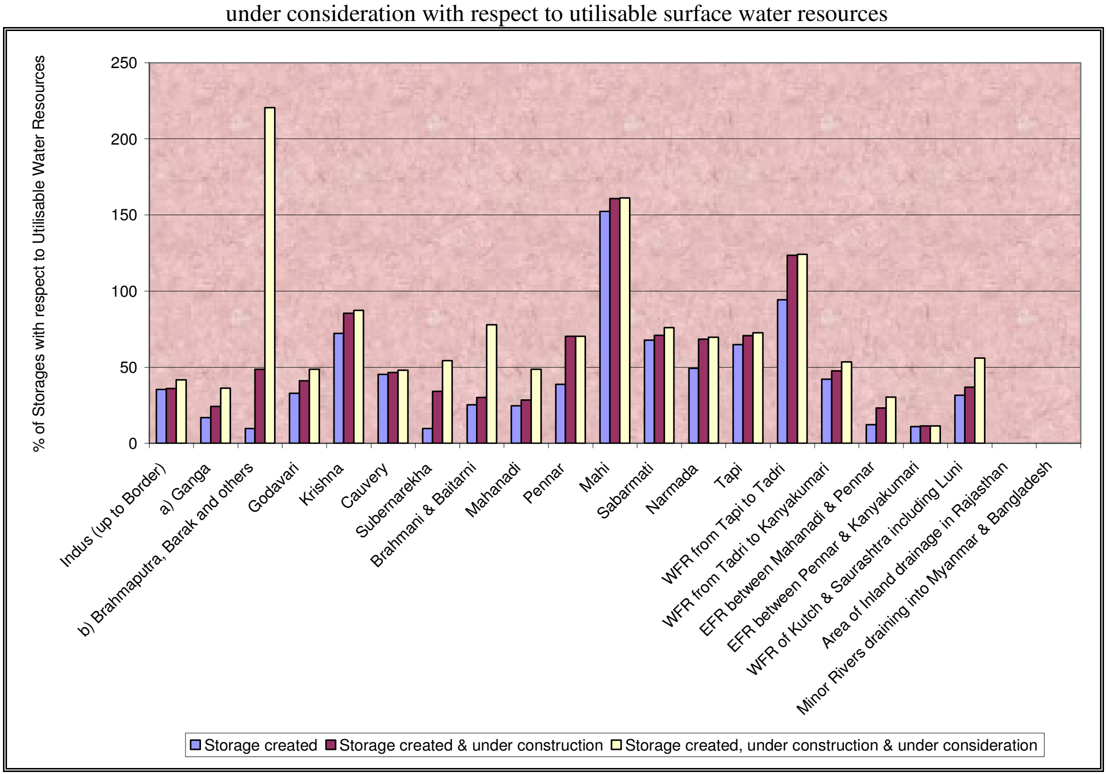


Figure - 5 % of storage created; storage created + under construction; and storage created + under construction + under consideration with respect to utilisable surface water resources

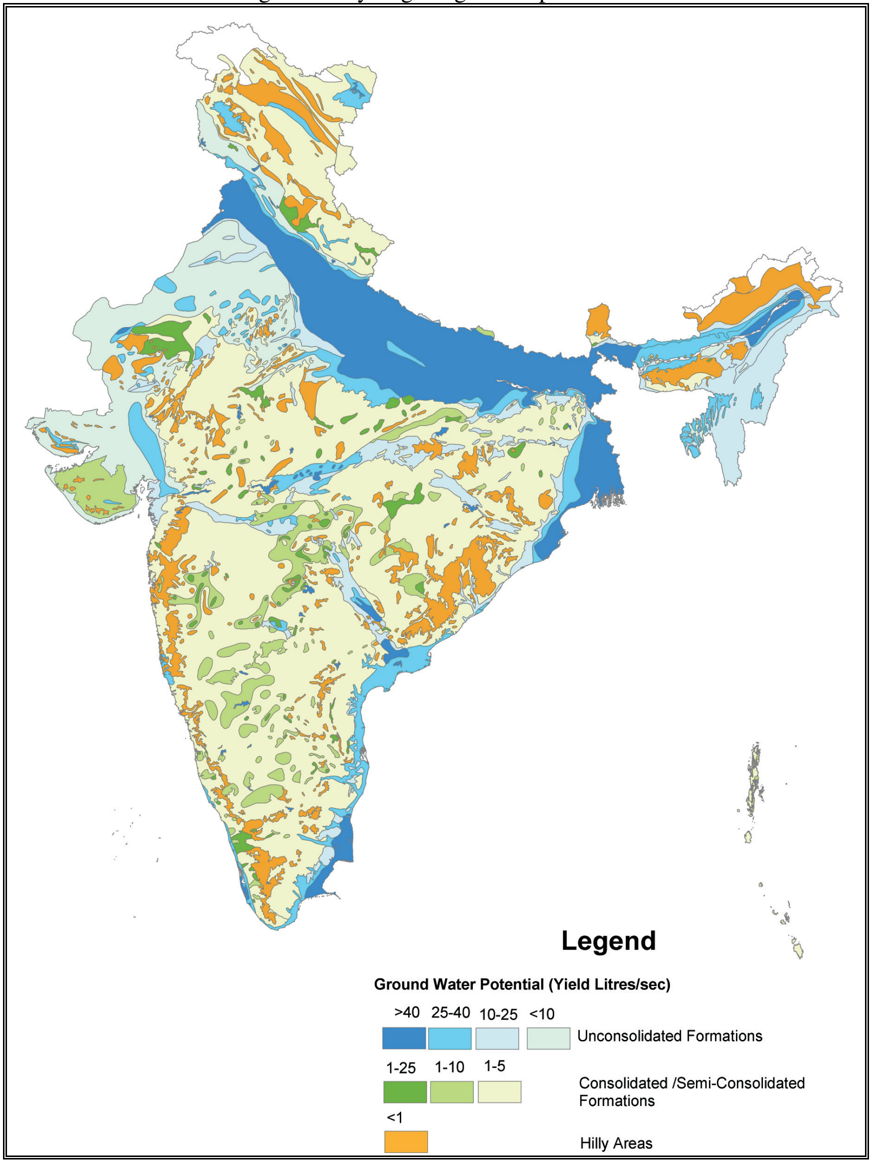


It may be seen from above figures that there is rapid development planned in the Brahmputra Barak & others basin followed by Brahmani & Baitarni and WFR of Kutch & Saurashtra including Luni basins. The storage development envisaged in the Brahmputra Barak & others and WFR from Tapi to Tadri basins is more than the assessed utilisable surface water resources in those basins whereas in Mahi basin the created storage is already more than the assessed utilisable surface water resources.

2.2 Groundwater resources

The groundwater resources have two components, viz. static and dynamic. The static fresh groundwater reserves (aquifer zones below the zone of groundwater table fluctuation) of the country have been estimated as 10812 km^3. The dynamic component is replenished annually, which has been assessed as 433 km^3. The hydrogeological map of the country showing different formations of groundwater potential with respect to its yield in litres/sec is given at Figure - 6.

Figure - 6 Hydrogeological Map of India



According to the NWP, development of groundwater resources is to be limited to utilization of the dynamic component of groundwater. The available State-wise RGWR, utilization and stage of development are given in the Table - 4.

Table - 4 Basin-wise Replenishable Groundwater Resources

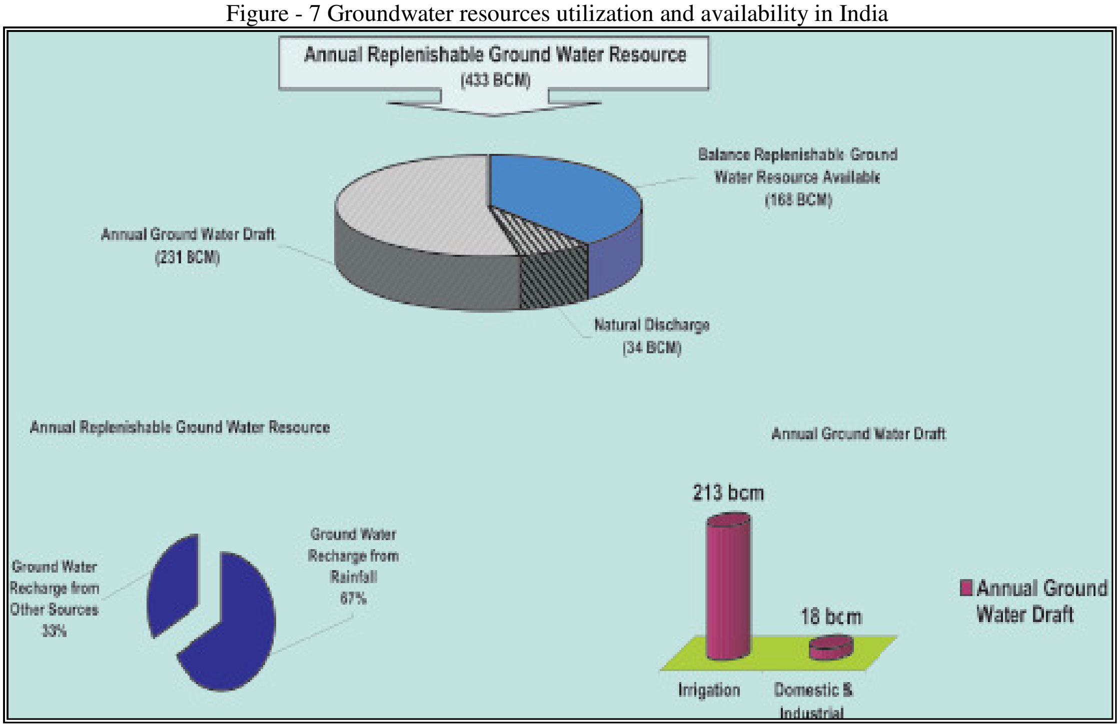
(in bcm)

Sl. No.	States / Union Territories	Annual Replenishable Ground Water Resource					Natural Discharge during non-monsoon season	Net Annual Ground Water Availability	Annual Ground Water Draft			Projected Demand for Domestic and Industrial uses upto 2025	Ground Water Availability for future irrigation	Stage of Ground Water Development (%)
		Monsoon Season		Non-monsoon Season		Total			Irrigation	Domestic and industrial uses	Total			
		Recharge from rainfall	Recharge from other sources	Recharge from rainfall	Recharge from other sources									
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	States													
1	Andhra Pradesh	16.04	8.93	4.20	7.33	36.50	3.55	32.95	13.88	1.02	14.90	2.67	17.65	45
2	Arunachal Pradesh	1.57	0.00009	0.98	0.0002	2.56	0.26	2.30	0.0008	0	0.0008	0.009	2.29	0.04
3	Assam	23.65	1.99	1.05	0.54	27.23	2.34	24.89	4.85	0.59	5.44	0.98	19.06	22
4	Bihar	19.45	3.96	3.42	2.36	29.19	1.77	27.42	9.39	1.37	10.77	2.14	15.89	39
5	Chattisgarh	12.08	0.43	1.30	1.13	14.93	1.25	13.68	2.31	0.48	2.80	0.70	10.67	20
6	Delhi	0.13	0.06	0.02	0.09	0.30	0.02	0.28	0.20	0.28	0.48	0.57	0.00	170
7	Goa	0.22	0.01	0.01	0.04	0.28	0.02	0.27	0.04	0.03	0.07	0.04	0.18	27
8	Gujarat	10.59	2.08	0.00	3.15	15.81	0.79	15.02	10.49	0.99	11.49	1.48	3.05	76
9	Haryana	3.52	2.15	0.92	2.72	9.31	0.68	8.63	9.10	0.35	9.45	0.60	-1.07	109
10	Himachal Pradesh	0.33	0.01	0.08	0.02	0.43	0.04	0.39	0.09	0.02	0.12	0.04	0.25	30
11	Jammu & Kashmir	0.61	0.77	1.00	0.32	2.70	0.27	2.43	0.10	0.24	0.33	0.42	1.92	14
12	Jharkhand	4.26	0.14	1.00	0.18	5.58	0.33	5.25	0.70	0.38	1.09	0.56	3.99	21
13	Karnataka	8.17	4.01	1.50	2.25	15.93	0.63	15.30	9.75	0.97	10.71	1.41	6.48	70
14	Kerala	3.79	0.01	1.93	1.11	6.84	0.61	6.23	1.82	1.10	2.92	1.40	3.07	47
15	Madhya Pradesh	30.59	0.96	0.05	5.59	37.19	1.86	35.33	16.08	1.04	17.12	1.74	17.51	48
16	Maharashtra	20.15	2.51	1.94	8.36	32.96	1.75	31.21	14.24	0.85	15.09	1.52	16.10	48
17	Manipur	0.20	0.005	0.16	0.01	0.38	0.04	0.34	0.002	0.0005	0.002	0.02	0.31	0.65
18	Meghalaya	0.79	0.03	0.33	0.005	1.15	0.12	1.04	0.00	0.002	0.002	0.10	0.94	0.18
19	Mizoram	0.03	0.00	0.02	0.00	0.04	0.004	0.04	0.00	0.0004	0.0004	0.0008	0.04	0.90
20	Nagaland	0.28	0.00	0.08	0.00	0.36	0.04	0.32	0.00	0.009	0.009	0.03	0.30	3
21	Orissa	12.81	3.56	3.58	3.14	23.09	2.08	21.01	3.01	0.84	3.85	1.22	16.78	18
22	Punjab	5.98	10.91	1.36	5.54	23.78	2.33	21.44	30.34	0.83	31.16	1.00	-9.89	145
23	Rajasthan	8.76	0.62	0.26	1.92	11.56	1.18	10.38	11.60	1.39	12.99	2.72	-3.94	125
24	Sikkim	-	-	-	-	0.08	0.00	0.08	0.00	0.01	0.01	0.02	0.05	16
25	Tamil Nadu	4.91	11.96	4.53	1.67	23.07	2.31	20.76	16.77	0.88	17.65	0.91	3.08	85
26	Tripura	1.10	0.00	0.92	0.17	2.19	0.22	1.97	0.08	0.09	0.17	0.20	1.69	9
27	Uttar Pradesh	38.63	11.95	5.64	20.14	76.35	6.17	70.18	45.36	3.42	48.78	5.30	19.52	70
28	Uttaranchal	1.37	0.27	0.12	0.51	2.27	0.17	2.10	1.34	0.05	1.39	0.08	0.68	66
29	West Bengal	17.87	2.19	5.44	4.86	30.36	2.90	27.46	10.84	0.81	11.65	1.24	15.32	42
	Total States	**247.88**	**69.51**	**41.83**	**73.15**	**432.42**	**33.73**	**398.70**	**212.38**	**18.04**	**230.44**	**29.12**	**161.92**	**58**
	Union Territories													
1	Andaman & Nicobar	-	-	-	-	0.330	0.005	0.320	0.000	0.010	0.010	0.008	0.303	4
2	Chandigarh	0.016	0.001	0.005	0.001	0.023	0.002	0.020	0.000	0.000	0.000	0.000	0.020	0
3	Dadara & Nagar Haveli	0.059	0.005			0.063	0.003	0.060	0.001	0.007	0.009	0.008	0.051	14
4	Daman & Diu	0.006	0.002	0.000	0.001	0.009	0.0004	0.008	0.007	0.002	0.009	0.003	-0.002	107
5	Lakshdweep	-	-	-	-	0.012	0.009	0.004	0.000	0.002	0.002	-	-	63
6	Pondicherry	0.057	0.067	0.007	0.029	0.160	0.016	0.144	0.121	0.030	0.151	0.031	-0.008	105
	Total UTs	**0.138**	**0.075**	**0.012**	**0.031**	**0.597**	**0.036**	**0.556**	**0.129**	**0.051**	**0.181**	**0.050**	**0.365**	**33**
	Grand Total	**248.01**	**69.59**	**41.85**	**73.19**	**433.02**	**33.77**	**399.25**	**212.51**	**18.09**	**230.62**	**29.17**	**162.29**	**58**

2.2.1. *Groundwater resources availability and utilisation scenarios*

The annual RGWR is contributed by two major sources – rainfall and other sources that include canal seepage, return flow from irrigation, seepage from water bodies and artificial recharge due to water conservation structures. The overall contribution of rainfall to country's annual RGWR is 67% and the share of other sources taken together is 33%. The over–all scenario of groundwater resources utilization and availability in the country is shown in Figure - 7.

Figure - 7 Groundwater resources utilization and availability in India



South–West monsoon being the most prevalent contributor of rainfall in the country, about 73% of country's annual replenishable groundwater recharge takes place during the Kharif period of cultivation. Keeping 34 km^3 for natural discharge, the net annual groundwater availability for the entire country is 399 km^3. The annual groundwater draft is 231 km^3 out of which 213 km^3 is for irrigation use and 18 km^3 is for domestic & industrial use. In general, the irrigation sector remains the main consumer of groundwater (92% of total annual groundwater draft for all uses). There has been considerable development in respect of utilization of groundwater resources. However, overall utilization of groundwater resources for the country as a whole is only 58% although in some of the areas (14.7% of the assessed blocks only), there are instances of over-exploitation.

2.2.2. *Stage of Groundwater Development*

The stage of groundwater development in the country is 58%. The status of groundwater development is comparatively high in the states of Delhi, Haryana, Punjab and Rajasthan and UTs of Daman & Diu and Pondicherry, where the Stage of Groundwater Development is more than 100%, which implies that in the these states, the average annual groundwater consumption is more than average annual groundwater recharge. In the states of Gujarat, Karnataka, Tamil Nadu and Uttar Pradesh, the average stage of ground development is 70% and above. In rest of the states/UTs the stage of groundwater development is below 70%.

Growing demand of water in agriculture, industrial and domestic sectors, has brought problems of over-exploitation of the groundwater resource, continuously declining groundwater levels, sea water ingress in coastal areas, and groundwater pollution in different parts of the country. The falling groundwater levels in various parts of the country have threatened the sustainability of the ground-water resource, as water levels have gone deep beyond the economic lifts of pumping. With rapid expansion in groundwater extraction, development-related problems have started emerging. Substantial decline of groundwater levels occurs even in blocks with sufficient groundwater resources due to climatic vicissitudes and localized development.

2.3 Glacier resources of Indian Himalaya

All the major north Indian rivers owe their origin to thousands of glaciers in the Himalayas. There are 9575 glaciers in the Indian Himalayas as per the latest updation of the glacier inventory maintained by the GSI. The GSI has started glaciological studies in 1840 and systematic studies involving demarcation of the glacier snout were undertaken since beginning of the last century. Compilation of glacier inventory was initiated in 1977 immediately after the constitution of the world glacier inventory body at Zurich.

The Himalaya is a large mountain system, influencing the interaction between climate, hydrology and environment. The total spread of Himalayas between latitude 25° and 35° N and longitude 60° to 105° E covers an area of 84.4 lakh km^2. The distribution of the areas at different altitudes is given in the Table - 5 as under:

Table - 5 Distribution of areas at different Altitudes in the Himalayas

Above 5400 M	5.6 lakh km^2
Above 3000 M	32.8 lakh km^2
Above 1500 M	46.0 lakh km^2
Total	**84.4 lakh km^2**

Indian part of the Himalayas above 1060 m covers an area of 3.5 lakh km^2 out of which 1.9 lakh km^2 forms a part of Jammu & Kashmir, Uttarakhand & Himachal Pradesh and the rest is covered by eastern Himalayas. Distribution of glaciers is controlled by the altitude, orientation, slope and climatic zone in which they fall. A detailed basin-wise inventory of 9575 Indian glaciers is tabulated below in the Table - 6.

Table - 6 Basin-wise inventory of Indian glaciers

Indus Basin	*No. of glaciers*	*Ganga Basin*	*No. of glaciers*
Ravi	172	Yamuna	52
Chenab	1278	Bhagirathi	238
Jhelum	133	Alaknanda	407
Beas	277	Ghagra	271
Satluj	926	Teesta	449
Indus	1796	Brahmaputra (Arunachal)	161
Shyok	2658		
Kishanganga	222		
Gilgit	535		
Total	**7997**		**1578**
Grand Total			**9575**

The Indus basin with its important tributaries flowing in Indian territory viz. Shyok, Nubra, Indus main, Satluj, Beas, Ravi, Chenab and Jhelum support majority of the Indian glaciers ie. 7997 which is 83.52% of the total Indian glaciers. There are 967 glaciers, besides Gangotri in Ganga basin including its tributaries viz. Yamuna, Bhagirathi, Alaknanda and Ghaghra. Brahmaputra basin including Teesta supports 610 glaciers. GSI has further worked out the areas of the glaciers in different basins as well as their volumes as given below in the Table - 7. The total area covered by the Indian glaciers is about 18054 km^2 whereas the volume is about 1291 km^3.

Table - 7 Basin-wise areas and volumes of Indian glaciers

Basin	*No. of glaciers*	*Area (km^2)*	*Volume (km^3)*
Indus			
Ravi	172	192.74	8.038
Chenab	1278	3058.99	206.15
Jhelum	133	94.18	3.3
Beas	277	599.06	36.94
Satluj	926	1250.86	60.99
Indus	1796	2165.46	104.6
Shyok	2658	7105.66	601.71
Kishanganga	222	174.28	5.93
Gilgit	535	8240	N.D.
Ganga			
Yamuna	52	144.47	12.21
Bhagirathi	238	755.43	67.02
Alaknanda	407	854.59	90.72
Ghagra	271	729.42	43.77
Brahmaputra			
Teesta	449	705.54	39.61
Arunachal	161	223.37	9.96
Total	**9575**	**18054.05**	**1290.95**

3. Global Scenario

3.1 IPCC on Climate Change and International Treaties

Keeping in view the scope, importance and potential of global climate change and its impact on the society, the WMO and the UNEP established the IPCC in 1988. The mandate of the IPCC is to make a comprehensive assessment of the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation. In fact, IPCC does not carry out research nor monitors climate related data or other relevant parameters. Its assessment is based mainly on peer reviewed and published scientific/technical literature. Based on the assessment, IPCC provides scientific, technical and socio-economic advice to world community, particularly to the 170 plus parties to the UNFCCC. It is open for all members of UN and WMO. The IPCC has three Working Groups and a Task Force. The objectives of each working group are well defined.

- *Working Group I* - assesses the scientific aspects of the climate system and climate change;
- *Working Group II* - assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adapting to it;
- *Working Group III* - assesses options for limiting GHG emissions and otherwise mitigating climate change; and
- *Task Force* - on National GHG Inventories is responsible for the IPCC National GHG Inventories Programme.

The panel meets in plenary sessions about once a year and evaluates the scientific development on different issues of climate change. It accepts/approves/adopts IPCC reports, decides on the mandates and work plans of the Working Groups and the Task Force. The IPCC also prepares Special Reports and Technical Papers on topics where independent scientific information and advice is deemed necessary and supports the UNFCCC through its work on methodologies for National GHG Inventories.

3.1.1. First Assessment Report of IPCC

First Assessment Report of IPCC was completed in 1990. This report played an important role in establishing the Intergovernmental Negotiating Committee for the UNFCCC by the UN General Assembly. Negotiations began in 1991 under UN auspices to formulate an international treaty on global climate protection. Those negotiations resulted in the completion by May 1992 of a FCCC. The Convention was opened for signature at the Earth Summit in Rio de Janeiro in June 1992, and it entered into force in March 1994. It provides the overall policy framework for addressing the climate change issue.

3.1.2. Second Assessment Report of IPCC

Second Assessment Report of IPCC was completed in 1995 which provided key input to the negotiations, which led to the adoption of the Kyoto Protocol. The Kyoto Protocol to the UNFCCC was adopted at third session of the COP to the UNFCCC on 11-12-97 in Kyoto, Japan. According to this protocol industrialized countries have to reduce their emissions of 6 GHG viz. CO_2, CH_4, N_2O, hydroflurocarbons, perflurocarbons, and sulfurhexafluride (excluding O_3, water vapours). Countries have to reduce emission of these GHG at least by 5% below 1990 levels in the commitment period of 5 years (2008-2012). In addition to cutting emissions from power plants and cars, developed countries can achieve their commitments by deducing the GHG emissions absorbed by some type of carbon dioxide sinks (like forests) from their gross emissions in the commitment period. Negotiations on reduction commitments for subsequent periods were to start not later than 2005. The Kyoto Protocol will enter into force 90 days after it is ratified by 55 industrialized nations, which contributed about 55% of total CO_2 emissions in 1990. Till 15-04-04, 122 countries had ratified or acceded to Kyoto Protocol. These countries represent 44.2% of total CO_2 emissions. United States, the world's largest emitter withdrew from Kyoto Protocol in March 2001. They argued that there was not enough sound science surrounding the climate change issue. Following the protocol would put a strain on the economy. They also argued that treaty does not require developing countries to curb their emissions. At present the only way that the protocol will enter into force is if Russia (17.4%) ratifies the agreement.

The legally binding emissions commitments under the Kyoto Protocol apply only to developed countries. Kyoto Protocol calls on both developed and developing countries to take a number of steps including; formulating and implementing climate change mitigation and adaptation measures, preparing national inventories of emission removals by "Carbon sinks". Cooperating in development and transfer of environmentally sound climate friendly technology, co-operating research and observations of climatic science, impact and response studies. Developing countries have no commitments to binding emissions reduction targets yet, because they are responsible for only a small portion of historic emissions.

India is also a party to the UNFCCC and the GoI attaches great importance to climate change issues. The convention aims to stabilize GHG concentrations in the atmosphere at levels that would prevent dangerous anthropogenic interference with the climate system. Eradication of poverty, avoiding risks to food production and sustainable development are three principles embedded in the Convention. Information provided in the Initial National Communications is in terms of the guidelines prescribed for Parties. Recently India has prepared inventory of gases for the base year 1994 as stipulated. Although India as a developing country does not have any commitments or responsibilities at present for reducing the emissions of GHG such as CO_2 that lead to global warming, it is likely that, sooner or later, large and rapidly developing countries such as India, China and Brazil may have to adopt a more pro-active role in controlling the GHG emissions. It is therefore, important to develop a clear understanding of our emission inventory, future projections and implications.

3.1.3. Third Assessment Report of IPCC

Third Assessment Report of IPCC was completed in 2001. It was submitted to the 7th COP to the UNFCCC and Parties agreed that it should be used routinely as a useful reference for providing information for deliberations on agenda items of the Conference of the Parties.

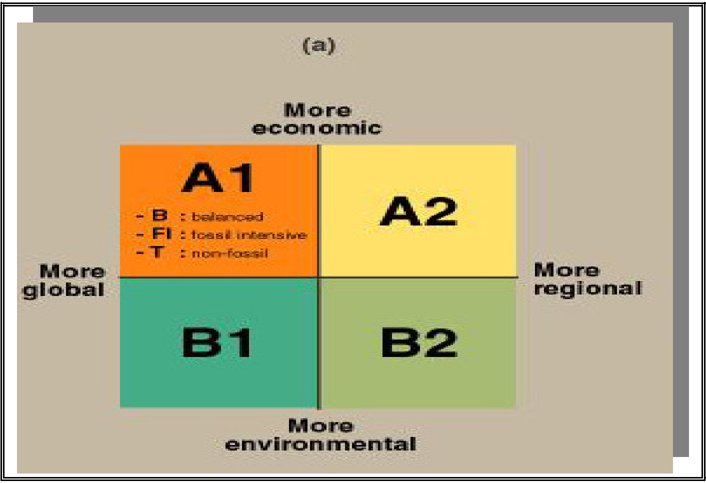
3.1.4. Executive Summary of Fourth Assessment Report of IPCC

Executive Summary of the Fourth Assessment Report of IPCC has been released in February 2007. The IPCC assessment reports point out that the major impact of global warming is on agriculture, hydrological cycle, biodiversity and the general eco-system. Important policy decisions both by developing as well as developed countries are needed to ensure that the human factor in this warming is reduced and minimized as much as possible. Environmentally sound technology and clean development mechanisms as proposed in Kyoto Protocol are needed to contain the growth of GHG. Transfer of proper technology to ensure this, is a very complex issue.

3.1.5. IPCC climate change scenarios (SRES scenarios A2, B2)

The IPCC, in their SRESs, has developed a wide range of future emissions scenarios, based on a variety of narrative 'storylines', each describing a possible future development of population, economies and energy sources. The range of scenarios includes interventions leading to reductions in sulphur emissions and introduction of new energy technologies. Any estimate of socio-economic trends over the course of the twenty-first century is necessarily very uncertain and highly subjective. Four representative SRES scenarios (A1, A2, B1 and B2), one each from the four SRES storylines and scenario families, and each of which assumes a distinctly different direction for future developments are shown in Figure - 8.

Figure - 8 IPCC climate change SRES scenarios



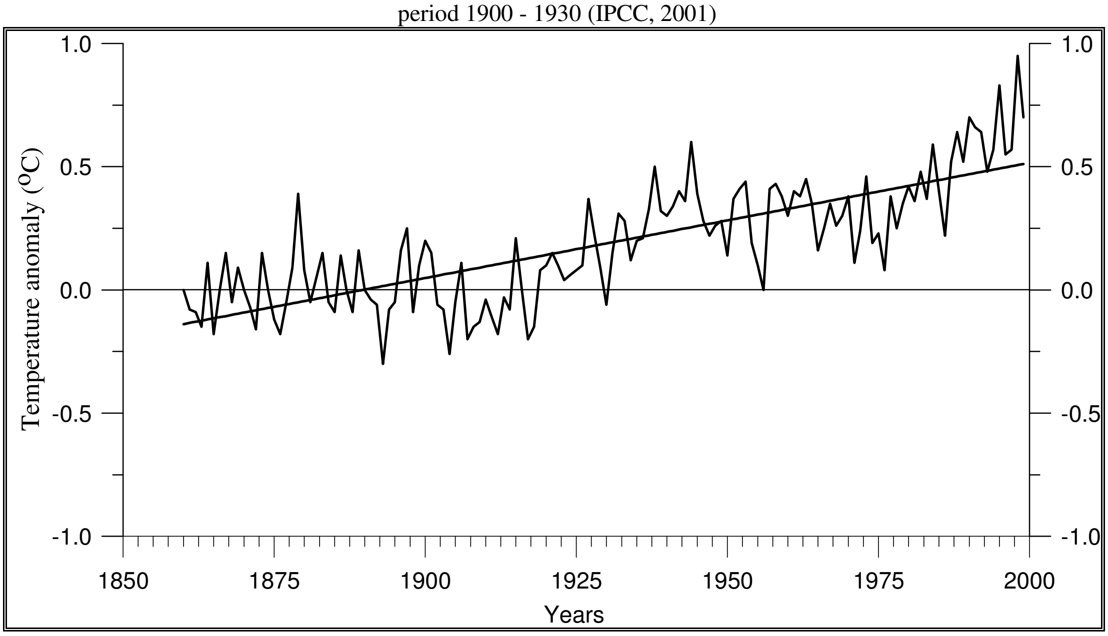
- A1: A world of rapid economic growth and rapid introductions of new and more efficient technologies.
- A2: A very heterogenous world with an emphasis on regional changes.
- B1: A world of dematerialization and introduction of clean technologies.
- B2: A world with an emphasis on regional solutions to economic and environmental sustainability.

3.2 Global climate change over last century

Concentrations of CO_2 and other trace gases in the atmosphere have increased substantially over the last century. Anthropogenic CO_2 emissions due to human activities are virtually certain to be the dominant factor causing the observed global warming. There are a number of studies to show the increase in temperature particularly since pre-industrial era. Recently, IPCC (2007) has indicated that the average global surface air temperature has increased by 0.74±0.18° C since the late 19th century. The linear warming trend over the last 50 years (0.13[0.10 to 0.16]° C per decade) is nearly twice that for the 100 years previous to that. The rate and duration of warming of 20th century has been found to be larger than any other time during the last 1000 years. Figure - 9 shows the trend of changes in globally average temperature over the last century. Temperature changes have not been uniform globally but have varied over regions and different parts of the lower atmosphere. The DTR has not changed from 1979 to 2004 as both day and night time temperatures have risen at about the same rate. Hot days/ heat index increased, while cold/ frost days decreased for nearly all land areas during 20th century. Continental precipitation increased by 5-10% over the 20th century in the Northern Hemisphere although decreased in some regions (e.g., north and west Africa, parts of Mediterranean).

It is observed that the extent of snow cover on the global scale has decreased by 10% since late 1960s. A widespread retreat of mountain glaciers has been observed in non-polar regions during the 20th century. Further, it is expected that glaciers and ice caps will continue to retreat during the 21st century. Climatic changes had a pronounced effect on the glacial and periglacial regime of the Alps. Since the middle of the past century, the areal extent of glaciations in the European Alps is reduced by 30-40%, whereas the volume of ice has been reported to be reduced by 50%. It has been reported that existing trend of changes in the volume of glaciers shows that melting of glaciers will accelerate in continental regions, North America, South America, Central Asia, sub-polar glaciers will contribute to sea level rise. The global mean sea level has risen between 0.10 m to 0.20 m during the 20th century.

Figure - 9 Observed rise in global mean temperature since 1860 relative to the average of observations over the period 1900 - 1930 (IPCC, 2001)



The apparent accelerated melting and deglaciation of the world's glaciers is considered as an indication of human-induced global warming and climate change. The areal extent of Arctic Sea ice has decreased by 2.7% per decade, with larger decrease in summer of 7.4% per decade. Studies also suggest further thinning of sea ice in the Arctic region. Moreover, permafrost and sea-ice extent are projected to decrease. Duration of ice cover of rivers and lakes decreased by about 2 weeks over 20th century in mid- and high latitude of the Northern Hemisphere. Greenland ice sheet is likely to lose mass during 21st century and contribute to the rise of sea level by few cm. Global models indicate that the local warming over Greenland is likely to be one to three times the global average. Antarctica ice sheet is likely to increase in mass during 21st century, but after sustained warming the ice sheet could lose significant mass and can contribute to sea level rise over next 1000 years. Global average sea level rose at an average rate of 1.8 mm per year over 1961 to 2003. The total rise in 20th century is estimated to be 0.17 m.

3.3 Future projections of global climate

Scenarios of future climate change are usually developed using the GCMs with different scenarios of GHG emissions. GCMs are complex 3-dimensional models of the land, atmosphere and oceans. However, inspite of some degree of confidence in the gross or aggregate estimates for climate parameters (such as globally averaged surface temperature) from these models, there is a great deal of uncertainty with regard to regional details. One of the weaknesses of GCM climate change predictions is that they cannot adequately resolve factors that might influence regional climates, such as the local effects of mountains, coastlines, lakes, vegetation boundaries, and heterogeneous soils etc.

For the next two decades a warming of about 0.2° C per decade is projected for a range of SRES emission scenarios. Even if the concentrations of all GHG and aerosols are kept constant at year 2000 levels, a further warming of about 0.1° C per decade could be expected. Under different GHG emission scenarios, the global averaged surface temperature is projected to increase by 1.4 to 5.8° C over a period of 1990 to 2100. The low-emission scenarios project the range of increase in temperature between 1.1 – 2.9° C, while high-emission scenarios project between 2.4 – 6.4° C. The striking feature is that the inter-annual variability of global temperature is much larger than the trend. According to simulations of global climate, it is very likely that nearly all land areas will warm more rapidly than the global average, particularly those at northern high latitudes during winter. In contrast, in south Asia and southeast Asia warming is projected to be relatively less than the global mean warming during summer and in southern South America in winter. The global mean sea level has been projected to rise by 0.09 m to 0.88 m between 1990 and 2100, which is much higher than the range (0.10 - 0.20 m) observed during 20th century.

For each degree celsius warming, global average precipitation is projected to increase by 2-4%, but at the regional scale both increases and decreases are projected. Global climate modelling studies suggest that the precipitation may increase or decrease by as much as 15% under the assumption of a doubling of atmospheric CO_2. Increases in the amount of precipitation are very likely in high latitudes, while decreases are likely in most subtropical land regions. It is predicted that increasing atmospheric concentrations of GHG would result in changes in frequency, intensity, and duration of the extreme events, such as more hot days, heat waves, heavy precipitation events, and fewer cold days. The impact of climate change is projected to have different effects within and between countries. Clearly, variations in key climatic parameters such as precipitation and temperature will produce significant changes in the hydrological regime (rainfall-runoff, snow and glacier melt runoff, evaporation, streamflow etc.) of a basin/country. The resulting changes in regional weather patterns will vary widely but there is widespread agreement that in many parts of the world the frequency and severity of both floods and droughts will increase.

Based on the global simulations of the climate for a wide range of scenarios, global average water vapour concentrations and precipitation are projected to increase during the 21st century. By the second half of the 21st century, precipitation will increase over northern mid to high latitudes. Increase in precipitation is also projected over Antarctica. At low latitudes there are both regional increases and decreases over land areas. Larger year to year variations in precipitation are expected over most areas where an increase in mean precipitation is expected. During 21st century snow cover and sea-ice extent in the Northern hemisphere are projected to decrease further and widespread retreat of glaciers and ice caps will continue. It is likely that Antarctica will gain mass due to higher precipitation in that region, whereas Greenland ice sheet is likely to lose mass because increase in runoff will exceed the increase in precipitation.

Regarding developing world the IPCC observed that:

- 75-250 million people across Africa could face water shortages by 2020.
- Glaciers and snow cover expected to decline, reducing water availability in countries supplied by melt water.
- Glaciers in the Himalayas are receding faster than in any other part of the world and, if the present rate continues, the likelihood of them disappearing by the year 2035 and perhaps sooner is very high if the Earth keeps warming at the current rate. The total area of the glaciers will likely shrink from the present 500000 to 100000 sq km by the year 2035.

The IPCC findings/observations however seem to be overly pessimistic as the findings of the GSI, which is continuously monitoring the Indian glaciers by established methods, is not that alarming. IPCC need to review the studies and parameters taken based on which it has published such observations.

3.4 UNDP Report

In its 2007-08 developmental report UNDP has highlighted the effect of climate change on different regions of the world covering all the aspects including water availability, rising sea level, flooding, biodiversity, human health, etc. The report has indicated that seven of Asia's great river systems will experience an increase in flow over the short term, followed by decline due to reduction in the glacier melt. The specific reference with respect to Indian rivers is given below:

- The flow of the Indus, which receives nearly 90% of its water from upper mountain catchments, could decline by as much as 70% by 2080.
- The Ganges could lose two-thirds of its July–September flow, causing water shortages for over 500 million people and one-third of India's irrigated land area.
- Projections for the Brahmaputra point to reduced flows of between 14 & 20% by 2050.

The Report further states that climate change scenarios for glacial melting will interact with already severe ecological problems and put pressure on water resources. In India, competition between industry and agriculture is creating tensions over the allocation of water between States. Reduced glacial flows will intensify those tensions.

The report has suggested the prevention, mitigation and adaptation strategies and recommended for:

(i) multilateral framework for avoiding its dangers;
(ii) sustainable carbon budgeting;
(iii) strengthening international cooperation; and
(iv) putting climate change adaptation at the centre of the post-2012 Kyoto framework.

3.5 Activities of WMO

The WCP is an authoritative international scientific programme whose goals are to improve understanding of the climate system and to apply that understanding for the benefit of societies coping with climate variability and change. The World Climate Programme was established following the staging of the First World Climate Conference in Geneva, Switzerland in February 1979.

WCIRP is one of the WCP four sub-programs and is targeted at assessing the impacts of climate variability and changes that could markedly affect economic or social activities and thus contribute to the development of a range of socio-economic response strategies that could be used by governments and the community. UNEP is the leading agency within WCIRP that implements the programme in partnership with WMO, FAO, IPCC and UNFCCC Secretariats. The main thrusts of WCIRP include:

- Testing methodologies for assessments of impacts of climate change and sea level rise;
- Promoting and improving coordination of national climate impact and response strategies programmes;
- Improving techniques for making inventories of sources and sinks of GHGs;
- Developing national strategies for responding to climate fluctuations and change;
- Improving dissemination of accurate, complete and timely information to governments and the public;
- Assessing air quality and air pollution mitigation strategies.

WCIRP was constituted in 1979 and since then UNEP contributed substantially to fulfilling the WCIRP goals by providing major inputs in the following core areas:

- Sustainable Development and Climate Change,
- Vulnerability Assessment and Cost Effective Adaptation,
- Integrating Land Use and Forestry Issues and Climate Change,
- Sustainable Energy and Climate Change Mitigation,
- Kyoto Mechanisms and National Policy Instruments,
- Technology,
- Finance and Insurance,
- Support to IPCC, Information, Dissemination and Outreach.

These activities resulted in improved methodologies for assessment of climate change impacts on local economies, enhanced coordination of national climate impacts and response strategies programmes, better techniques for making inventories of sources and sinks of GHGs, new national strategies for responding to climate fluctuations and change and wide dissemination of accurate, complete and timely information to governments and the public.

3.6 Activities of UNESCO

UNESCO affirmed that climate change is affecting our environment, our societies, and our cultures. Finding solutions to mitigate the negative impacts and adapt to changing conditions requires approach that unites sound, unbiased science with social and cultural considerations. The UNESCO, with over 40 activities in all programme sectors, provides a unique forum for addressing climate change and its impacts on the environment and human society. The IHP is one of the important programme for freshwater under natural sciences sector of UNESCO which has launched IHP-VII programme with various themes of which theme-1 proposes to address the climate change issues particularly with respect to water resources under its five focal areas as given below:

Theme-1: Adapting to the Impacts of Global Changes in River Basins and Aquifer Systems

- Focal area-1.1: Global changes and feedback mechanisms of hydrological processes in stressed Systems
- Focal area-1.2: Climate change impacts on the hydrological cycle and consequent impact on water resources
- Focal area-1.3: Hydro-hazards, hydrological extremes and water-related disasters
- Focal area-1.4: Managing groundwater systems' response to global changes
- Focal area-1.5: Global change and climate variability in arid and semi-arid regions

3.7 World Bank views

In the Report of the World Bank on *India's Water Economy Bracing for a Turbulent Future* by John Briscoe, it has been stated that there are strong indications that climate change is likely to affect India in a number of ways. There is little uncertainty about some of these impacts.

As global temperatures continue to rise, this will affect that "water banks" (glaciers) which are a prominent part of the Himalayan water system. While there is clear evidence of deglaciation across the whole of the Himalayas, the effect on river flows is likely to be substantially different in different areas. Climate change is likely to substantially increase overall monsoonal rainfall in India, but this is likely to be poorly distributed in the sense that much of the additional rainfall will probably be high-intensity storm events.

While the exact shape of the future climate regime is uncertain, it is very likely that there will be greater variability -both of droughts and floods. As was shown in a detailed examination of US water practices by the NOAA, the best preparation for managing unpredictable future changes is to put in place a water resource infrastructure and management system which is driven to a much greater degree by knowledge (including but not limited to hydrologic knowledge), and which is designed to be much more flexible and adaptive and operated as such.

The World Bank Report on *Development and Growth in North-East India* (The Natural Resources, Water and Environment Nexus), April, 2008 states that "It is not clear to what extent climate change has been incorporated into the Brahmaputra master plan.

Studies indicated that initially the impact of snow melting in the high Himalayas will increase flood discharges in the Himalayan catchments over the coming decades (IPCC 2001). Singh

(1998) suggests that an increase in surface temperatures will lead to a rise in the snow melt, increasing the risk of floods in northeast India during the wet season. An assessment of the implications of climate change for hydrological regimes and water resources in the Brahmaputra basin using scenarios developed from the Hadley Center model simulations indicates that, once the snow melt effect has passed, by the year 2050, the average annual runoff in the Brahmaputra River will decline by 14%. On the other hand, according to information available with MoWR, studies carried out by the GSI indicate that glaciers may also recede due to sub-normal snowfall, higher temperatures during summer, less severe winters, or a combination of all of them. Under this scenario there would be less increase in flooding than predicted by other models."

World Bank has also published a Policy Research Working Paper on "Estimating Global Climate Change Impacts on Hydropower Projects: Applications in India, Sri Lanka and Vietnam" wherein from India it particularly studied Vishnugad Pipalkoti Hydro Electric Project. The report states that the results are still tentative in terms of both methodology and implications; but the analysis shows that the calibrated dynamic forecasts of hydrological series are much different from the conventional reference points in the 90 percent dependable year. The paper also finds that hydrological discharges tend to increase with rainfall and decrease with temperature. The rainy season would likely have higher water levels, but in the lean season water resources would become even more limited. The amount of energy generated would be affected to a certain extent, but the project viability may not change so much. It concludes that more case studies are necessary for drawing general implications, such as hydropower design alternatives. The mitigation measures against uncertain climate changes must have a cost implication in economic and social terms. Hence, a broad and consistent assessment will be needed at the project preparation stage.

3.8 Other foreign countries

Almost all the world countries have taken note of the climate change issues and have started studies/planning for understanding the specific impacts particularly on water resources among other sectors for taking effective adaptation and/or mitigation measures. Various reports have been published on web-media by the Government agencies. Some of the reports found on the web are as given below:

United States: has produced a publication on "The Effects of Climate Change on Water Resources in the United States" under its Climate Change Science Program Synthesis and Assessment. Report's Findings are summerised as following:

- Consistent with streamflow and precipitation observations, most of the continental United States experienced reductions in drought severity and duration over the 20th century. However, there is some indication of increased drought severity and duration in the western and southwestern United States (these apparent reverse trends result because increased evaporative demand associated with warmer temperatures more than balances precipitation increases).
- There is a trend toward reduced mountain snowpack and earlier spring snowmelt runoff peaks across much of the western United States. This trend is very likely attributable at least in part to long-term warming, although some part may have been played by decadal-scale variability, including a shift in the phase of the Pacific Decadal Oscillation in the late 1970s. Where earlier snowmelt peaks and reduced summer and fall low flows have already been detected, continuing shifts in this direction are very likely and may have substantial impacts on the performance of reservoir systems.
- Water quality is sensitive to both increased water temperatures and changes in precipitation. However, most water quality changes observed so far across the continental United States are likely attributable to causes other than climate change.
- Stream temperatures are likely to increase as the climate warms, and are very likely to have both direct and indirect effects on aquatic ecosystems. Changes in temperature will be most evident during low flow periods, when they are of greatest concern. Stream temperature

increases have already begun to be detected across some of the United States, although a comprehensive analysis similar to the one done for streamflow trends has yet to be conducted.

- A suite of climate simulations conducted for the IPCC's Fourth Assessment Report shows that the United States may experience increased runoff in eastern regions, gradually transitioning to little change in the Missouri and lower Mississippi river basins, to substantial decreases in annual runoff in the Interior West (Colorado and the Great Basin).
- Trends toward increased water use efficiency are likely to continue in the coming decades. Pressures for reallocation of water will be greatest in areas of highest population growth, such as the Southwest. Declining per capita (and, for some cases, total) water consumption will help mitigate the impacts of climate change on water resources.
- *Findings Related to Current Observing Systems* Essentially no aspect of the current hydrologic observing system was designed specifically to detect climate change or its effects on water resources. Many of the existing systems are technologically obsolete, are designed to achieve specific, often incompatible management accounting goals, and/or have significant data collection gaps in their operational and maintenance structures. As a result, many of the data are fragmented, poorly integrated, and unable to meet the predictive challenges of a rapidly changing climate.

The European Union: identified water-related climate change impacts cutting across a number of key concerns for adaptation policies like extreme weather events, water supply, droughts and floods. It has been observed in the water cycle that:

- the average increase in the observed annual mean temperature across the European continent is 0.8° C. The temperatures during the winter season have in general increased more than during the summer,
- annual precipitation over Northern Europe has increased by between 10 and 40% in the last century while the Mediterranean basin has experienced up to 20% reduction in precipitation,
- the summer of 2003 was very likely the hottest summer and the last 30 years appear to have had the warmest climate within the last five centuries.

Changes in river flows have been assessed, and variations have been observed both in terms of increases and reductions in flow. It was possible to attribute some of the increases in river flow to increased precipitation. There is no evidence that flooding in Europe has been systematically increasing in frequency or intensity.

In general, the hydrological cycle is expected to become enhanced as global temperatures increase. For every degree Celsius of warming theoretically the air can absorb 7% more water vapour. Climate models predict an increase in precipitation of approximately 3% for each degree increase in temperature. The expected impacts of climate change across Europe on the water cycle include the following:

- projections up to 2100 show precipitation increase in the north of Europe (mostly in winter) and decrease in summer precipitation in the south of Europe,
- extreme precipitation will occur more frequently, especially in winter, which may lead to more frequent flooding,
- in central and southern Europe, the drought risk is likely to increase,
- changes in precipitation patterns may alter the availability of surface water, which could lead to increased exploitation of groundwater resources,
- reduction of snow and ice cover in combination with higher potential evaporation may lead to decreased river discharges and downstream water availability in summer,
- sea-levels rise may affect fresh water resources in low-lying coastal areas by saline intrusion,
- there may be an increased risk of forest fires during droughts.

Water quality can change in response to climate change, through the increased mobility of chemical compounds, changes in hydrology and changes in timing of biological and meteorological patterns. Water quality in particular relates to nutrients, oxygen, natural organic matter and hazardous substances, contained in the water, as well as to the temperature of the water. Peak discharge (flash) events can cause water quality problems by causing a "flush" of sediment or water pollutants, or indirectly by causing a leaching of waste disposals and water treatment facilities. Flash events can also result in the spread of pathogens. Changes in lake water temperatures and resultant impacts have been observed.

Government of Japan: Panel of Infrastructure Development under Ministry of Land, Infrastructure, Transport and Tourism of Government of Japan has drafted a Policy Report on "Climate Change Adaptation Strategies to Cope with Water-related Disasters due to Global Warming" in June 2008 in which they have spelled out Basic directions for adaptation strategies and implementation of adaptation measures etc.

China: in its "initial national communication on climate change" brought out a chapter on "Impacts of Climate Change and Adaptation". In the para "Water Resources" it has indicated reduction in run-off of varying magnitude of about 0.96% to 36.64% per decade in the six major river basins. It has recognized increased drought situation, reduced precipitation and increased flood situation in last 2-3 decades. It has also indicated a 21% loss in total area of glaciers. It has projected increase in average annual run-off depth in some areas by 24% whereas decrease in some areas by 2-10%.

Impacts of proper water resources management: The economic impact of floods, droughts, and related phenomenon like forest fires can be considerable. Resilience to the water-related variability will depend on water storage capacity, which varies across the world. Reservoir storage is much greater in North America and Australia, than in Africa, for instance. There is an even greater disparity between the developed countires and others in terms of per capita storages. Water security is an essential element for climate adaptation.

4. Initiatives Taken by MoWR, GoI

Prime Minister's Council on Climate Change, in its first meeting held on 13-07-07 decided an action for MoWR as "Institutions should be mandated to initiate studies for major river basins of rivers whose waters come from snow melt". As a follow-up of the meeting taken by Hon'ble Prime minister, Secretary (WR) took a meeting on 27-08-07 to discuss further course of action by MoWR to assess the contribution of snowmelt and glaciers to river system and the need for consolidated action programme for research.

4.1 Standing Committee for assessment of impact of climate change on water resources

MoWR constituted a Committee for "Snowmelt Run-off and its Assessment" under the Chairmanship of Member (RM), CWC in March 2006. Realizing the importance of impact of climatic change on water resources characteristics in general and that on the glacier-melt and snow-melt in particular, the MoWR re-constituted this committee as the Standing committee for "Assessment of Impact of Climatic Change on Water Resources" under the Chairman, CWC on 27-09-07.

4.1.1. Meeting of the re-constituted Standing Committee

The first meeting was held on 27-11-07. It was decided inter-alia by the Committee that a compilation may be made on (A) works done by different organizations in the field; (B) data availability with the organizations; (C) list of experts and manpower available for such specialized studies/works and (D) proposed action plan.

The information has since been received from CWC, Brahmaputra Board, NRSA, NWDA, Survey of India & NIH as briefed below:

- *CWC*: (A) CWC has attempted "Trend analysis of flows in major Indian rivers in the context of climate change"; (B) CWC is the main organization for hydrological data collection on the major river basins in the country. The list of sites and data availability has already been published as "Hydrological Observation Stations in India under CWC"; (C) A Climate Change Cell has started functioning in the CWC under Chief Engineer, P&D with seven Director level Officers as members.
- *Brahmaputra Board:* The Board has created a Climate change Cell for taking up the related works. However, it has intimated that no work has been carried out by the Board so far in respect of Climate Change issues. The Board has submitted data availability, periodicity and procedure for dissemination; manpower and other resources availability.
- *NRSA:* has intimated that "Seasonal snowmelt runoff forecasting in Sutlej basin" is a ongoing work taken up by the Agency; The Agency has submitted data availability, periodicity and procedure for dissemination; manpower and other resources availability
- *NWDA:* has intimated that no work has been carried out by the Agency so far in respect of Climate Change issues.
- *NIH:* has done substantial work in the field of glaciology and snow-melt over the years. It has submitted information about manpower and works done, reports/papers published so far The Institute has created a Climate change Cell for taking up the related works. Officers of all three Climate change cells are meeting frequently for better coordination and information exchange.
- *CGWB:* has intimated that no work has been carried out by the Board so far in respect of Climate Change issues. However necessary inputs on groundwater component in

Ganga, Brahmaputra & Indus River Basin for studies on the aforesaid subject will be provided by the Board.

- *SOI:* has intimated that no work has been carried out on the subject matter and no manpower can be spared due to acute shortage of staff.
- *WIHG***:** has done substantial work in the field of glaciology and snow-melt over the years. It has submitted information about manpower and works done, reports/papers published so far**.**
- *GSI:* has done substantial work in the field of glaciology and snow-melt over the years and is carrying out a scientific assessment on the recession of glaciers. It has submitted information about manpower and works done, data availability, reports/papers published so far.
- *GB Pant Institute of Himalayan Environment & Development:* has done substantial work in the field of glaciology and snow-melt over the years. It has submitted information about manpower and works done, data availability, reports/papers published so far.

4.2 XI FYP Programme of CWC

Necessary provision have been made under the XI Plan scheme "Development of WRIS" for establishment of site and monitoring of the glaciers, snow and river flows. The Scheme inter-alia includes two components viz. "Snowmelt runoff forecasting in Himalayan River Basins" and "Studies and Monitoring of Water bodies and Glacial Lakes in the Himalayas affecting India". The activities proposed under first component include Snowmelt Runoff Forecasting in the Himalayan River Basins in Chenab, Beas, Yamuna, Ganga and Sutlej with the help of Remote Sensing inputs and by continuing field observations at existing and proposed new observatories. Eight hydrological observation stations are proposed at Chilla Top (modernization), Sirshi/Koksar/Tonli/Udaipur (any one) in Chenab Basin; Kothi (modernization) and Pulga near Barshaini in Beas Basin; Hanuman Chetti and Kufri in Yamuna Basin and Joshimath and Dabrani in Ganga Basin. NRSA would develop model for snowmelt-runoff forecast using remote sensing inputs and field data collected by CWC. A provision of Rs.5.74 crore has been kept for this component. The estimated cost of second component is Rs.5.80 crore in which the work has been proposed to be taken up with the help of NRSA.

4.3 Knowledge sharing

4.3.1. National Workshop by NWA

A national workshop was organized by NWA on 05/06-12-07 at Pune. The main recommendations of the workshop are as following:

- Impact of all aspects of climate change as identified by IPCC (4th Action Report) on the hydrologic cycle has not received adequate attention. Any other aspects on basin/regional level have to be incorporated. Whatever work is being done, or is contemplated by the Standing Committee of MoWR/CWC on Climate Change, is also focused mainly on such impacts on water sector as are arising out of increased snow melt and glacier retreat, in the rivers that have a snow melt or glacier melt contribution. Other aspects should be included in the TOR of the Standing Committee.
  Although it has been said that the hydrologic cycle will intensify; flood/drought frequency and intensity will increase; start, duration and cessation of rainy season may be affected; and Evapo-transpiration may increase; but these impacts are yet to be investigated and quantified in Himalayan and peninsular river basins by way of water availability and its use in different sectors.
- There is an urgent need on taking up R&D (assessments) on impacts of climate change on existing water uses from facilities created, so far.
- CWC should have a dedicated organization to address aforesaid issues if necessary, through outsourcing. The organization may setup its website/blog.

- CWC should organize regular brain storming sessions to generate fresh ideas.
- Issues that need immediate attention of water resource planners and managers:
  - Existing storages require enhancement and provision of carry over;
  - Whether design flood of existing projects needs to be reviewed in view of climate change;
  - Whether any change is required in the methodology of computing design flood for future projects ;
  - Whether any change is required in the procedure for assessing water needed for different uses.

4.3.2. Brain Storming Session by NIH

A brain storming session on "Effect of Climate Change on Water Resources and Adaptation Strategies" was organized by NIH on 24-04-08 at New Delhi. The session was addressed by Mr. Asit K. Biswas a world figure in water resources management. The recommendations of the session are as following:

- There is a need to prepare a report on the "Impact of Climate Change on Water Resources and Adaptation Strategies" covering the different regions of India.
- Long term monitoring of water resources in different regions is required to be taken up throughout India.
- Guidelines are required to be formulated for the planning, designing and operation of water resources projects considering the impacts of climate change.
- High level group is required to be constituted including the experts from various organizations/institutions from different disciplines to tackle the impact of climate change in the water resources sector.
- Additional storages are needed for meeting various demands particularly for the rain-fed areas of the country in the light of the possible impacts of climate change.

4.3.3. Theme Papers on Climate change

NIH has prepared a special edition of "Jalvigyan Sameeksha" (Hydrology Review), which has a compilation of technical Papers on the Theme of "Impact of Climatic Change on Water Resources". The suggestions in some of the theme papers are:

In the theme Paper "Impact assessment of climate change on water Resources of Two River systems of India" analysis of two sample river basins namely, Godavari and Tapi was done and it was observed that the impacts of Climate change are not uniform and are varying across the river basins. The initial analysis has revealed that the GHG scenario may deteriorate the conditions in terms of severity of droughts and intensity of floods in various systems.

In another theme Paper "Assessment of Impact of Global Climatic Change on Precipitation at Regional Scales" a broad overview of different approaches of downscaling and uncertainty of modeling in assessing hydrological implications of global climate Change with a case study of Orissa meteorological subdivision has been discussed.

4.3.4. State of the Art Report

NIH has prepared a State of the Art report on "Effect of Climate change on Water Resources' which deals with International initiatives, GHG and Global warming, Impact of Climate Change, modeling climate change and its impacts and effects of Climate Change already happening.

4.4 Establishment of Chairs in IITs/NITs

Recognising the need of more interaction between academic research and applied engineering and technology, MoWR in its second meeting on "Effect of Climate Change on Water

Resources" held on 02-01-08 taken by Secretary (WR) decided that CWC would initiate action for establishment of Chair Professors in six academic Institutes as given in Table - 8 below:

Table - 8 Proposed Chairs in IITs & NITs

Name of Institute	*Basin for study*
• National Institute of Technology, Srinagar	Indus basin
• Indian institute of Technology, Roorkee	Indus basin
• National Institute of Technology, Patna	Ganga basin
• Indian institute of Technology, Kanpur	Ganga basin
• Indian institute of Technology, Guwahati	Brahmaputra basin
• Indian institute of Technology, Kharagpur	Brahmaputra basin

Accordingly, discussions were held with the Institutes and after mutual agreement on various aspects including objective, financing, review mechanism etc. a consolidated proposal for setting up Chair Professor in all six Institutes is under consideration of MoWR. The main objectives of the Chair are as following:

- To take part in the academic programme of the respective Institute as full time professor/ faculty in the related department and coordinate HRD programs in water resources sector.
- To develop R&D and academic programme relevant to the needs of CWC and other organizations of MoWR in the related areas.
- To initiate and develop HRD programmes relevant to the needs of CWC and other organizations of MoWR and to coordinate courses for their Officers.
- To review available design standards and suggest necessary changes/modifications to accommodate the effect of climate change in design of water resource systems.

4.5 Initiative taken/Studies conducted by different Organizations

The information about various organizations and academic institutes involved or which have carried out studies with respect to effects of climate change on water resources aspects in particular has been collected from various sources and given in brief in alphabetic order below. There are other many organizations which are contributing in the related fields of water resources which will be appended as the information is received.

Allahabad University: Allahabad University, has taken up few studies on real time trace analysis of ice cores and prediction of Indian monsoon behaviour using Antarctic sea ice concentration.

BSIP: has developed a strong knowhow in the field of palaeo-climatic reconstruction through tree ring and palynology. The scientists have also attempted correlation of glaciological events by pores and pollen studies.

CSRE, IIT, Bombay: is utilizing SAR interferometry for monitoring glacier movement on Gangotri and Siachen glaciers. CSRE is also taking up work on optical and microwave remote sensing for mapping of the snow cover and glaciological studies. The center has also organized training courses and workshops on snow/ ice studies aided with remote sensing.

DIAT: has undertaken studies on snow physics, snow mechanics and avalanches modeling.

DST: is involved in coordinating the glaciological programme in the country through PAMC-HG. It also financially supports the approved field projects and organisation of training courses and seminar / symposiums through other central/state organisations and institutes and also provides guidance.

GB Pant Institute of Himalayan Environment and Development, Almora: carries out studies on hydrometry, estimation of suspended sediment load and its characteristics. The projects undertaken include Gangotri glacier. A new centre of this institute has also become operational in Sikkim. Some proposed area of study include "*Glacier response function, and climate change impact*" for already established Glacier field stations at Gangotri and Milam to understand impact of climate change on glaciers and on watershed benefits provided by Himalayan glaciers to downstream areas; "*Environmental and social Consequences: vulnerability assessment and coping mechanism*" to focus on (a) Analysis on sufficiency of long-term climate data for clear understanding of extreme events in the form of flash flood, cloud burst or GLOF and associated vulnerability and risks assessment in Himalayan context, (b) Developing community based coping mechanism for the Indian Himalayan region, and Increasing awareness about the glacier retreat extreme and other related disaster among the dwellers of the area; (c) "*Capacity building and training*" to start regular student and research staff trainings in collaboration with other expert organizations in order to cater to specific training needs both in the laboratory and field conditions before employing manpower for actual studies to overcome acute shortage of trained manpower on glacier and other high mountain studies in harsh climatic conditions.

GSI: is the primary organization for making inventory of the glaciers in the country and to monitor them. Glaciological studies in GSI date back to 1840. During 1851-1973 the glaciological studies were confined to mapping of glacier snout and geo-morphological studies. With the inception of Glaciology Division in 1974, the department has taken great strides and carried out studies on all the aspects of glaciology including mass balance, hydrometry, suspended sediment, dynamics, secular movement, glacier inventory, palaeo-glaciation, etc. The department is also engaged in human resource development through conductance of glaciology training courses. Several seminars/ workshops have also been organized.

HNB Garhwal University, Srinagar, Uttarakhand: has undertaken studies on monitoring of glacier snout, glacial geo-morphological mapping, etc. in parts of Bhagirathi and Mandakini valleys.

IITM: is engaged in collation and analysis of climate data collected by various organisations and has also carried out extensive studies on paleo-climatic reconstruction. It functions as a national centre for basic and applied research. It is a unique research organisation in South-Asia covering almost all aspects of atmospheric sciences and meteorological research. IITM is active in studying long-term climate change from observed and proxy data as well as model diagnostics and assessment of climatic impacts, with a particular focus on the Indian summer monsoon.

IISc Bangalore: is working on a project sponsored by INCOH titled as "Assessment of water resources under climate change scenarios at river basin scale" and a collaborative research proposal with Columbia University is also under process on the related subjects.

IIT Delhi: is contributing a lot in various institutions of the Government like NATCOM and published a report on "Assessment of climate change impacts on water resources" besides other related works.

IIT Roorkee: has done few studies on snow characteristics and snow cover mapping using remote sensing techniques.

IMD: is the main organization for meteorological data collection through its observation network located across the country. It provides current and forecast meteorological information to the country, warns against severe weather phenomena like tropical cyclones, norwesters, duststorms, heavy rains and snow, cold and heat waves, etc. It has mandate also to conduct and promote research in meteorology and allied disciplines.

JNU: The School of Environmental Science and Centre for the Study of Regional Development are actively involved in glaciological research. School of Environmental Science has developed specilisation in the study of hydro-chemical characteristics and discharge measurement while Regional Development Centre has carried out studies related to glacial geomorphology, palaeo-geographic and palaeo-climatic reconstruction along with monitoring of snout. School of Environmental Science has also organized training course and seminar/ workshop.

Jammu University, Jammu: Department of Geography, Jammu University has carried out studies on glacial geo-morphological mapping, monitoring of glacier snout, glacial sediments, etc on Naradu Bamak glaciar, Himachal Himalaya and Durung glacier, in J&K Himalaya.

Lucknow University, Lucknow: The centre for Advance studies in Geology has carried out studies on lichenometry, glacial geomorphology, monitoring of glacier snout, etc of Gangotri glacier. At present studies are being undertaken on Pindari glacier, Kumaon Himalaya.

NCAOR: is an autonomous institution under Department of Ocean Development. The centre is designated as nodal agency for coordination and implementation of India's Antarctic Programme including maintenance of Indian station in Antarctica, besides various other research activities.

NIH: is involved with discharge measurement of glacier melt water, estimation of suspended sediment load, snow cover assessment and runoff modeling, etc. It has also carried out few studies on glacier snout monitoring. The glacier studied include Gangotri, Dokriani, etc. The institute has organized several workshops and seminars.

Palampur University, Palampur: an attempt has been made on compilation of glacier inventory of part of Himalaya using GPS and WGS 84 data by the University.

PRL: has carried out studies on dating of glacier ice using isotopes. It has also acted as member of the expeditions launched by GSI and DST.

SAC: through its water studies division has developed a strong knowhow in the field of application of remote sensing, both optical and microwave, in the studies of snow, ice and glaciers. The work included glacier inventory, snow cover assessment, glacier mass balance and monitoring of glacier snout. The centre has also organized a short term training course in optical and microwave remote sensing.

SASE: is involved in mapping and monitoring of snow cover using satellite data studies on snow characteristics including snow mechanics, snow physics, metamorphism, avalanche studies including forecasting and their control. It has established a network of automatic weather stations and collecting valuable meteorological data. SASE has taken up studies on snow melt runoff of Parvati basin (in collaboration with SAC, Ahmedabad) and glacier faces using SAR data (in collaboration with IIT, Bombay). It has also organized several international and national seminars/workshop from time to time.

SOI: provides the topographic maps on various scales. It has been a member of the earlier expeditions launched by GSI and DST. It has also published inventory of some of the large Himalayan glaciers.

UPRSAC: has carried out studies on monitoring of snow cover using optical and microwave remote sensing, glacial hydrology through spectral response of melt-water along with dynamics of surging glacier.

WIHG: has been engaged in studies on glacier mass balance, flow, snout mapping, etc of Dokriani glacier. It has also participated in the DST sponsored expedition to Chhota Shigri glacier. Some work on glacier inventory using GPS & WGS 84 data has also been carried out.

4.6 Institutional arrangement of GoI

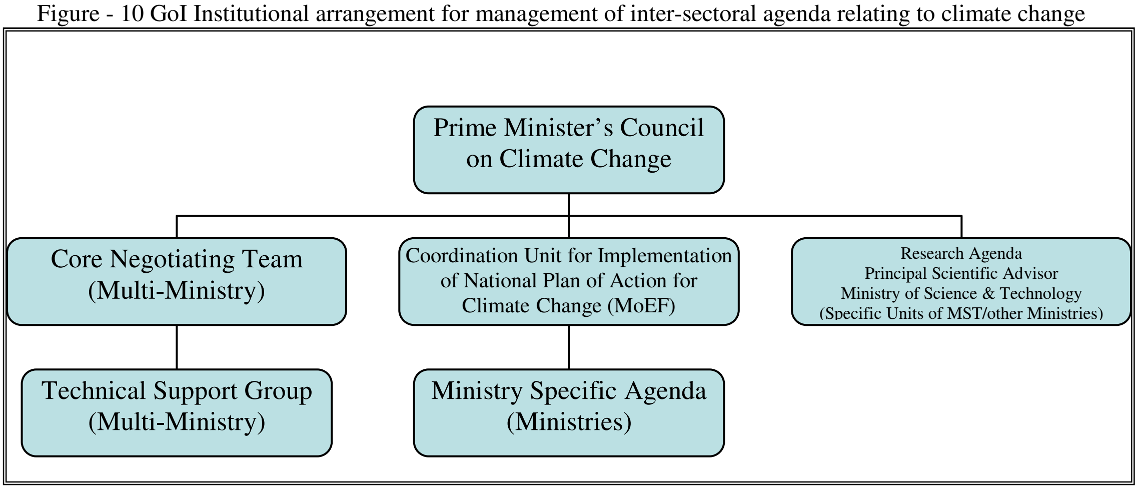
GoI has adopted an Institutional arrangement including proposed different bodies for management of inter-sectoral agenda relating to climate change as given below in Figure - 10.

- **Prime Minister's Council on Climate Change**: apex body for policy guidance on matters relating to international negotiations, coordinated national action on domestic agenda, and review of implementation of the national action plan on climate change including its R&D agenda.
- **Policy guidance Group for International Negotiations**: Minister of water resources is a member of policy Guidance group headed by prime Minister. The group will guide policy for major international negotiations.
- **Core Negotiating Team**: This team will lead in international Negotiations, ensure continuity of dialogue, be responsible for building alliances & providing leadership to the group of developing countries. Chairman, CWC is a member of Core Negotiating team. All

international delegations on issues relating to the agenda of climate change will need to be approved at the level of the Prime Minister.

- **Technical support Group**: This group will assist Core negotiating team for policy/technical support. It is a multi-ministry mechanism consisting of identified officials selected by the Core negotiating team for supporting it with policy/technical assistance.
- **Nodal Officer/Point Person in selected Ministries**: to deal with issues relating to climate change agenda, at the level of Secretary/Special Secretary/Additional Secretary. The MoWR has not been mentioned in the list of Ministries where from Nodal Officer/Point Person has been sought for. The Ministry concerned will be responsible to report on status of action in respective areas at regular interval to (a) Principal Secretary to the PM; (b) Member Convenor, PM's Council on climate change; (c) MoEF; and (d) MEA.
- **Coordination Unit for Preparation of National Plan of Action**: MoST will finalize the National Action Plan. Inputs will be from PM's Council, MoEF and Planning Commission. It will develop National Action Plan and submit to PM's Council on climate change.
- **Unit for Coordinated Implementation of National Plan**: MoEF is the coordinating body and is to setup a unit for coordinated implementation. Secretary, MoEF will present bi-monthly reports to the Member-Secretary of PM's Council on climate change and to Cabinet Secretary. Each Ministry associated with a component of action under national action plan will setup its own unit for implementation and report to the coordination unit of the MoEF.
- **MoST to Monitor Research Agenda**: MoST, its agencies and other Ministries having research related agenda under National Action Plan will undertake activites under the overall guidance of the Principal Scientific Advisor to the Government. MoST would be nodal agency for reporting to PM's Council on climate change through Principal Scientific Advisor to the Government.
- The Policy guidance group for international negotiations and the Core negotiating team will be serviced by MoEF which will also coordinate identification of nodal officer/point person in the selected Ministries and implementation of National Plan of Action.
- The work related to monitoring of research agenda will be serviced by DST.

Figure - 10 GoI Institutional arrangement for management of inter-sectoral agenda relating to climate change



4.7 Long-term Action Plan of MoWR

Water resource is the most vulnerable sector in the climate change scenario. Accordingly, MoWR took various steps for taking up relevant studies and related data collection in the coming years as given in the Table - 9. The activities have been planned upto May 2012 with organization of an International symposium at the end.

Table - 9 Action plan of MoWR

#	*Activities*	*Action to be initiated by*	*Time*
I. 1	**Short Term Action:** Organization of a Brain Storming Session to discuss all related issues with experts including international experts.	NIH	Feb 2008 (postponed to April 2008)
2	Finalization of the Long Term Action Plan	CWC	Feb 2008

#	*Activities*	*Action to be initiated by*	*Time*
3	**Preparation of a Preliminary Consolidated Report on Effect of Climate Change on Water Resources** [On the Basis of the analysis of time series of rainfall data and flow data analysis of related secondary information particularly about snowmelt and glacier melt and the results of the studies carried out by NIH]	CWC	Jun 2008
II. 1	**Long Term Action:** Establishment of Chairs in IITs/NITs (submission of agreed MOUs with the Institutes to MoWR)	CWC	Jun 2008
2	Establishment of additional observation sites for snowmelt and glacier melt assessment. (a) Review of Locations and specifications	Climate Change Cells	Jun 2008
	(b) Establishment of additional observation sites.	CWC	
3	Development of appropriate model for three major basins i.e. Ganga, Brahmaputra and Indus and one for peninsular rivers for predicting the flow series under varying conditions (a) Identification of steps and procedure (examine replication of Gangotri study - DST project for other basins)	NIH	Dec 2008
	(b) Data acquisition	Climate Change Cells	
	(c) Development of model	NIH	
4	Identification and Calibration of Simulation Models for operation of the water resources facilities and study of the performance of the Systems with different flow series generated under varying conditions (Refer II.3)	Climate Change Cells	Mar 2009
5	Organization of National Workshops to discuss the findings of the Studies	NIH	May 2009
6	Preparation of Interim Report and mid-term review of the progress	CWC	Jul 2009
7	Review of the findings of the Interim Report and identification of Course Correction Measures	CWC	Sep 2009
8	Implementation of identified corrective measures and revision of the studies	CWC	Dec 2009
9	Report to be brought out on the cumulative progress Report for period ending Mar 2010 Report for period ending Sep 2010 Report for period ending Mar 2011 Report for period ending Sep 2011 and so on	CWC	 Apr 2010 Oct 2010 Apr 2011 Oct 2011
10	Final Report	CWC	Mar 2012
11	Organization of International Symposium	CWC	May 2012

Note: CWC will review the progress made by all concerned organizations (CWC, BB, NIH and the IITs, NITs. etc.) and submit consolidated report to MoWR in the first week of Apr., Jul., Oct. and Jan. respectively.

4.8 Observations of Working Group on water resources for XI FYP

The working group on water resources recognized the importance of the climate change in planning of water resources and observed as following:

The impending climate change, caused by the GHG emissions, is now an established fact. The meteorologists have developed a set of mathematical models known as GCM. These models can be used to simulate the behavior of the atmosphere and paint "what if" scenarios for various levels of GHG emissions. Using these models, the weather experts have predicted that global warming will intensify the hydrologic cycle; more intense rainfall will occur in fewer spells; the floods and droughts both will become more intense; the floods will be more frequent; the rainfall will shift towards winter; and there may be a significant reduction in the glaciers mass, resulting in increased flows in the initial few decades but substantially reduced flows thereafter.

So far, the discussion on climate change is mostly taking place in the domain of atmospheric physics. The hydrologists are yet to translate what it means for the water availability, its distribution in time and space, and changes in demand. An increase in mean temperatures would increase the energy flux for evapo-transpiration. The increased potential evapo-transpiration in the forests could trigger major changes in the environment, and in the farms it would result in an increased crop water requirement. The changes in seasonal temperatures could change the crop seasons. The discussion on climate change is now emerging out of descriptive phase and entering the quantitative phase. Enough data is now available to paint “what if” scenarios for different possibilities, and to formulate some tentative plans to respond to these possibilities.

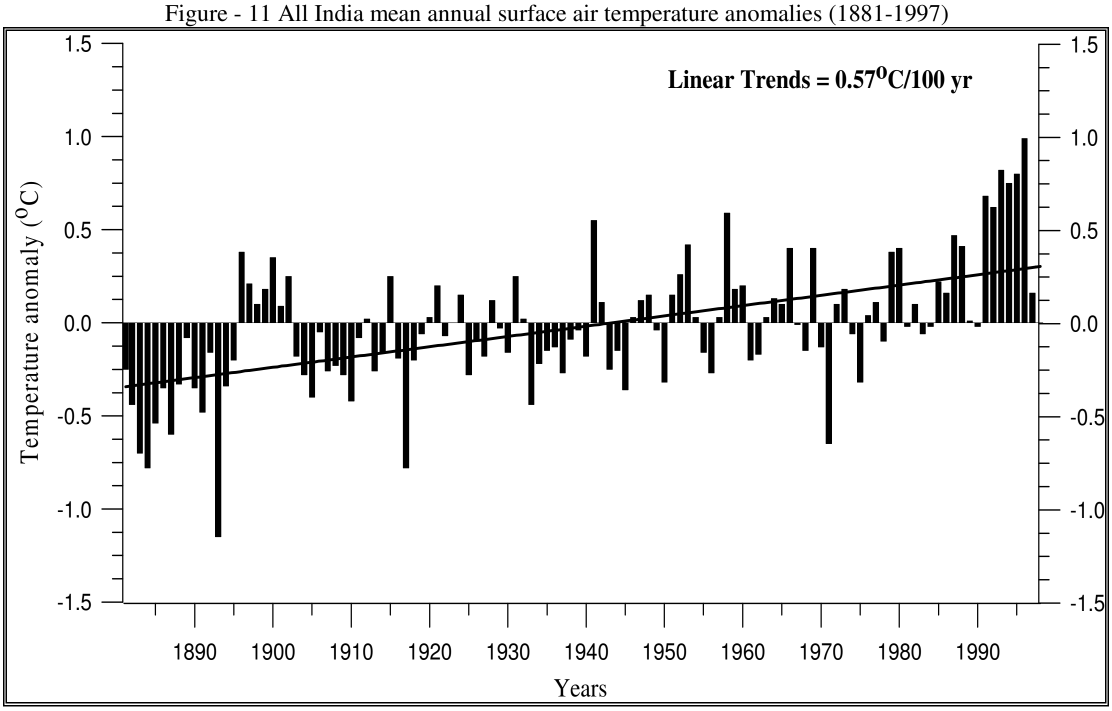
It is an accepted fact that even in the post climate change scenario, systems that are more controlled will fare better than systems that are less controlled. In water resources parlance, control means engineering infrastructure that enables the water managers to store and transfer water with greater certainty, thus reducing the impact of uncertainty. Therefore, dealing with climate change is going to require more infrastructures.

5. Trends of Climate Change in India

5.1 Temperature

In India several studies have been carried out to determine the changes in temperature and rainfall and its association with climate change. However, investigators used different data length and now studies have been reported using more than a century data. All such studies have shown warming trend on the country scale. Estimates of temperature anomaly were better estimated using long-term series data. An analysis of the seasonal and annual air temperatures from 1881 to 1997 by Pant and Kumar (1997) shows that there has been an increasing trend of mean annual temperature by the rate of 0.57°C per 100 years. Trend of all India mean annual surface air temperature anomalies is shown in Figure - 11. The trend and magnitude of global warming over India/Indian sub-continent over last century has been observed to be broadly consistent with the global trend and magnitude. In India, warming is found to be mainly contributed by the post-monsoon and winter seasons. The monsoon temperatures do not show a significant trend in any part of country except for significant negative trend over Northwest India.

Figure - 11 All India mean annual surface air temperature anomalies (1881-1997)



Earlier studies also showed increasing trend of annual mean temperature. During 20th century, an analysis of long term temperature records (1901-1982, 73 stations) has shown increasing trend of mean annual surface air temperatures over India (Hingane et al., 1985). It was observed that about 0.4° C warming has taken place on country scale during the period of eight decades. Studies carried out on regional basis show that temperature fluctuations do not show increasing trend over the entire country. Temperatures show cooling trends in the northeast and northwest India. Moreover, Hingane et al. (1985) observed that trend of increase in mean annual temperature over the whole country was a result of rise in the maximum temperature; but later studies carried out by Sinha, Ray et al. (1997) have shown that the changes in mean annual temperature are partly due to rise in the minimum temperature related to enhanced extent of urbanization. Thereafter findings by Mukhopadhyay et al. (1999) have confirmed that there is clear signal of urbanization in these warming, i.e. that there is a steeper rise in the minimum temperature in urban locations.

Further, examination of long-term variation in the annual mean temperature of highly industrial and densely populated cities like Bombay and Calcutta has shown increasing trend in annual mean temperature at Bombay and Calcutta by 0.84°C and 1.39°C per 100 years, respectively (Hingane, 1995). These warming rates are much higher than the values reported for the country as a whole. Studies in the neighbouring country (Bangladesh) have also shown warming trends. In the past, a number of studies on climate change and its possible implications on Bangladesh have been undertaken (Ahmad and Warrick, 1996; ADB, 1994). The consensus was that over the past 100 years, the broad region encompassing Bangladesh has warmed by 0.5ºC (Ahmad and Warrick, 1996).

Studies of historical rates of relative sea-level rise in the South Asian region indicate an average annual relative sea-level rise of 0.67 mm/yr (Gable and Aubrey, 1990). There was a rising trend in the sea level at Mumbai (Bombay) during 1940-86 and Chennai (Madras) during 1910-33 (Das and Radhakrishnan, 1991). A rise of sea level by 0.08 m with a corresponding fall in the pressure was confirmed during 1901-40 as per the studies on the atmospheric and tide gauge data (Srivastava and Balkrishnan, 1993).

NIH (2007) has carried out Basin-wise assessment of temperature variability and trends in the northwest and central India. In this study, seasonal and annual trends of changes in maximum temperature (T_{max}), minimum temperature (T_{min}), mean temperature (T_{mean}), temperature range (T_{range}), highest maximum temperature (H_{max}) and lowest minimum temperature (L_{min}) have been examined on the basin scale. Longest available records for 43 stations, varying from 90 to 100 years, over the last century were used in the analysis. The study has been carried out for 9 river basins in northwest and central part of India. Table - 10 summarizes the results of different seasons for different basins. A higher rate of warming/cooling has been observed in some pockets in a large basin like Ganga. The trends of changes in temperature suggest that majority of basins (7 river basins: Ganga, Indus-lower, Mahanadi, Mahi, Narmada, Brahamani & Subaranrekha, and Tapi) have experienced an increasing trend in mean annual temperature over the last century, while 2 basins (Sabarmati and Luni & other small rivers) have experienced cooling trends. For the warmer basins the range of increase in mean annual temperature varied between 0.40 to 0.64° C per 100 years and for the cooler basins it varied between –0.15 to -0.44° C per 100 years (Table - 10). Figure - 12 shows spatial patterns of linear trends in annual mean temperature (% of mean/100 years) for different river basins during last century (1901-2000). A comparison of magnitude of warming and cooling trends of different river basins indicates that Narmada basin experienced maximum warming as compared to other basins, while Sabarmati river basin has shown the largest cooling trend. The higher rate of warming in annual mean temperatures in the Narmada basin is attributed to a significant and similar magnitude increase in both T_{max} and T_{min}. In the case of Sabarmati, both T_{max} and T_{min} have shown decreasing trends with the dominating effect of a decrease in T_{min}. The distribution of changes in mean temperature on the regional scale shows that, except for some small pockets, a broad warming trend has been observed across the whole study area.

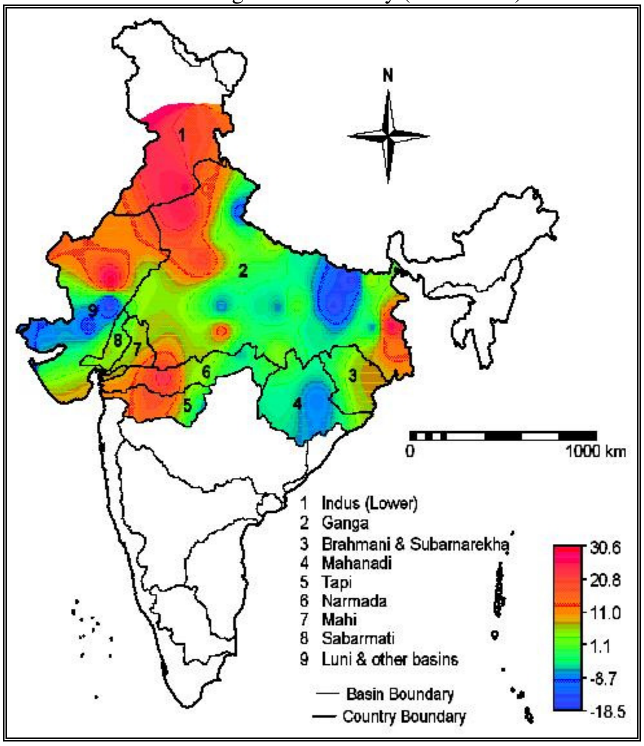
Seasonal analysis of different variables show that the maximum changes in T_{max} and T_{mean} were observed in the post-monsoon season, while T_{min} experienced maximum changes in the monsoon season. For the monsoon season, increase in T_{max} and decrease in T_{min} counterbalanced the trends in T_{mean} providing the least variations in T_{mean}, but largest variation in T_{range} (0.93° C/100) for this season. The majority of basins have shown increasing trend in T_{range} in the range of 0.09 to 1.78° C/100 years. Both H_{max} and L_{min} have shown increasing trend in the study area. This analysis provides scenarios of temperature changes, which may be used for the sensitivity analysis of water availability for different basins and accordingly planning and implementation of adaptation strategies can be followed.

Table - 10 Trends and magnitude of changes in different temperature variables (°C/100 year) for different river basins in the study region

#	*River basins*	T_{mean}					T_{max}					T_{min}					T_{range}					H_{max}	L_{min}
		S1	*S2*	*S3*	*S4*	*S5*	*S1*	*S2*	*S3*	*S4*	*S5*	*S1*	*S2*	*S3*	*S4*	*S5*	*S1*	*S2*	*S3*	*S4*	*S5*	*S5*	*S5*
1	Indus (lower)	0.39	0.30	-0.04	0.87	0.50	1.03	0.75	0.53	1.13	1.39	-0.21	-0.18	-1.00	0.22	-0.33	1.81	0.92	1.19	1.09	1.78	0.71	-0.13
2	Ganga	0.63	0.19	0.02	0.92	0.44	1.00	0.58	0.68	1.17	0.90	0.36	0.05	-0.63	0.77	0.04	0.52	0.58	0.95	0.35	0.72	0.60	0.49
3	Brahamani & Subarn.	0.84	0.02	0.03	0.73	0.40	0.59	0.08	0.54	0.83	0.54	1.13	0.33	-0.28	0.79	0.29	-0.33	0.06	0.77	0.13	0.28	0.27	1.10
4	Mahanadi	0.62	0.29	0.34	0.99	0.61	1.09	0.51	0.85	1.30	1.10	0.92	0.78	-0.09	0.91	0.38	0.25	0.60	1.05	0.41	0.68	0.69	0.67
5	Tapi	0.47	0.49	0.19	0.72	0.46	0.46	0.33	0.30	0.58	0.43	0.39	0.38	0.04	0.65	0.37	0.21	-0.22	0.26	-0.14	0.09	-0.06	0.74
6	Narmada	0.60	0.75	0.31	1.00	0.64	0.50	0.58	0.44	0.85	0.58	0.71	1.05	0.13	1.02	0.59	-0.20	-0.26	0.32	-0.24	-0.02	0.19	1.11
7	Mahi	0.10	0.55	0.24	0.50	0.47	0.13	0.40	0.52	0.34	0.36	0.15	0.73	0.24	0.74	0.50	0.02	-0.20	0.12	-0.40	-0.04	-0.19	0.30
8	Sabarmati	-1.30	-0.10	0.06	-0.94	-0.44	-0.43	0.01	0.22	-0.24	-0.03	-2.11	-0.08	0.00	-1.52	-0.77	1.80	0.22	0.27	1.43	0.87	0.47	-2.22
9	Luni & others	-0.39	-0.33	0.08	-0.37	-0.15	0.60	0.01	0.41	0.35	0.44	-1.34	-0.44	-0.17	-0.88	-0.62	2.08	0.62	0.63	1.38	1.17	-0.47	-0.94
10	All NW&C basins	0.44	0.19	0.09	0.64	0.35	0.92	0.46	0.60	1.02	0.81	0.04	0.08	-0.44	0.40	-0.05	0.87	0.59	0.93	0.67	0.84	0.34	0.18

S1: Winter S2: Pre-monsoon S3: Monsoon S4: Post-monsoon S5: Annual

Figure - 12 Spatial patterns of linear trends in annual mean temperature (% of mean/100 years) for different river basins during the last century (1901-2000).



5.1.1. Future scenario of temperature

Future warming scenarios have been generated for the Indian sub-continent using GCM. Lal (2001) developed climate change scenarios over Indian sub-continent under the four SRES based on the data generated in numerical experiments with Atmosphere and Ocean coupled GCM (A-O GCM) of the CCSR/NIES, Japan to predict changes in temperature and temporal and spatial variability of the monsoon rainfall. It is projected that over the inland regions of the Indian sub-continent, the mean surface temperature may rise between 3.5° C and 5.5° C by 2080 (Lal, 2001). On seasonal basis, the projected surface warming is higher in winter than during summer monsoon. The spatial pattern of temperature change has a large seasonal dependency. The spatial distribution of surface warming suggests that north India may experience an annual mean surface warming of 3° C or more by 2050s. GCM models have simulated peak warming of 3° C over north and central India in winter. Over much of the southern peninsula, the warming is likely to be under 2° C during winter season. The surface temperature rise would be more pronounced over northern and eastern region (~2° C) during the monsoon season. Future projection of increase in temperature and changes in precipitation over Indian subcontinent are shown in Table - 11.

Table - 11 Climate change projections for the Indian sub-continent

Scenarios		*Increase in temperature (°C)*	*Change in rainfall (%)*
2020s	Annual	1.00 – 1.41	2.16 – 5.97
	Winter	1.08 – 1.54	(-)1.95 – 4.36
	Monsoon	0.87 – 1.17	1.81 – 5.10
2050s	Annual	2.23 – 2.27	5.36 – 9.34
	Winter	2.54 – 3.18	(-)9.22 – 3.82
	Monsoon	1.81 – 2.37	7.18 – 10.52
2080s	Annual	3.53 – 5.55	7.48 – 9.90
	Winter	4.14 – 6.31	(-)24.83 – 4.50
	Monsoon	2.91 – 4.62	10.10 – 15.18

5.1.2. Collaborative Programme of MoEF & DEFRA

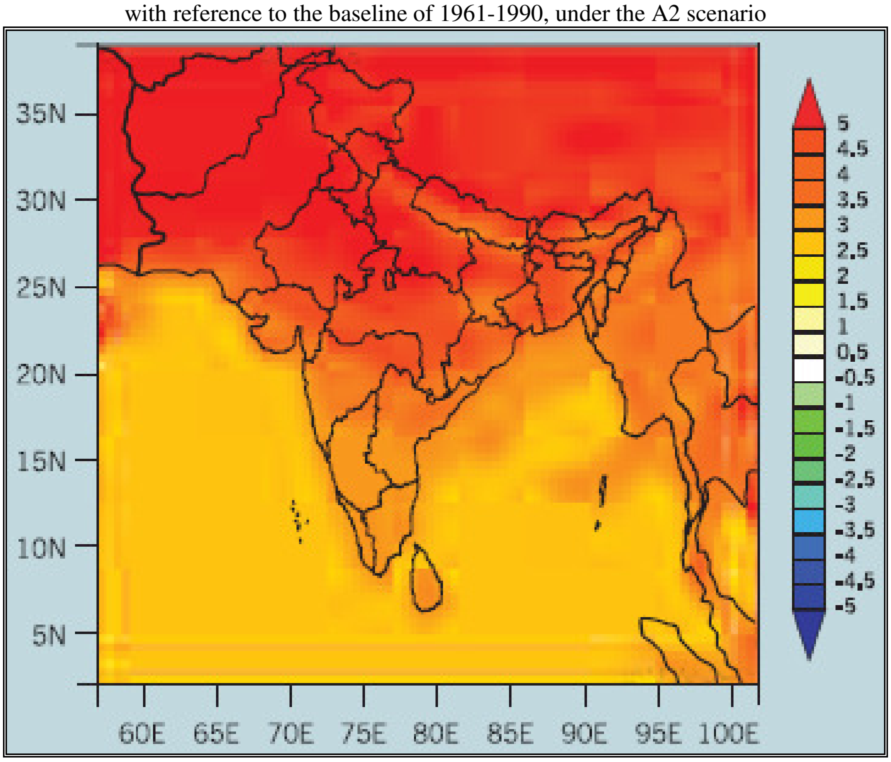
Eight inter-related research projects were carried out by MoEF & DEFRA as a part of a collaborative programme, and a summary for each of these projects was prepared. Two of the eight projects developed climate change scenarios and socio-economic scenarios for India, and this data was used by the other six projects to ensure consistency in assessing climate change impacts. The other six projects then looked at the impacts of climate change on specific topics, namely sea level, water resources, agriculture, forests, industry, and human health by different Indian organizations.

An RCM was set up for the South Asian domain and run to simulate the climate for the present (1961-1990) and a future period (2071-2100). The high-resolution regional simulations generated using the RCM were compared with observed regional climatological data to verify the model's ability to realistically represent the regional climatological features in India, especially for the summer monsoon season. Climate change is affected by population and economic growth, and therefore the socio-economic forecasts are important to understand how different growth scenarios might impact on the degree of climate change. Two different socioeconomic scenarios were incorporated into the model, both characterised by regionally focused development but with priority to economic issues in one (referred to as A2) and to environmental issues in the other (referred to as B2).

5.1.2.1. Regional projections of climate change over India

The RCMs have shown significant improvements over the global models in depicting the surface climate over the Indian region, enabling the development of climate change scenarios with substantially more regional detail. This project has generated high-resolution climate change scenarios not only for different States of India, but also for other South Asian nations, refer Figure - 13 for spatial patterns of the changes in annual mean surface air temperature (ºC) for the period 2071-2100 with reference to the baseline of 1961-1990, under the A2 scenario.

Figure - 13 Spatial patterns of the changes in annual mean surface air temperature (ºC) for the period 2071-2100 with reference to the baseline of 1961-1990, under the A2 scenario



Some of the major results of this project are:

- Model simulations under scenarios of increasing GHG concentrations and sulphate aerosols indicate marked increase in both rainfall and temperature over India into the 21st century.
- The change in rainfall under the B2 scenario is relatively less than that under the A2 scenario.
- There are substantial spatial differences in the projected rain fall changes. The maximum expected increases in rainfall (10 to 30%) occur over central India.
- There is no clear evidence of any substantial change in the year-to-year variability of rainfall over the next century.
- Surface air temperature shows comparable increasing trends in A2 as well as B2 scenarios. The temperatures are projected to increase by as much as 3 to 4° C towards the end of the 21st century.
- The warming is widespread over the country, and relatively more pronounced over northern parts of India.

5.1.2.2. Needs for further research

This study on climate change patterns for India represents a first step towards understanding the science behind the range of impacts. While the scenarios developed in this project are indicative of the expected range of rainfall and temperature changes, the quantitative estimates still have large uncertainties associated with them. Further research is needed to strengthen assessments and reduce uncertainty in predictive models. Specifically, additional research is required to:

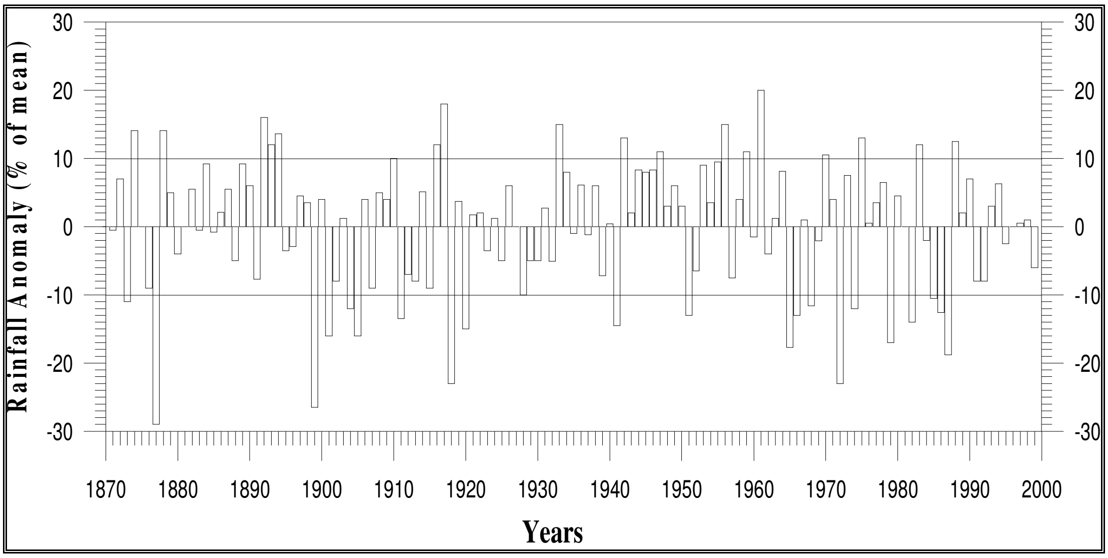
- Improve the models by minimising the known biases in simulating observed regional climatic patterns, especially the Indian summer monsoon;
- Develop an ensemble of plausible scenarios in the regional context;
- Improve spatial resolution for regional/local manifestations of climate change impacts;
- Develop sensitivity studies for regional/local manifestations of climate change impacts; and
- Develop predictive models that focus on short term variations as well as longer-term change, to help guide policy making over time.

5.2 Rainfall

Studies related to changes in rainfall over India have shown that there is no clear trend of increase or decrease in average annual rainfall over the country (Mooley and Parthasarathy, 1984; Sarker and Thapliyal, 1988, Thapliyal and Kulshrestha, 1991). The examination of trend of annual rainfall over India has indicated that 5 year running mean has fluctuated from normal rainfall within ± one standard deviation (Thapliyal and Kulshreshtha, 1991). Summer monsoon rainfall anomalies for all India are shown in Figure - 14. Though the monsoon rainfall in India is found to be trendless over a long period of time, particularly on the all India scale (Mooley and Parthasarathy, 1984), but there are pockets of significant long-term rainfall changes (Koteswaram and Alvi, 1969; Jagannathan and Parthasarathy, 1973; Raghavendra, 1974; Chaudhary and Abhyankar, 1979).

A comprehensive study using the monthly rainfall data for 306 stations distributed over India was attempted by Rupa Kumar et al. (1992). They showed that areas of north-east peninsula, north-east India and north-west peninsula indicate widespread decreasing trend in the Indian summer monsoon rainfall. On the other hand, they reported a widespread increasing trend in monsoon rainfall over the west coast, central peninsula and north-west India. The decreasing trend ranges between -6 to -8% of the normal per 100 years while the increasing trend is about 10 to 12% of the normal per 100 years. Though these trends are statistically significant, but they account for a relatively small part of the total variance in the rainfall. Srivastava et al. (1998) have supported the existence of a definite trend in rainfall over smaller spatial scale. Sinha Ray and De (2003) have summarized the existing information on climate change and trends in the occurrence of extreme events with special reference to India. They concluded that all India rainfall and surface pressure shows no significant trend except some periodic behavior. The frequency of heavy rain events during the south-west monsoon has shown an increasing trend over certain parts of the country (Sinha Ray and Srivastava, 1999). On the other hand, decreasing trend has been observed during winter, pre-monsoon and post-monsoon season. They have tried to attribute dynamical and anthropogenic causes for this variation.

Figure - 14 All India summer monsoon rainfall anomalies (1871-1999) (Lal, 2001)



Lal (2001) and MoEF (2004) reported that rainfall fluctuations in India have been largely random over a Century, with no systematic change detectable on either annual or seasonal scale. However, areas of increasing trend in the seasonal rainfall have been found along the West Coast, North Andhra Pradesh and Northwest India and those of decreasing trend over East Madhya Pradesh, Orissa and Northeast India during recent years. Mirza et al. (1998) have carried out trend and persistence analysis for Ganges, Brahmaputra and Meghna river basins. They have shown that precipitation in Ganges basin is by and large stable. One of three subdivision of the Brahmaputra basin shows a decreasing trend while another shows an increasing trend.

NIH (2007) has studied changes in rainfall and relative humidity in different river basins in the northwest and central India. In this study seasonal and annual trend of changes in rainfall, rainy days, heaviest rain and relative humidity have been studied over the last century for nine different river basins in the northwest and central India. Majority of river basins have shown increasing trend both in annual rainfall and relative humidity. The magnitude of increased rainfall for considered river basins varied from 2 to 19% of mean per 100 years. Maximum increase in rainfall is observed in the Indus (lower) followed by the Tapi river basin. Broadly, a regional pattern of changes in rainfall trend (% of mean/100 years) over the last century has been noted, as depicted in Figure - 15. A summary of the results of different seasons for different river basins has been given in Table - 12. Seasonal analysis shows maximum increase in rainfall in the post-monsoon season followed by the pre-monsoon season. There were least variations in the monsoon rainfall during the last century and winter rainfall has shown decreasing trend. Most of the river basins have experienced decreasing trend in annual rainy days with maximum decrease in the Mahanadi basin. The heaviest rain of the year has increased by 9 to 27 mm per 100 years over different river basins, being maximum increase for Brahamani & Subaranrekha river basin. A combination of increase in heaviest rainfall and reduction in the number of rainy days suggest the possibility of increasing severity of floods. Such information is very useful for the planning, development and management of water resources in the study area.

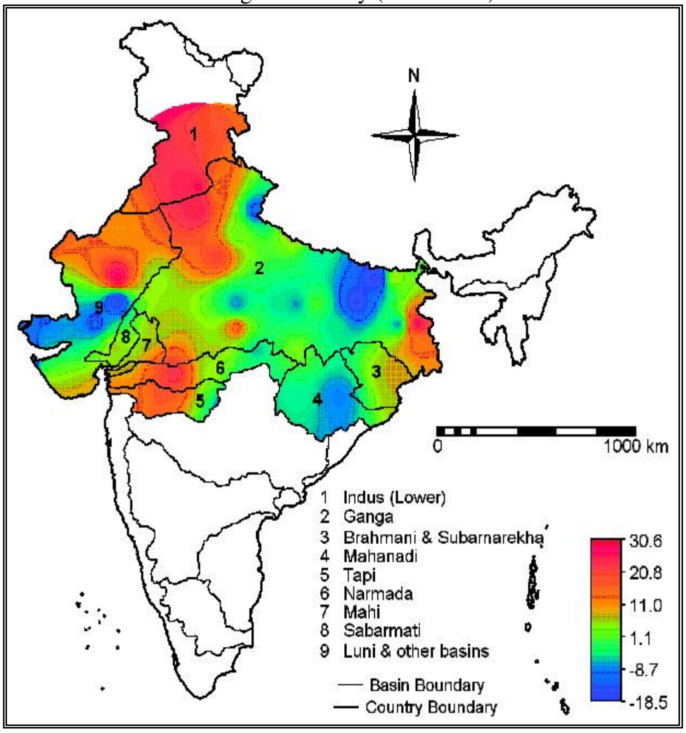
Further, trend of changes in relative humidity show that, like rainfall, majority of river basins also experienced increasing trend in relative humidity both on seasonal and annual scales. Increase in annual mean relative humidity for six river basins has been found in the range of 1 to 18% of mean per 100 years, while decrease for 3 river basins was -1 to -13% of mean per 100 years, providing net increase in the study area by 2.4% of mean per 100 years. It is understood that increase in areal extent of vegetation cover as well as rainfall over the last century has increased the moisture in the atmosphere through enhanced evapo-transpiration, which in turn has increased the relative humidity.

Table - 12 Trends and magnitude of changes in rainfall (% of mean/100 years), rainy days (% of mean/100 years) and heaviest rain (mm/100 years) for different river basins in the study region

#	River basins	Rain					Rainy days					Heavy Rain
		S1	*S2*	*S3*	*S4*	*S5*	*S1*	*S2*	*S3*	*S4*	*S5*	*S5*
1	Indus (lower)	3.51	22.53	13.93	46.91	19.03	-16.71	14.64	0.57	11.58	5.96	22.16
2	Ganga	0.25	10.07	1.74	13.68	3.16	-16.82	2.02	-2.31	6.80	-3.49	9.31
3	Brahamani & Subarn.	-19.31	19.76	2.32	10.57	3.40	-29.59	9.53	-3.96	-3.94	-5.80	27.03
4	Mahanadi	-9.33	-0.27	-5.31	10.63	-4.70	-22.34	2.67	-5.34	-9.96	-9.83	16.60
5	Tapi	-24.46	-12.21	11.11	0.13	9.62	-34.01	-10.44	-0.66	0.26	-1.01	18.16
6	Narmada	2.74	-9.58	8.18	-8.04	6.92	-9.52	-17.54	-1.05	-5.80	-1.89	18.47
7	Mahi	63.05	-63.58	6.29	61.86	6.98	-18.63	-66.00	-2.37	29.97	-2.45	11.81
8	Sabarmati	42.60	-22.44	0.09	93.61	2.07	10.93	-57.91	-4.50	41.08	-0.76	15.11
9	Luni & others	-10.49	2.58	-1.12	86.52	4.94	-39.49	-15.44	-3.40	57.44	-5.42	15.05
	All NW&C basins	-2.02	5.54	2.87	31.28	5.18	-21.86	-3.29	-5.30	14.93	-3.23	14.17

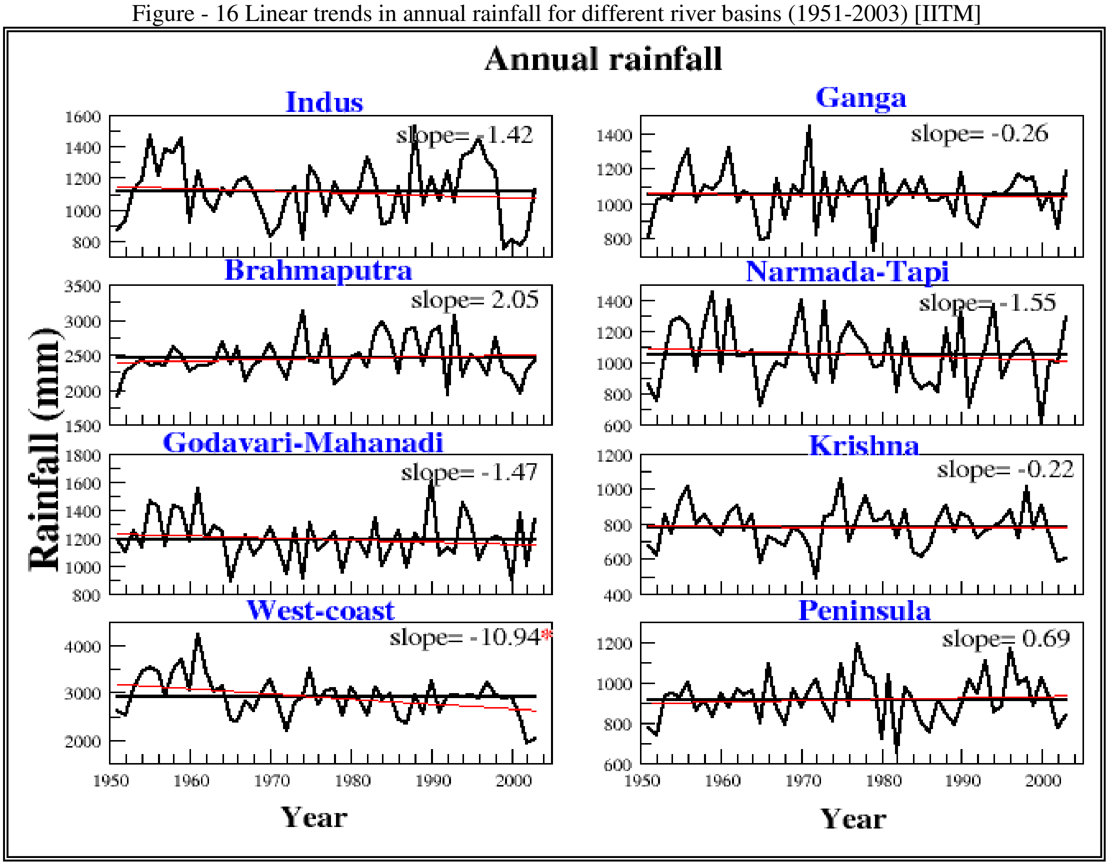
S1: Winter S2: Pre-monsoon S3: Monsoon S4: Post-monsoon S5: Annual

Figure - 15 Spatial patterns of linear trends in annual rainfall (% of mean/100 years) for different river basins during last century (1901-2000)



IITM has studied using mathematical model basin-wise daily gridded rainfall data for a period of 1951-2003. The model simulated daily rainfall data for the period 1961-1990 (baseline scenario with no sulphur runs). The results are shown below in graphical form in Figure - 16.

Figure - 16 Linear trends in annual rainfall for different river basins (1951-2003) [IITM]



The rainfall analysis (annual rainfall) carried out by IITM for various river basins indicate that the Brahmaputra & Peninsular river basins show an increasing trend whereas the Indus, Ganga, Narmada, Godavari, Krishna and West Coast indicate a falling trend in the annual rainfall of varying magnitude. It has been observed that the period of data considered for the study has considerable bearing on its results for example a data series of first half of the century may give contradictory results if the data series of second half of the century or say whole century is considered.

5.2.1. Future scenario of rainfall

In order to predict the changes in the temporal as well as spatial variability of the monsoon rainfall in response to increases in radiative forcing of the atmosphere, climate change scenario over Indian sub-continent under the four SRES 'Marker' emission scenarios have been developed based on the data generated in numerical experiments with A-O GCM of the CCSR/NIES, Japan (Lal, 2001). These four emission scenarios cover a wide range of the main demographic, technological, and economic driving forces of future emissions; each describes a different world evolving through the 21st century and leads to different GHG emission concentration trajectories. Warming is projected to be significant in post-monsoon and winter seasons.

The projected scenarios for rainfall over Indian subcontinent for different seasons by 2020, 2050 and 2080 are given in Table - 11. The increase in annual mean precipitation over the Indian sub-continent is projected to be 7 to 10% by 2080s. Winter precipitation may decrease by 5 to 25% in the Indian sub-continent. An increase of 10 to 15% is projected in area-average summer monsoon rainfall over the Indian sub-continent. Over northwest India, during monsoon season an increase of about 30% or more is suggested by 2050s. The western semi-arid margins of India could receive higher than normal rainfall in the warmer atmosphere. It is likely that date of onset of summer monsoon over India could become more variable in future. IPCC (2001) has indicated that variability in Asian summer monsoon is expected to increase along with changes in the frequency and intensity of extreme climate events in this region. All climate models simulate an enhanced hydrological cycle and increases in annual mean rainfall over South Asia (under non-aerosol forcing).

5.2.2. Study by IITM

The “Impact of Climate change on Water Resources” has been studied by the IITM. The climate change scenarios were developed using the RCMs developed by the Hadley Centre for Climate Prediction and Research, UK, for the Indian subcontinent. Predictions are typically reported for the medium-high emissions (A2) or medium-low emissions (B2) scenarios as outlined by the IPCC to give an indication of impacts of differing levels of GHG. In some cases the RCMs were coupled with more specific models, such as vegetation models for forestry impact, in order to provide more detailed and sector specific predictions. These were tested by comparing existing data on climate changes with predicted changes according to the model, and incorporating the projected socio-economic scenarios for India (eg. population and economic growth) that can drive GHG emissions and thus influence climate change.

This research provides projections of rainfall, temperature, monsoon characteristics and extreme events for all regions of India. Socio-economic scenarios were developed in parallel. The research outlines four potential development scenarios for India, and their associated population and economic growth (factors which will affect climate change). The IITM carried out this study on the impact of climate change on water resources with the following objectives:

- To make a detailed analysis of the spatio-temporal variability of precipitation over the major river basins of India based on long term recorded data.
- To estimate past changes in surface water availability and their sensitivity to climatic variability.
- To validate climate model simulations of daily precipitation over major river basins in India.

- To estimate the changes in water quality at selected sites in the Krishna basin.
- To prepare scenarios of water availability and extreme events, under different climate change scenarios, using the model simulated data.

One of the major activities of IITM has been to undertake hydro-meteorological analysis of various river basins of India, with special attention to precipitation extremes.

5.2.2.1. Description of methodology

The project focused on an impact assessment of climate change on the country's three major river basins: Krishna, Ganga, and Godavari. Summer monsoon rainfall contributed 70 – 90% of rainfall in these basins. IITM began by conducting a daily precipitation analysis, to determine a baseline for assessing future changes. The analysis was carried out using daily-observed rainfall data from about 1000 stations throughout the country for the period from 1901-1995. The observed data was then compared with control simulations, in terms of monthly, seasonal and annual climatologies as well as spatial patterns of extremes, numbers of rainy days, precipitation intensities, etc., to assess the strength of the model predictions. The regional climate model HadRM2 was then used to study the impacts of climate change on water resources.

5.2.2.2. Predicted climate change impacts on water

Spatial patterns of the changes in summer monsoon rainfall (%) for the period 2071-2100 with reference to the baseline of 1961-1990, under the A2 scenario is shown in Figure - 17. In general the rainfall is showing increasing trend all over India except some parts of north-west and southern India. The changes in number of rainy days in a year are also shown in Figure - 18.

Figure - 17 Spatial patterns of the changes in summer monsoon rainfall (%) for the period 2071-2100 with reference to the baseline of 1961-1990, under the A2 scenario

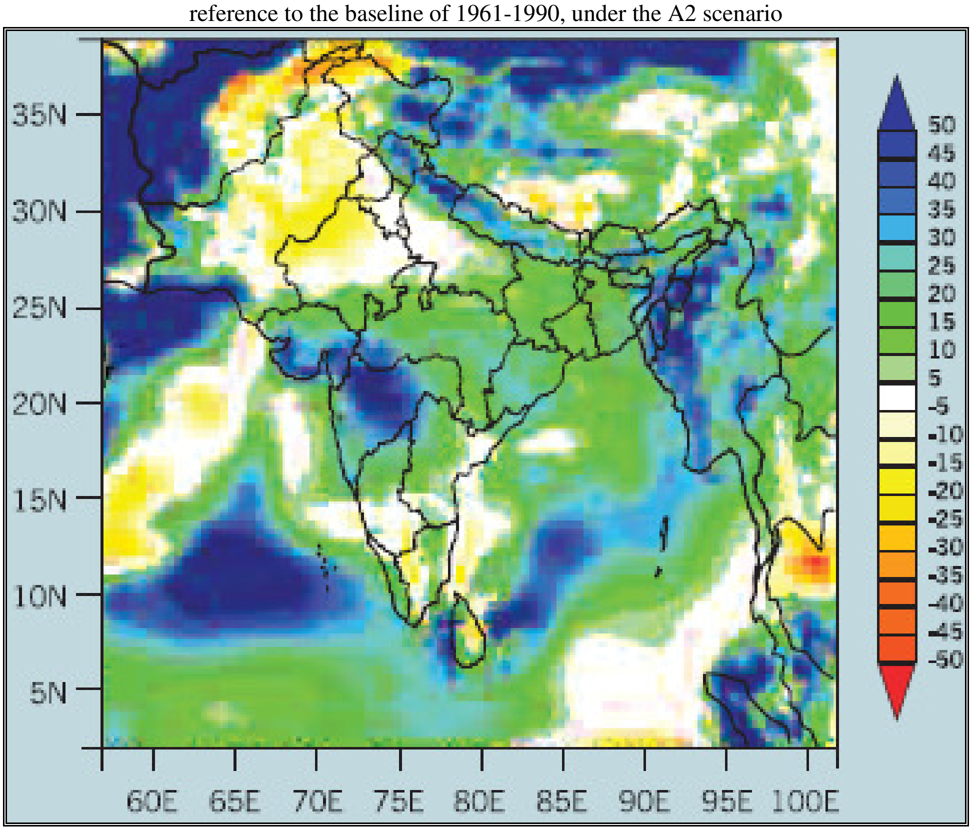


Figure - 18 Changes in Annual Number of Rainy Days (A2 Scenario)

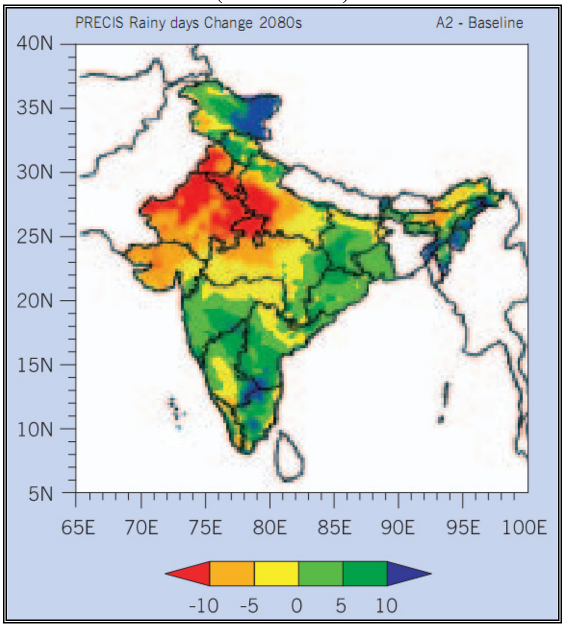
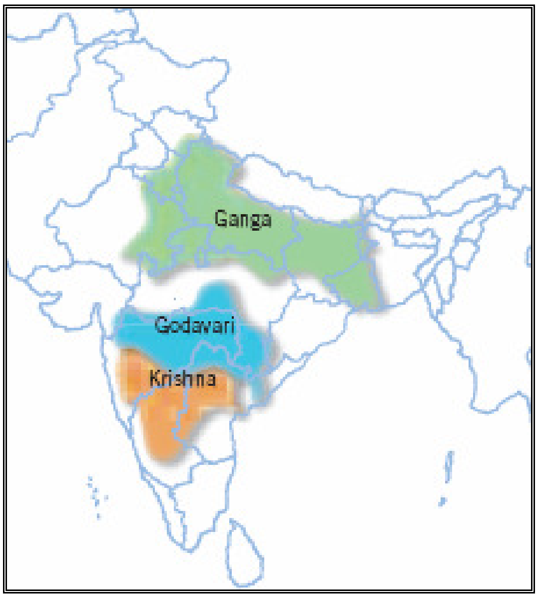


Figure - 19 Study Basins by IITM



- The hydrological cycle is predicted to be more intense, with higher annual average rainfall as well as increased drought.
- There is a predicted increase in extreme rainfall and rainfall intensity in all three river basins towards the end of the 21st century (Figure - 19). The Godavari basin is projected to have higher precipitation than the other two.
- The intensity of daily rainfall is also predicted to increase.
- Changes in the number of rainy days were also examined, with results indicating decreases in the western parts of the Ganga basin, but with increases over most parts of the Godavari and Krishna basins.
- Thus surface water availability showed a general increase over all 3 basins (though future populations projections would need to be considered to project per capita water availability.

The findings of the study for impact of climate change on water resources including annual rainfall as well as annual flows in the three basins is tabulated in Table - 13.

Table - 13 Predictions for the annual rainfall and annual flows for three basins

River Basin	*Baseline (1961-1990)*		*Future (2071-2100)*	
	Annual Rainfall (cm)	*Annual Flow (km^3)*	*Annual Rainfall (cm)*	*Annual Flow (km^3)*
Krishna	91	60	112	67
Godavari	166	98	201	116
Ganga	134	482	150	543

5.2.2.3. Perceived Policy implications of these predictions

Changes in precipitation can affect a variety of planning issues, such as:

- Planning and design of hydrological structures;
- River basin management, flood control and drought management; and
- Urban planning and industrial development.

Other policy implications beyond immediate water supply issues include:

- Agricultural policy will require more flexible food policies that can anticipate the selection of crops for the planting season.
- Forest policy will need to account for erosion mitigation measures in areas where precipitation is predicted to be high.

- Wastewater treatment and sewerage planning will need to address overflow and capacity issues related to intense precipitation.
- Development of water-intensive industries will need to take account of siting issues related to changes in precipitation.

5.2.2.4. Needs for further research

Potential areas for further research include:

- Spatial development of existing models to allow greater precision in climate change predictions.
- Agricultural research on crops that are drought/flood resistant.
- Social science research on the impacts of higher precipitation throughout these river basins on water quality / management.
- Analysis of river discharge data.
- Water availability including groundwater.

5.2.3. Study by IISc

IISc has taken up a study on "Assessment of Water Resources under Climate Change Scenarios at River Basin Scale" in Feb. 2006. The study is being funded by INCOH through NIH. The main objectives of the study are:

- To analyze long-term rainfall and runoff processes, water demands and extreme hydrological events in Mahanadi and Krishna river basins of India;
- To identify a set of climate variables affecting the magnitude, temporal and spatial variability of streamflow and evapo-transpiration;
- To develop stochastic/statistical relationships between the climate variables and the two hydrologic variables (streamflow and evapo-transpiration) for the two river basins;
- To construct long term future hydrologic scenarios by downscaling GCM outputs to hydrologic variables at basin scale for a diverse range of climate change scenarios;
- To study the implications of climate change on water resources in the two river basins in terms of changes in water availability, water demands, and magnitude and frequency of hydrologic extremes;
- To suggest measures for sustainable management of surface water resources in the selected river basins, based on key findings; and
- To provide guidelines to the policy makers regarding adaptation of water resource projects to mitigate the impact of climate change.

The study is progressing and the work on following topics has been taken up, so far:

- Downscaling of GCM simulations to rainfall over Orissa
- Nonparametric methods for modeling GCM and scenario uncertainty
- Downscaling precipitation to river basin in India for IPCC SRES scenarios using support vector machine
- Hydrologic variability and uncertainty analysis through hydroclimatic teleconnection
- Statistical downscaling of GCM simulations to streamflow

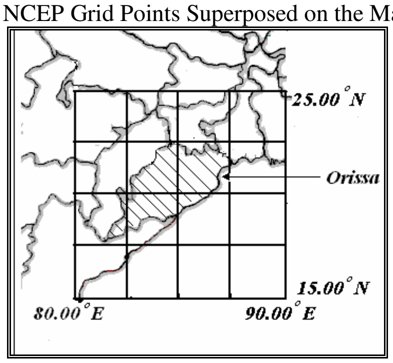
Out of the above five topics, first three dealt with rainfall aspect details of findings of which are given below and remaining two which are dealing with streamflow simulations aspects would be discussed in the following para.

5.2.3.1. Downscaling of GCM simulations to rainfall over Orissa

Downscaling, in the context of hydrology, is a method to project the hydrologic variables (e.g., rainfall, streamflow) at a smaller scale based on large scale climatological variables (e.g., mean sea level pressure) simulated by a GCM. Methods of downscaling include (a) dynamic downscaling, which uses complex algorithms at a fine grid-scale (typically of order of 50 km × 50 km) describing atmospheric processes nested within the GCM outputs commonly known as Limited Area Models or RCM and (b) statistical downscaling, that produces future scenarios based on statistical relationships between large scale climate features and hydrologic variables. In the present work, the statistical downscaling model was developed to project the rainfall over an Orissa meteorological subdivision. The model includes Principal Component Analysis, Fuzzy Clustering and Linear Regression.

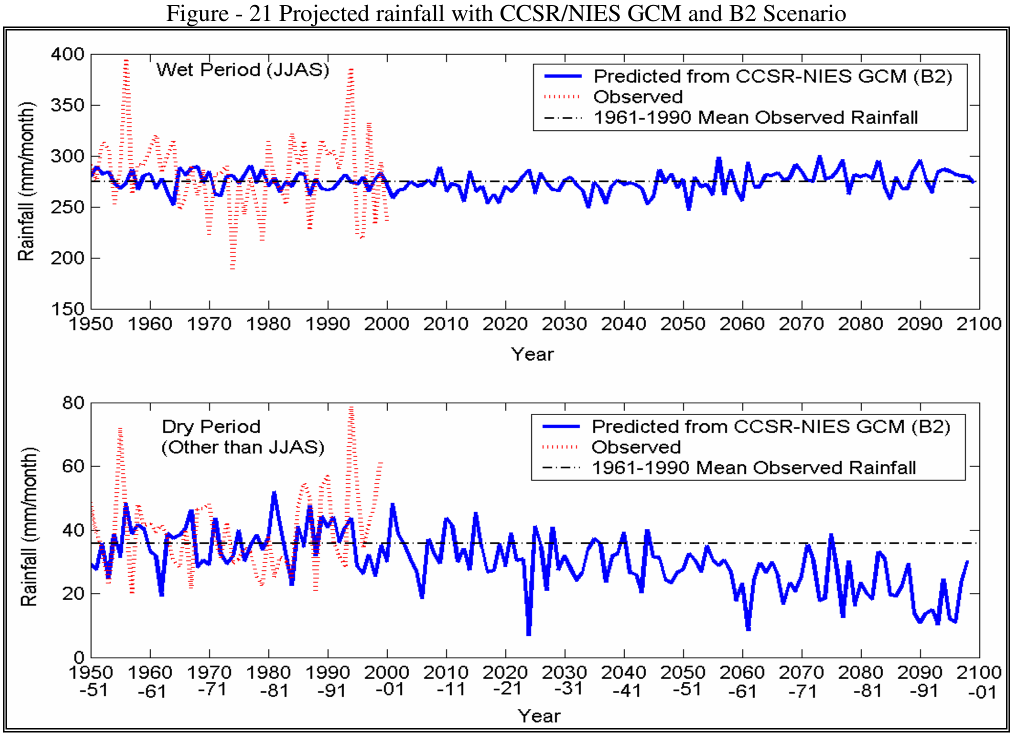
The Orissa meteorological subdivision located on the eastern coast of India, extends from 17^o N to 22^o N in latitude, and 82^o E to 87^o E in longitude (Figure - 20). The monthly area weighted precipitation data of Orissa meteorological subdivision in India, from January, 1950 to December 2002, was obtained from IITM. This data set is being used in the downscaling as predictand. Primary source of this data is the IMD. Selection of the predictor is an important step in statistical downscaling. The predictors, used for downscaling should be: (1) reliably simulated by GCMs, (2) readily available from archives of GCM outputs, and (3) strongly correlated with the surface variables of interest. Precipitation can be related to air mass transport and thus related to atmospheric circulation, which is a consequence of pressure differences and anomalies and thus MSLP is used as the predictor for downscaling in most of the earlier models. Based on that study, the methodology uses MSLP as predictor for downscaling.

Figure - 20 NCEP Grid Points Superposed on the Map of Orrisa



The statistical downscaling model developed for Orissa meteorological subdivision is a hybrid model of weather typing and transfer function. Fuzzy clustering is used to classify gridded MSLP into weather types or classes, and then linear regression is used for projecting the precipitation. Gridded monthly MSLP data from 1948 to 2002, used in the training of downscaling are obtained from the NCEP/NCAR reanalysis project for a region spanning 15^0 N - 25^0 N in latitude and 80^0 E - 90^0 E in longitude that encapsules the study region. Reanalysis data are outputs from a high resolution atmospheric model that has been run using data assimilated from surface observation stations, upper-air stations, and satellite-observing platforms. Results obtained using these fields therefore represent those that could be expected from an ideal GCM. A usual practice in hydroclimatology is to use reanalysis data, when observed data is not available. The monthly data of the predictor variable is extracted from http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml. Principal component analysis is used to reduce the dimensionality of the dataset and also to convert the correlated variables to uncorrelated variables. Fuzzy clustering is performed to derive the membership of the principal components in each of the clusters and the memberships obtained are used in regression to statistically relate MSLP and rainfall. Correlation Coefficient (R) between the observed and predicted precipitation, which is considered as the goodness of fit of the regression model is obtained as 0.924. The statistical relationship thus obtained is used to project the future rainfall from GCM output, which are available online in the IPCC data distribution centre (http://www.mad.zmaw.de/IPCC_DDC/html/ddc_gcmdata.html). A sample projection for CCSR/NIES GCM with B2 scenario is presented in Figure - 21, which shows reduction of rainfall in dry season.

Figure - 21 Projected rainfall with CCSR/NIES GCM and B2 Scenario

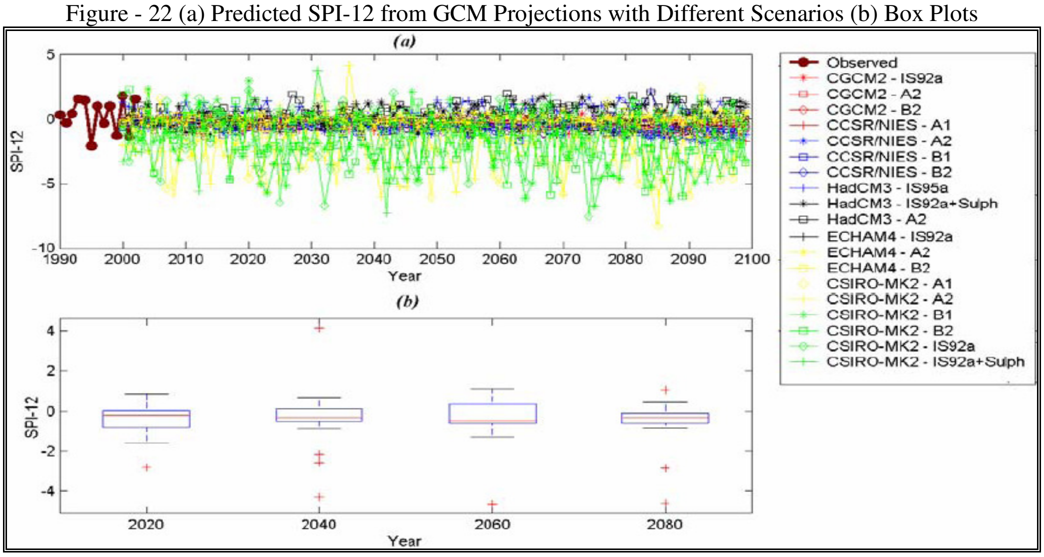


5.2.3.2. Nonparametric methods for modeling GCM & scenario uncertainty

Climate change estimates on regional or local spatial scales are burdened with a considerable amount of uncertainty, stemming from several sources. For estimates based on downscaling of GCM outputs, different levels of uncertainty are related to: (i) GCM uncertainty or inetrmodel variability (use of different GCMs), (ii) scenario uncertainty or interscenario variability, (iii) different realizations of one GCM due to parameter uncertainty (intramodel variability) and (iv) uncertainty due to downscaling methods. It is widely acknowledged that disagreements between different GCMs and scenarios over regional climate changes represent a significant source of uncertainty. Only the first two sources of uncertainties are considered here to project the future drought scenario and are modeled with nonparametric approaches.

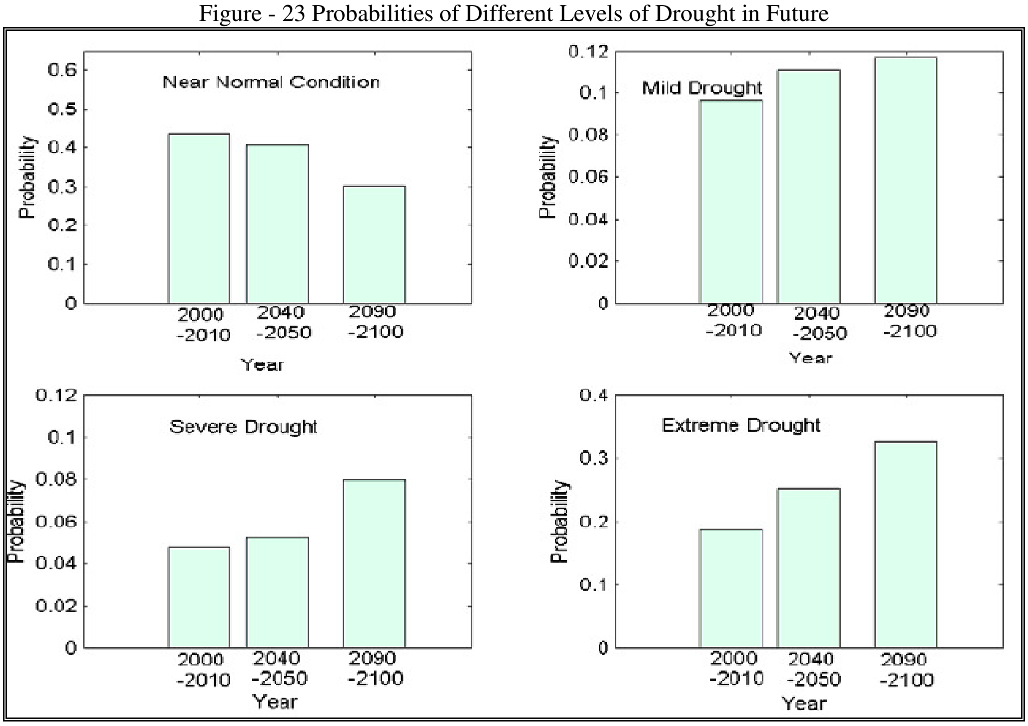
Using the downscaling technique described above, future rainfall scenario is obtained for all the available GCMs with scenarios. After bias correction, equiprobability transformation is used to convert the precipitation into SPI-12, an annual drought indicator, based on the values of which a drought can be classified. The projected SPI-12 obtained with GCMs and scenarios are presented in Figure - 22 (a) and (b), which show that the SPI-12 time series downscaled from one GCM is entirely different from that of another and also a considerable dissimilarity exists among two scenarios of any particular GCM. A single time series of SPI-12 generated from a GCM for a particular scenario represents a single trajectory among a number of realizations derived using various scenarios with GCMs and can not by itself represent the future drought condition.

Figure - 22 (a) Predicted SPI-12 from GCM Projections with Different Scenarios (b) Box Plots



Assuming future SPI to be a random variable at every time step, nonparametric method based on orthonormal series are used to determine the nonparametric pdf of SPI, as it is very unlikely that the small sample of available GCM outputs will follow a particular parametric distribution. Probabilities for different categories of future drought are computed from the estimated pdf at a decadal scale. The probabilities of different levels of droughts are presented in Figure - 23, which shows there is an increasing trend in the probability of extreme drought and a decreasing trend in the probability of near normal condition.

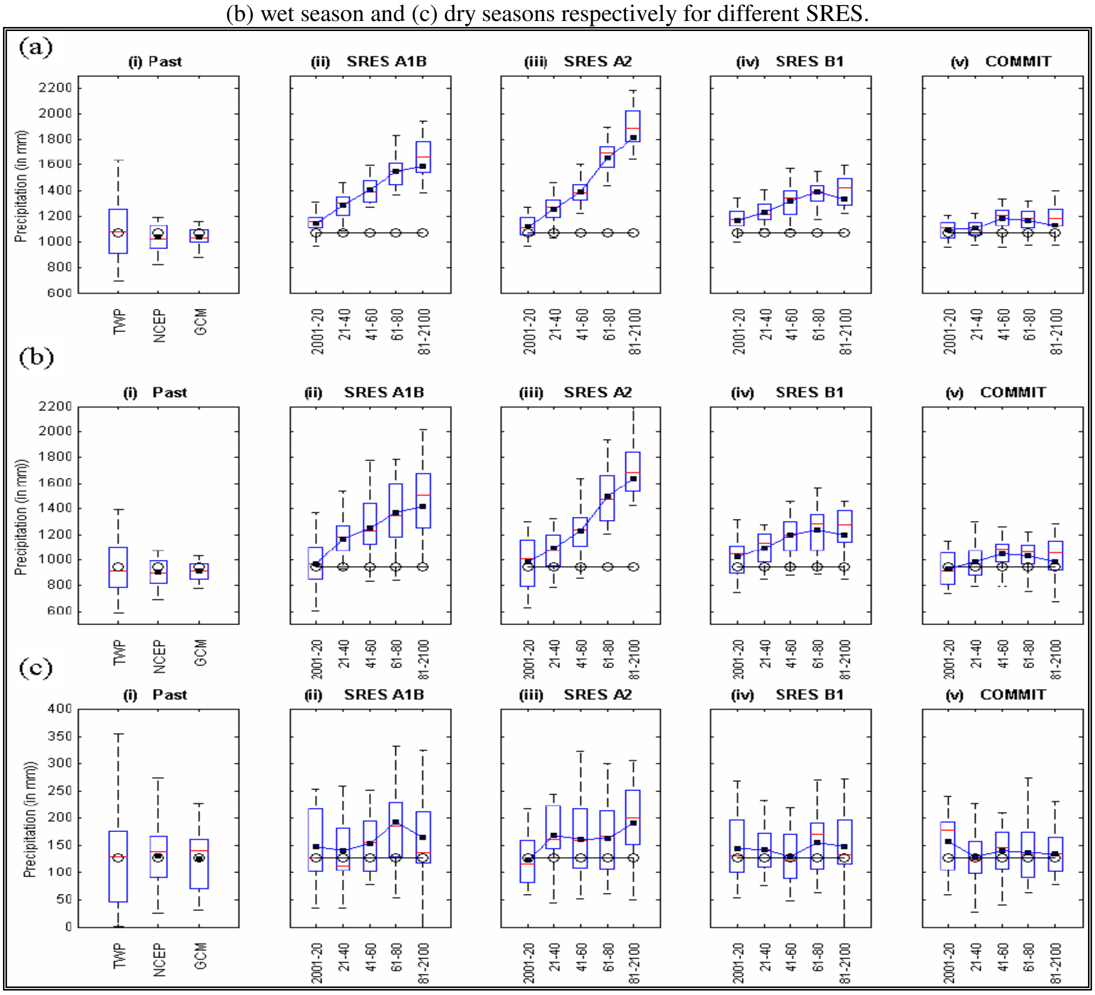
Figure - 23 Probabilities of Different Levels of Drought in Future



5.2.3.3. Downscaling precipitation to river basin for IPCC SRES scenarios using SVM

A method is developed to downscale monthly precipitation to river basin scale in Indian context for SRES using SVM. Probable predictor variables are extracted from (i) the NCEP reanalysis dataset for the period 1971-2000 and (ii) the simulations from the third generation Canadian GCM3 for SRES emission scenarios A1B, A2, B1 and COMMIT for the period 1971-2100. These variables include both the thermodynamic and dynamic parameters and those which have a physically meaningful relationship with the precipitation. The NCEP variables which are realistically simulated by Canadian GCM3 are chosen as potential predictors for seasonal stratification. The seasonal stratification involves identification of (i) the past wet and dry seasons through classification of the NCEP data on potential predictors into two clusters by the use of K-means clustering algorithm and (ii) the future wet and dry seasons through classification of the Canadian GCM3 data on potential predictors into two clusters by the use of nearest neighbor rule. Subsequently, a separate downscaling model is developed for each season to capture the relationship between the predictor variables and the predictand. For downscaling precipitation, the predictand is chosen as monthly precipitation for the river basin, whereas potential predictors are chosen as the NCEP variables which are correlated to the precipitation and are also realistically simulated by Canadian GCM3. Developed method is demonstrated through application to Malaprabha reservoir catchment in Krishna river basin, India, which is considered to be a climatically sensitive region. The Canadian GCM3 simulations are run through the calibrated and validated SVM downscaling model to obtain future projections of predictand for each of the four emission scenarios considered. The results appear to be robust with respect to predictor variables, since many of the variables which undergo changes in a changed climate scenario are considered in predictor selection. The results shown in Figure - 24 indicate that the precipitation is projected to increase in future for almost all the scenarios considered. The projected increase in precipitation is high for A2 scenario, whereas it is least for COMMIT scenario.

Figure - 24 Typical precipitation results obtained from the SVM based downscaling model for (a) annual values (b) wet season and (c) dry seasons respectively for different SRES.



In a similar manner probable predictor variables are identified to downscale temperature, wind speed and humidity and these variables are also downscaled to the river basin scale. Considerable sensitivity analysis is carried-out to study the effect of predictor variables in downscaling. In addition, in the case of wind speed and humidity, downscaled values of monthly data are further disaggregated to daily scale for various IPCC SRES scenarios.

Disaggregated values thus obtained will be used in a conceptual rainfall-runoff model to get the streamflows in the river basin for different projected IPCC SRES scenarios.

5.3 River Flows by CWC

Study on "*trend analysis of flows of major Indian rivers in the context of climatic change*" has been attempted by the analysis of flow data of major rivers including Ganga, Brahmaputra, Chenab and Sone at a few sites to understand the trend in monsoon and non-monsoon flows. Results of simple linear regression are given in Table - 14 below indicating slope of the fitted line in each case i.e. Monsoon, Non-monsoon and Annual flow data. The slope of the trend shows +/- rise/fall in flows in hm^3/year.

Table - 14 Linear trend analysis of river flows

Name of site/ Basin	***Slope of the trend (hm^3/year)***		
	Monsoon	*Non- monsoon*	***Annual***
Rishikesh/ Ganga	-160.88	6.69	**-154.19**
Bhimgoda / Ganga	-7.67	21.24	**13.57**
Kanpur / Ganga	-205.03	36.50	**-168.54**
Varanasi / Ganga	-630.54	14.17	**-616.37**
Patna/Ganga	1604.10	250.87	**1855.00**
Farakka/Ganga	-2423.10	261.19	**-2161.90**
Akhnoor / Chenab	-48.64	-46.06	**-94.69**
Panchratna / Brahmaputra	-2549.50	-975.51	**-3525.00**
Inderpuri barrage	-337.37	-80.56	**-417.93**
Japla / Sone	**159.35**	**76.69**	**236.04**

The analysis & conclusion of the study, which should be considered only with its limitations detailed further below, is as follows:

(a) The analyses of flows based on linear regression of some of the sites in Ganga basin indicate a falling trend except at few locations during monsoon but rising trend during non-monsoon. However, the trend is falling on annual flow basis. To understand trend at upstream sites inputs from snow and glacier studies should be coupled.

(b) The Brahmaputra basin also indicates a falling trend both in monsoon and non-monsoon.

(c) The statistical trend in the data is indicated only at Patna, Varanasi and Panchratna during monsoon flow and Patna, Inderpuri, Japla and Panchratna during non-monsoon period whereas at all other sites statistically there is no trend.

(d) No consistent trend has been observed in Sone basin.

(e) In the light of above diverging analysis and the limitations it may be concluded that:

  i. There is a need for more comprehensive study by taking into account all available data.
  ii. There is need for identification of causes in case of change in flow pattern in the rivers distinctly attributable to the finer demarcation of climate change and variability.
  iii. There is a need for capacity building and exposure towards the standard practices being followed internationally.

The main limitation of the preliminary study has been not accounting for the various important factors, mainly consumptive uses, affecting flow of the river over a long period of time including (i) Irrigation/agriculture development; (ii) Industrial development; (iii) Population growth; (iv) Improved life style; (v) Increased extraction of groundwater; (vi) Changes in precipitation; (vii) Changes in glacial regime etc. in the catchment of the river.

The trend thus found may not be true reflection of the changes in the flow at the site of observation. The other limitations & further works of the above study are listed as below:

(a) The data as identified in Para above is available with different agencies including of State Governments and therefore data collection is a huge task. The limited data of 30-40 years which has been analysed in most of the cases may not be the true reflection of the changes in the flow at any location. By and large 35 years of data is a representation of one full Hydrological cycle only.

(b) The present study needs to be updated to asses the impact of climate change or any trend as such after collecting additional longer period data.

(c) The consistency of monsoon flow data has to be established with respect to rainfall data. The non-monsoon data for consecutive years which by and large represents the base flow and the return flow is the indication of water utilisation which again depends on the storage position of the reservoirs in the upstream of the observation points. The consecutive dry and wet years will have impact on the estimate of the rising or falling trend. These aspects need to be looked into further.

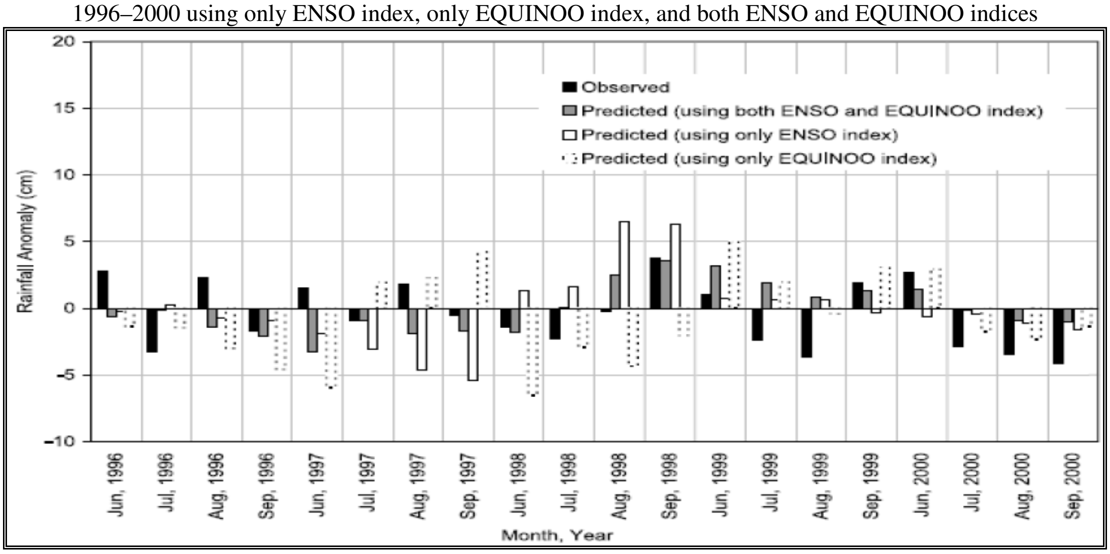
(d) Analytical capabilities to differentiate between impact due to climate variability and climate change have to be developed and other technical considerations have also to be studied/ or built into the analysis to have a clear assessment of impact of climate change.

(e) A serious need has been felt for capacity building particularly for this new subject. To understand the climate change phenomenon in proper perspective and to apply the knowledge gathered intelligently on the Indian water resources systems from micro level to macro level and also to understand the works being carried out by various organizations in Government or Non- Government sector with a view to present a correct picture before the people backed with the factual data. The policy and the training needs of the manpower at various levels is required to be identified and training imparted at the earliest.

5.3.1. Hydrologic variability and uncertainty analysis through hydroclimatic teleconnection

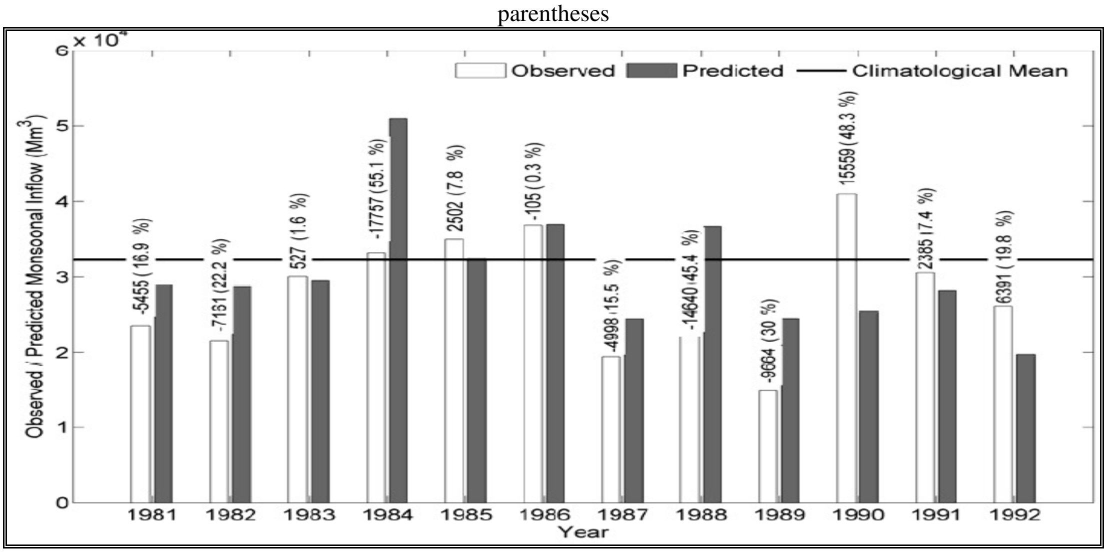
Hydroclimatic teleconnection between hydrologic variables and large-scale atmospheric circulation phenomena is gaining considerable interest in recent years due to its potential use for analyzing variability and uncertainty of hydrologic variables. Dependence of Indian summer monsoon rainfall (ISMR) on large-scale oceanic-atmospheric circulation phenomena from tropical Pacific Ocean (ENSO) and Indian Ocean regions (EQUINOO) is analyzed. The potential of ENSO and EQUINOO for predicting ISMR is investigated by Bayesian dynamic linear model (BDLM). A major advantage of BDLM is that it is able to capture the dynamic nature of the cause-effect relationship between large-scale circulation information and hydrologic variables, along with uncertainties associated Figure - 25.

Figure - 25 Comparison between observed and predicted monthly rainfall anomaly for monsoon months during 1996–2000 using only ENSO index, only EQUINOO index, and both ENSO and EQUINOO indices



Another method is developed to capture the dependence between the teleconnected hydroclimatic variables based on the theory of copula and is used to predict ISMR. Having established the hydroclimatic teleconnection on a comparatively large scale, it is also explored for basin-scale hydrologic variables. Basin-scale hydroclimatic association with both ENSO and EQUINOO at seasonal and monthly scale is used in the form of a CI for forecasting flows into Hirakud reservoir on Mahanadi River in India, both at seasonal and monthly scale respectively. Seasonal inflow predictions are shown in Figure - 26.

Figure - 26 Observed and predicted monsoon season inflows into Hirakud reservoir using the information of CI. Mm^3 are shown corresponding to each year. Percentage of errors (with respect to long term-mean) is shown within parentheses

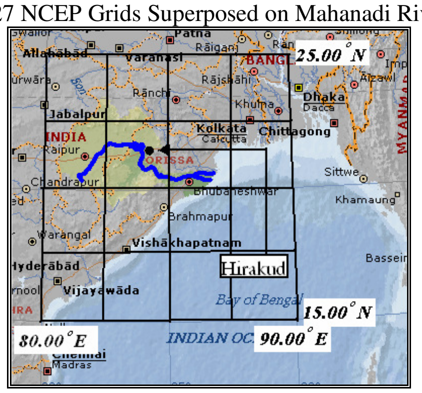


Monthly streamflows are predicted with better accuracy considering information of previous streamflow and large-scale atmospheric circulations together using artificial neural networks whose architecture is optimally chosen using genetic algorithms. A frame-work for effective utilization of these streamflow predictions for optimal reservoir operation is developed.

5.3.2. *Statistical downscaling of GCM simulations to streamflow*

Water resources planning requires the information about future streamflow of a region to combat the hydrologic extremes resulting from climate change. For the prediction of streamflow it is required to downscale GCM projections with appropriate methods. A statistical downscaling model based on PCA, fuzzy clustering and RVM is developed by IISc to predict the monsoon streamflow of Mahandi river at upstream of Hirakud reservoir, from GCM projections of large scale climatological data.

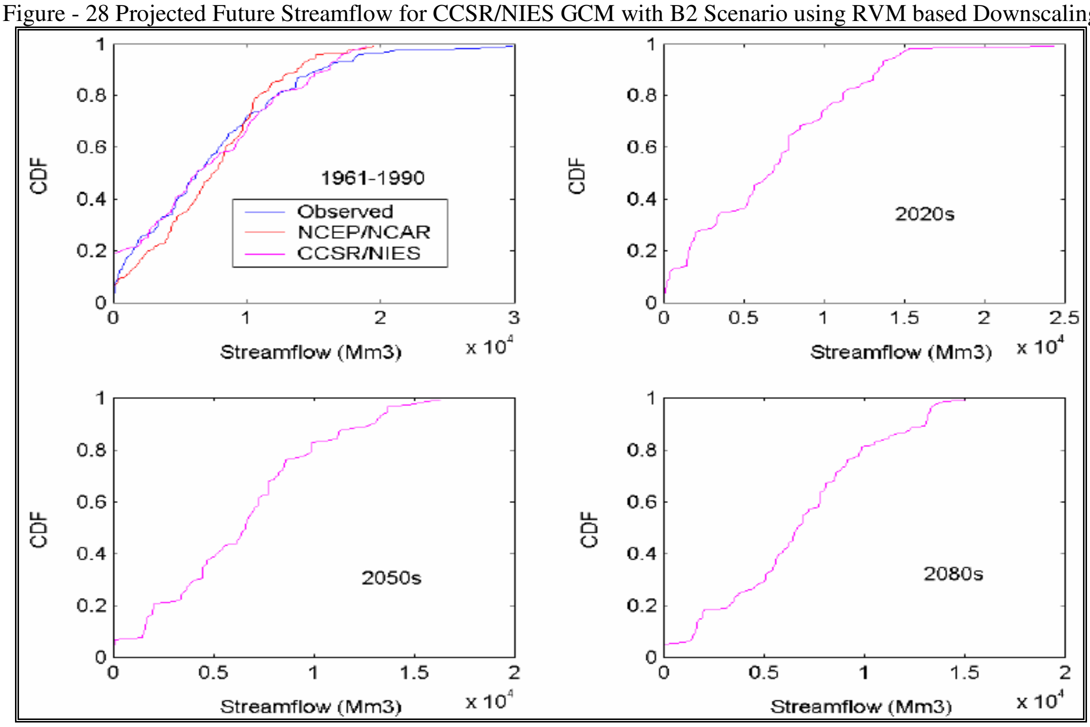
Figure - 27 NCEP Grids Superposed on Mahanadi River Basin



The Hirakud reservoir is located on Mahanadi river in Orissa State on the east coast of India Figure - 27. The latitude and the longitude of the location are 21.320N and 83.450E respectively. The monthly inflow to Hirakud dam from 1961 to 1990, was obtained from Department of Irrigation, Government of Orissa, India. Due to the absence of any major control structure upstream to Hirakud dam, the inflow to the dam is considered as unregulated flow. Mahanadi is a rain-fed river with high streamflow in monsoon (June, July, August and September) due to heavy rainfall and therefore the ground water component with infiltration is insignificant compared to the streamflow during the monsoon season. In the non-monsoon season, infiltration to ground water is quite significant in absence of rainfall, resulting in low streamflow in Mahanadi with almost dry conditions. Thus, only for the monsoon season the streamflow can be modeled with the climatological variables without considering ground water component. Therefore the monthly monsoon flow data of Mahanadi from year 1961 to year 1990 is used in the downscaling model as predictand. Monsoon streamflow can be considered broadly as the resultant of rainfall and evaporation. Rainfall is a consequence of MSLP, geopotential height and humidity whereas evaporation is mainly guided by temperature and humidity. Therefore, 2m surface air temperature, MSLP, 500hPa geopotential height and surface specific humidity are considered as the predictors for modeling Mahanadi streamflow in monsoon season.

Mahanadi river is at the same location as that of Orissa meteorological subdivision and therefore the same grid points, which are used for Orissa meteorological subdivisions, are also used for Mahanadi river basin. Principal component analysis is used to reduce the dimensionality of the predictor dataset and also to convert the correlated variables to uncorrelated variables. Fuzzy clustering is performed to derive the membership of the principal components in each of the clusters and the memberships obtained are used in RVM regression model. The objective of the work is to present the advantage of using RVM over state-of-the-art SVM and also to compare the performances of different kernel functions in a downscaling model. It is observed that RVM with heavy tailed RBF performs best in downscaling. Projections of monsoon streamflow of Mahanadi River at Hirakud with the corresponding CDF are presented for the time slices 1991-2005, 2020s, 2050s and 2080s in Figure - 28 with the GCM developed by CCSR/NIES and B2 scenario.

Figure - 28 Projected Future Streamflow for CCSR/NIES GCM with B2 Scenario using RVM based Downscaling



5.4 Observations of GSI

The studies carried out by GSI also reveal that the glaciers are receding. The causative factors are stated to be subnormal snowfall, higher temperature during summer, less severe winter or a combination of all them. Thus, even the reduction in the snowfall in the catchment may lead to recession of the glaciers without any appreciable change in the melting regime, the recession of the glaciers alone may not necessarily mean release of excess water in the Glacier-fed Himalayan Rivers. The GSI has further stated that if the recession is only due to higher melting of the Glacier, then there may be some increase in the river discharge.

However, this process is a very slow one and if the past is any key to the future, then heavy floods may be an apprehension only.

Even in Himalayan region, the rate of recession in different climatic zones is found to be variable in different years. This variable rate of recession can be attributed to several factors like micro as well as macroclimate, orography, size of the glacier, nature of nourishment, etc.

6. Basin-wise Impacts of Climate Change on Water Resources

The discussion until now suggests that:

(a) there is climate change phenomenon at global level as well as regional/national level; (b) the climate change is affecting various aspects of the human lives and ecology; (c) water resources is among the most vulnerable sectors to be affected by the climate change; (d) there is a lot of variation in the findings about the impacts by the different agencies at each level ie. global level as well as regional/national level; and (e) there is a strong need to take up the studies at basin level and at project level backed by long-term related observed data. (f) the climate change is likely to affect the hydrological cycle, which will result in (i) more rainfall in lesser time; (ii) decrease in number of rainy days; (iii) overall increase in precipitation; (iv) increased glacialmelt-runoff initially and then afterwards decrease; (v) increase in runoff but less ground water recharge?; (vi) increase in flood events particularly of flash floods; (vii) increase in drought like situations; and some other related issues like (viii) increase in landslide events in hilly areas etc.

All the 20 river basins in India are different from each other in terms of spatial and temporal water resources availability; topography; geo-morphological characteristics; meteorological behaviours etc. and therefore, need focused attention separately. But considering importance of snow and glacier melt in the Himalayan Rivers and their vulnerability to climate change, special attention is needed for the Himalayan river basins. Therefore, further discussion should be on impacts of climate change on basin-wise water resources and related areas. Since some studies have already been undertaken for four regions/basins ie. (a) Indus basin; (b) Ganga basin; (c) Brahmaputra basin; and (d) peninsular India, a detailed discussion on primarily these is considered.

6.1 Indus basin

The Indus, which is one of the greatest rivers of the world, rises near Mansarovar in Tibet and flows through Kashmir and Pakistan before fall in the Arabian Sea. Its important tributaries flowing in Indian Territory are Shyok, Nubra, Indus, Satluj, Beas, Ravi, Chenab and Jhelum. Main features of the basin are as follows:

- Catchment area in India: 321289 km^2 (Total: 1165500 km^2)
- Average annual runoff: 73.31 km^3
    - utilizable surface water resources: 46.00 km^3
    - estimated replenishable groundwater resources: 26.49 km^3
- Total of storage created, under creation & under consideration: 19.14 km^3
    - live storage capacity created so far: 16.29 km^3
    - live storage capacity under creation: 0.28 km^3
    - live storage capacity under consideration: 2.58 km^3
- No. of glaciers: 7997 (83.52% of the total Indian glaciers)
    - Area of glaciers: 23000 km^2
    - Volume of glaciers: 1030 km^3
    - Equivalent water resources: 875 km^3 (considering a multiplying factor of 0.85)
- Co-basin States
    - Chandigarh - complete
    - Haryana - partly
    - Himachal Pradesh - partly
    - Jammu & Kashmir complete
    - Punjab - complete
    - Rajasthan - partly

The three States partly in the Indus also drain into Ganga (Yamuna) basin for some areas.

6.1.1. *Status of Irrigation Development*

Irrigation Development statistics are collected & compiled State-wise by the individual States and accordingly status upto X Plan in Table - 15 is of the co-basin States. State-wise Population (as per 2001 census) supported by the water resources for drinking and other purposes is given in the Table - 15.

Table - 15 Status of Irrigation development in Indus basin

Thousand hectare

State	*Population as per 2001 census (Million)*	*Ultimate Irrigation Potential*		*Status upto X Plan (Major & Medium)*	
		Major & Medium	*Minor*	*Potential created*	*Potential utilised*
Chandigarh	0.90	-	-	-	-
Haryana	21.14	3000	1512	2191.36	1909.69
Himachal Pradesh	6.08	50	303	15.45	8.89
Jammu & Kashmir	10.14	250	1108	203.30	184.09
Punjab	24.36	3000	2967	2604.67	2530.02
Rajasthan	56.51	2750	2378	2890.35	2611.60

6.1.2. *Status of Hydropower Development*

The basin has some large multipurpose projects like Bhakra Project; Pong Dam (360 MW); and Ranjit Sagar (600 MW) project and a few large size ROR schemes like Dehar (990 MW); Nathpa Jhakri (1500 MW); Salal (690 MW); Dulhasti (390 MW); Baglihar (450 MW) and various other medium and small ROR schemes which are dependent on water resources availability.

Hydropower potential of the Indus River System has been assessed as 19988 MW at 60% LF as given in Table - 16 out of which only 4035.35 MW (20.2 %) has been developed so far.

Table - 16 Hydropower potential in Indus basin

Basin	*No. of Schemes*	*Firm power (MW)*	*Probable installed capacity (MW)*	*Potential at 60% LF (MW)*
Indus	47	723	2377	1205
Jhelum	22	979	2657	1632
Chenab	37	3559	11318	5932
Ravi	20	946	2534	1577
Beas	34	1189	3372	1981
Sutlej	30	4597	11574	7661
Total	**190**	**11993**	**33832**	**19988**

6.1.3. *Status of flood management*

The State-wise flood management status in the basin as on March 2006 is given in Table - 17.

Table - 17 Status of flood management in Indus basin

Lakh hectare

State	*Flood prone Area as assessed by RBA*	*Flood prone Area as reported by States for XI Plan*	*Area protected as reported by States upto March 2006*
Haryana	23.50	23.50	20.00
Himachal Pradesh	2.30	2.31	0.12
Jammu & Kashmir	0.80	5.14	2.17
Punjab	37.00	40.50	31.90
Rajasthan	32.60	32.60	0.82

6.1.4. *Status of water quality*

Water quality position is relatively better in Indus basin. CPCB has worked out riverine length for different Bio Chemical Oxygen Demand (BOD) values, in mg/L, as indicator of organic pollution after analysing 10 years of data, is as given below:

- Length of river for BOD > 6 mg/L (severely polluted): 70 km (1.70%)
- Length of river for BOD 3-6 mg/L (moderately polluted): 132 km (3.20%)
- Length of river for BOD < 3 mg/L (relatively clean): 3917 km (95.10%)
- Total length of the river including tributaries: 4119 km

6.1.5. *Status of glaciers retreat*

Average water yield per unit area of the Himalayan Rivers is almost double that of the south peninsular river systems, which indicates the importance of snow and glacier melt contribution from high mountains. The sub-basin wise details of the glaciers have been tabulated in Table - 7. GSI has monitored the glaciers in Indus basin and found that they are retreating, in general based on the long-term data ranging from 15 years to 90 years. The observed retreat in the glaciers is varying from 2.5 m/year to 40 m/year however, average annual retreat of the majority of the glaciers is about 0.30% of their total length. Retreat status of some of glaciers in the basin has been given in the Table - 18.

Table - 18 Retreat position of glaciers in Indus basin

Name of glacier	*Period*	*Average retreat (m/year)*
Chhota Shigri	1962-1995	6.8
Bara Shigri	1906-1995	29.8
Sonapani	1906-1957	17.6
Hamtah	1961-2005	14.4
Miyar	1961-1996	16.4
Triloknath	1968-1996	17.86
Yoche Lungpa	1963-2006	19.53
Mulkila	1963-2006	14.77
Nagpo Tokpo	1962-1998	6.4
Man Talai (Gl. no. 115)	1989-2004	23.3
Sara Umga	1989-2004	43.3
Beas Kund	1963-2003	18.8
Gl. no. 30	1963-2003	13.8
Jobri	1963-2003	2.5
Tal	1963-2005	39.88
Manimahesh	1968-2005	29.05
Machoi	1905-1957	9.62
Likir	1964-1999	10.00

6.1.6. *Hydrological and hydro-meteorological data collection*

Hydrological and hydro-meteorological data collection is being carried out by CWC, IMD, SASE, State Governments & Project Authorities (BBMB) on regular basis and by the Research or Academic Institutes for shorter duration for the purpose of specific studies. CWC has a network of 33 nos. hydrological observation sites out of which 14 are in Himachal Pradesh and 19 are in Jammu and Kashmir. Data collection has been started in the basin since 1961 but most of the sites were opened in seventies and therefore data is available for about 35 years. However monitoring of water quality has been started recently about 8 years back. The details of the CWC observation sites are given in Table - 19. The dissemination of hydrological data to any other agency requires approval of MoWR and is chargeable.

Table - 19 Hydrological data collection sites of CWC in Indus basin

Parameter observed	*Number of sites*	
	Himachal Pradesh	*Jammu and Kashmir*
Gauge	2	0

	Number of sites	
Gauge & Discharge	9	9
Gauge, Discharge & Water Quality	0	5
Gauge, Discharge & Sediment	1	1
Gauge, Discharge, Sediment & Water Quality	2	4

Parameter-wise details of the sites are summerised as following:

• Gauge sites:	33 no.
• Discharge sites:	31 no.
• Sediment observation:	8 no.
• Water Quality monitoring:	11 no.

In addition to above CWC has started one snow hydrological observatory in Beas basin at Kothi since Nov. 2003 (earlier it was at Chopal and data is available for 1992 to Oct.2003) and two observatories in Chenab basin at Chilla Top & Batote since 1992.

Government of Punjab operates a network of 58 sites which are proposed to be modernized under Hydrology Project-II – a World Bank funded Project. BBMB is also maintaining data collection network and the same is under modernization whereas Himachal Pradesh is finalizing its data collection network and starting data observation under Hydrology Project-II.

Remote sensing data and satellite imageries of the area are available with NRSA which are provides to the users on charges basis.

6.1.7. Studies carried out on various aspects of water resources

In recent decades, the hydrological characteristics of the watersheds in the Himalayan region seem to have undergone substantial changes as a result of extensive land use (e.g. deforestation, agricultural practices and urbanization), leading to hydrological disasters, enhanced variability in rainfall and run-off, extensive reservoir sedimentation and pollution of lakes. Climate change and its impact on the hydrological cycle and nature of hydrological events have posed an additional attention to this mountainous region of the Indian subcontinent. Extreme precipitation events have geomorphologic significance in the Himalayas, where they may cause widespread landslides. The response of hydrological systems, erosion processes and sedimentation in this region could alter significantly due to climate change. In the light of these water resources related issues there is a need for scientific studies and analysis to understand the various phenomenon related to the relevant topics as listed below:

- Glaciology
- Snow hydrology
- River hydrology and sedimentation
- Irrigation
- Floods including flash floods & GLOF and drainage
- Hydro-power
- Water quality
- Ground water

Various studies have already been undertaken by the related Government organizations, scientific/research organizations and academicians which are summarized below:

6.1.7.1. Snow distribution with altitude in the Chenab basin

Singh et al. (1994) investigated the behaviour of snow distribution with elevation in the Chenab basin located in the western Himalayan region. Snowfall data of 26 stations situated at different elevations in different ranges was considered. Maximum snowfall was found to be about at 2500 m on the windward and at 1800 m on the leeward side in the middle Himalaya in this basin. Greater Himalayan region experienced lesser snowfall than the middle Himalaya in this catchment. The study has revealed that average number of snow days increase with elevation, but intensity decreases. Considering all ranges, it is found that at an elevation of about 3000 m, solid and liquid precipitations equally contribute to annual precipitation.

6.1.7.2. Regional flow duration curve for River Chenab

Arora et al (2005) carried out a study with the objective of examining the effect of altitude on water availability estimates for the various sub-basins of the Chenab river basin (mean elevation of the basin is 3600 m). The daily flow data of 11 gauging sites varying from 14 years to 23 years in the Chenab river basin has been utilized. The daily flow data of nine gauging sites has been utilized for developing the regional relationships for water availability computations. It is observed that the flow for a given dependability increases with catchment area and decreases with latitude. The flows of the catchments at higher altitudes exhibit larger variability in comparison to the catchments at lower altitudes. The regional relationships are recommended for use by field engineers.

6.1.7.3. Topographical influences on precipitation distribution in different ranges of Western Himalayas

Singh et al (1995) studied the seasonal and annual distribution of rainfall and snowfall with elevation for the outer, middle and greater Himalayan ranges of Chenab basin in the western Himalayas. Rainfall and snowfall exhibited different trends with elevation on the windward and leeward slopes of the three ranges of Himalayas. Variation of snowfall with elevation was more prominent in comparison to variation in rainfall. In the greater Himalayan range it is found that rainfall decreases exponentially with elevation and snowfall increase linearly. Rainfall becomes negligible at elevation beyond 4,000 m on the windward side of the greater Himalayan range.

6.1.7.4. Spatial Distribution and Seasonal Variability of Rainfall in Mountainous basin in the Himalayan Region

Arora et al. (2006) studied the average distribution of precipitation and provides essential input for understanding the hydrological process. The role of complex topography in mountainous basins makes the spatial distribution of precipitation different than the plain areas. Besides the rugged topography, the Himalayan basins also face the problem of limited physical accessibility and data availability. In this study, seasonal and annual distribution of rainfall with elevation and distance from the lower most station (Akhnoor) has been studied for the Chenab basin (western Himalayas). A reduction in rain gauges from 42 to 19 has resulted in an increase in the estimate of mean annual rainfall by 14% with respect to the estimate obtained using 42 stations network.

6.1.7.5. Stream flow Simulation of Satluj River

Singh and Quick (1992) carried out streamflow simulation for the Satluj River in the Western Himalayan region using UBC Watershed Model. Snowmelt and glacier melt runoff constitutes the major part of flow during spring and summers in this river. The results indicate that combining two hydrologically different watersheds into a single watershed reduces simulation or forecasting accuracy. It is reported that areal distribution of precipitation is the most important factor in the streamflow simulation because snowpack is built up by the model from precipitation-elevation relationships.

6.1.7.6. *Effect of orography on precipitation in the western Himalaya*

Singh and Kumar (1997) studied the precipitation distribution with altitude for the Satluj and Beas basins in the western Himalayas. Rainfall increases linearly with the elevation for both basins in the outer Himalayan region. The middle Himalayan range of the Beas basin has rainfall gradient of 106 mm per 100 m on windward side and 13 mm per 100 m on leeward side. Different trends of rainfall variation with elevation are observed in different seasons in the middle Himalayan range with a linear increase in annual rainfall. Rainfall follows an exponential decreasing trend with altitude in the greater Himalayan range. In the greater Himalayas, average annual rainfall is about one-sixth of the outer Himalayas rainfall in the Satluj basin. Maximum rainfall is in the middle Himalayan range in the Beas basin. Snowfall gradients for the Spiti and Baspa sub-basins are 43 mm per 100 m and 10 mm per 100 m, respectively. All stations recorded more than 60% snow contribution to annual precipitation. Extrapolation of the relationship indicates that snow and rain contribute equally at about 2000 m, and all precipitation occurs as snow above 5000 m.

6.1.7.7. *Snow and glacier melt in the Satluj River at Bhakra Dam*

Singh and Jain (2002) determined the snow and glacier melt contribution in the Satluj River at Bhakra. Keeping in view the availability of data for the study basin, a water balance approach was used and a water budget period of 10 years (October 1986-September 1996) was considered for the analysis. It was found that the average contribution of snow and glacier runoff in the annual flow of the Satluj River at Bhakra Dam is about 59%, the remaining 41% being from rain.

6.1.7.8. *Assessment of sedimentation in Bhakra Reservoir*

Jain and Singh (2002) used a remote-sensing approach for assessment of sedimentation in Bhakra Reservoir, on the Satluj River. Multi date remote sensing data (IRS-IB, LISS II) provided the information on the water-spread area of the reservoir, which was used for computing the sedimentation rate. The revised capacity of the reservoir between maximum and minimum levels was computed using the trapezoidal formula. The loss in reservoir capacity due to sedimentation for a period of 32 years (1965-1997) was determined to be 807.35 Mm^3, which gives an average sedimentation rate of 25.23 Mm^3/year whereas the same was 20.84 Mm^3/year as per hydrographic survey data for the same period.

6.1.7.9. *Effect of warmer climate on snow-covered area in Satluj basin*

Singh and Bengtsson (2003) investigated the effect of warmer climate on the depletion of snow-covered area for the Satluj River basin located in the western Himalayan region in India. Snowmelt runoff contributes substantially to the annual streamflow of this river. In order to study the impact of three warming scenarios (T+1, T+2 and T+3° C), more than 160 new snow depletion curves were prepared for different elevation zones of the basin over the study period of nine years (1985/86-1990/91 and 1996/97-1998/99). The impact of warmer climate on accelerating the depletion of snow-covered area is found to be higher in the early and late parts of the ablation season. The consequences of faster disappearance of snow from the basin are discussed in terms of the hydrology and climatology of the basin.

Further Singh and Bengtsson (2005) studied the impact of warmer climate on melt and evaporation for rainfed, snowfed and glacierfed basins located in the western Himalayan region. Hydrological processes were simulated under current climatic conditions using a conceptual hydrological model which accounts for the rainfall-runoff, evaporation losses. Snow and glacier melt. After simulations of daily observed streamflow (R2 = 0.90) for 6 years, the model was used to study the impact of warmer climate on melt and evaporation. Based on the future projected climatic scenarios in the study region, three temperature scenarios (T+1, T+2 and T+3° C) were adopted for quantifying the effect of warmer climate. The comparison of the effect of warmer climate on different types of basins indicated that the increase in evaporation was the maximum for snowfed basins. For a T+2° C scenario the annual evaporation for the rainfed basins increased by about 12%, whereas for the snowfed basins it increased by about 24%. The high increase of the evaporation losses will reduce the runoff. It was found that under a warmer climate, melt was reduced from snowfed basins, but increased from glacierfed basins. For a T+2° C scenario, annual melt was reduced by about 18% for the studied snowfed basin, while it increased by about 33% for the glacierfed basin. Thus, Impact of warmer climate on the melt from the snowfed and glacierfed basins was opposite to each other. The study suggests that out of three types of basin, snowfed basins are more sensitive in terms of reduction in water availability due to a compound effect of increase in evaporation and decrease in melt. The water availability from the complex basins will be reduced on long-term basis, when the areal extent of glaciers will decrease due to higher melt rate at initial stages.

6.1.7.10. Estimation of Sediment yield for a rain, snow & glacier fed River

Jain et al. (2003) made an assessment of sediment yield for the Satluj River. Two approaches were used for the assessment of sediment yield (i) relationship between suspended sediment load and discharge and (ii) empirical relationship. The sediment-discharge relationship was developed using daily data for a period of three years (1991-1993) for different basins and was applied for each basin for the years 1994 and 1996 for estimation of sediment yield. The second approach, which gives annual sediment yield, has been used for a small intermediate basin only because of data availability constraints.

6.1.7.11. Modelling of streamflow and its components for Satluj basin with predominant snowmelt yields

Singh and Jain (2003) developed a conceptual snowmelt model, which accounts for both the snowmelt and rainfall runoff and applied it for daily streamflow simulation for the Satluj River basin. The model, designed primarily for mountainous basins, conceptualizes the basin as a number of elevation zones depending upon the topographic relief. The basic inputs to the model are temperature, precipitation and snow-covered area. The model performed well for both calibration and simulation periods. The model was also used to estimate the contribution from the snowmelt and rainfall to the seasonal and annual flows.

6.1.7.12. Relating air temperatures to the depletion of snow covered area in Satluj basin

Singh et al. (2003) developed a procedure for evaluating depletion of SCA using mean air temperature. The study was carried out for Satluj basin. Reference date for computing CTM was considered March 1. Data of three ablation seasons (1987-1989) were used to establish relationship between SCA and CTM. It was found that depletion of SCA is exponentially correlated with CTM (R2 > 0.98). This method has a potential for estimating missing data and extending time series on daily, weekly or monthly basis. Once the depletion trend is established in the basin in the first part of melt season, SCA can be simulated with good accuracy using CTM data for the rest of the period of melt season. Such applications can reduce the number of satellite images required for obtaining SCA information. A forecast of SCA can also be made using forecasted air temperatures. Impact of climate change on depletion of SCA over the melt period indicated that for the considered range of temperature increase (1-3° C), melting area of snow increased linearly with increase in temperature. An increase in temperature by 2° C enhanced the melting area of snow over the melt season by 5.1%.

6.1.7.13. Hydrological sensitivity of Satluj basin to climate change

Singh and Bengtsson (2004) investigated the sensitivity of water availability to climate change for the Satluj River basin which receives contributions from rain, snow and glacier melt runoff. About 65% of the basin area is covered with snow during winter, which reduces to about 11% after the ablation period. The hydrological response of the basin was simulated using different climatic scenarios over a period of 9 years. Adopted plausible climate scenarios included three temperature scenarios (T+1, T+2, T+3° C) and four rainfall scenarios (P-10, P-5, P+5 and P+10%). Under warmer climate, a typical feature of the study basin was found to be reduction in melt from the lower part of the basin owing to a reduction in snow covered area and shortening of the summer melting season and, in contrast, an increase in the melt from the glacierized part owing to larger melt and an extended ablation period. Thus, on the basin scale, reduction in melt from the lower part was counteracted by: the increase from melt from upper part of the basin, resulting in a decrease in the magnitude of change in annual melt runoff. The impact of climate change was found to be more prominent on seasonal rather than annual water availability. Reduction of water availability during the summer period, which contributes about 60% to the annual flow, may have severe implications on the water resources of the region.

6.1.7.14. Impact assessment of climate change on the hydrological response of Spiti basin

Singh and Kumar (2005) examined the affect of climate change on snow water equivalent, snowmelt runoff, glacier melt runoff and total streamflow and their distribution for the Spiti river. The total streamflow of this river has a significant contribution from snow and glacier melt runoff. Snow water equivalent reduces with an increase in air temperature. However, no significant change is found in the snow water equivalent of the Spiti basin by the projected increase in air temperature. An increase of 2° C in air temperature reduced annual snow water equivalent in the range of 1 to 7%. Changes in precipitation caused proportional changes in snow water equivalent. It is found that annual snowmelt runoff, glacier melt runoff and total streamflow increase linearly with changes in temperature (1-3° C), but the most prominent effect of increase in temperature has been noticed on glacier melt runoff for this high altitude. For example, an increase of 2° C in air temperature has enhanced annual snowmelt runoff, glacier melt runoff and total streamflow in the range of 4-18%, 33-38% and 6-12% respectively. The effect of change in precipitation (P-10 to P+10%) suggests a linear increase in snowmelt runoff and total streamflow, while in general, glacier melt runoff is inversely related to changes in precipitation. Snowmelt runoff is found more sensitive than glacier melt runoff to changes in precipitation (P-10 to P+10%). Under a warmer climate scenario, snowmelt runoff and glacier melt runoff cause an earlier response of the total streamflow and a change in flow and a change in flow distribution. The seasonal analysis of total streamflow indicates that an air temperature produces an increase in the pre-monsoon season followed by an increase in the monsoon season.

6.1.8. Activities of MoWR

Besides other regular activities of related data collection, ongoing scientific studies etc. MoWR is setting up two chairs in IIT Roorkee and NIT Srinagar for taking up related studies in the basin in particular. It has also been decided that NIH would take up development of a model for Pandoh dam as per the long-term action plan of the MoWR detailed at para-0. Trend analysis of river flows on 10-daily basis, mainly for inputs to irrigation impact studies, has been taken up by CWC for its discharge observation sites in all the basins. However, more accurate scenario would emerge only when the data of water withdrawal by different projects in the basin, which are maintained by the Project Authorities/State Governments are integrated in the analysis.

CWC has taken up the work of development of WRIS in XI Plan wherein all the water resources related data would be consolidated and put on GIS with the help of SAC and NRSA. Such an activity would boost the related studies in water resources sector as well as accuracy of findings would be improved due to availability of refined and cross-checked database. Under development of WRIS one component viz. “Studies and Monitoring of Water bodies and Glacial Lakes in the Himalayas affecting India” would deal with inventorisation and monitoring of water bodies and glacial Lakes using satellite data and remote sensing technology. Opening of two new sites has also been envisaged besides modernization of existing two sites each in Chenab and Beas basins.

6.1.9. Discussion on status of water resources aspects and studies

The Indus basin is endowed with plenty of water resources particularly with the glacial wealth. The stage of irrigation potential created in co-basin States is about 87% which is better than potential created at national level of about 72%. Percentage of storage already created with respect to average annual flow of the basin is about 22% which is also better than the percentage at national level of about 11.7%. The stage of development of hydropower in the basin is in line with stage of development at national level. The basin is not considered as flood prone and the river water quality is comparatively better than the other Himalayan basins. The Himalayan Rivers generally carry high silt load and rivers in Indus basin is not an exception. The basin supports population of about 119 Million in its co-basin States.

The climate change is likely to affect identified aspects of hydrology of the basin and thus various sectors dependent of water resources are going to be affected but when and how much is the vital question to be answered before taking up the mitigative or adaptive measures. The various studies carried out by the scientists, academicians and research organizations and Government departments mainly concentrated on meteorological, hydrological including glaciology and snow sciences. It has broadly been brought out that:

(i) There is rising trend in temperature in the basin, however minimum temperature has shown falling trend. Further rise in temperature has been predicted. (*specific studies are further needed*);

(ii) There is falling trend in rainfall in the basin (IITM), whereas the Indus (lower) shows rising trend (NIH). Number of rainy days as well as heavy rain events are also increasing (NIH). (*Basin specific studies for prediction for rainfall as well as for flows are needed*);

(iii) Glaciers of the basin are retreating with varying magnitude which depend on their size, orientation etc. (GSI). (*Sub-basin-wise averaging of water equivalent of glacier melt runoff studies are needed for considering mitigation measures*);

(iv) Various what-if analysis scenarios have been generated for effect of rise in temperature by 1°/2°/3° C as well as change in precipitation by -10/-5/+5/+10% in Chenab, Satluj and Spiti sub-basins on snowmelt as well as on glacier melt runoff. It has been found that: (a) such changes would affect seasonal flows more prominently in comparison to annual flows; (b) rise in temperature would increase glacier melt runoff more in comparison to snowmelt runoff; (c) the scenarios are different for different sub-basins and even within a basin variations are there depending upon altitude in the same basin; (d) an estimate of runoff from glacier melt and snowmelt can be made based on prediction of air temperature. (*Findings of the studies may be extended to the water resources facilities in the basin for optimizing the operation of the same*).

These studies are based on short-term data collected for the purpose of study only and long-term data collected by the national agencies. Some of the investigators have found data inadequate also for the studies. Findings of one study indicate that reduction in rain gauge network gave substantially higher estimate of annual rainfall. An accurate and validated database from an optimized data collection network is essential for the credible studies and the actionable recommendations. With the ensuing worldwide phenomenon of climate change which is likely to affect water resources scenarios the data collection for different parameters involved in hydrological cycle becomes very important for better understanding and planning

accordingly. *Therefore, it is necessary to review the data collection network of the basin for at national level by the central agencies involved in data collection in the field and network be strengthened accordingly. The responsibility for data collection be with central agencies to maintain uniformity and transparency as the data validation would be a major problem if left with multiple agencies including State agencies.*

Though the areas on which studies have already been carried out need to be further investigated with the recent data collected as the climate change is a dynamic process and the nation should be ready for the adaptation and mitigation, *some of the areas have yet not been investigated including (a) prediction for meteorological extreme events, including heavy one-*

day rainfall and flash floods, (b) temporal shift of precipitation, (c) effect of de-glaciation on sedimentation, (d) analysis of river flows on 10-daily basis after including extractions by the projects in the basin and return flows and likely future scenarios. (e) effect on irrigation water requirement and other consumptive uses or say on demand side, (e) effect on hydropower projects, (f) inventory of glacial lakes and their vulnerability for outburst due to increase in temperature, (g) effect on water quality, (h) effect on groundwater resources and (i) snowmelt characteristics and glacier retreat.

6.2 Ganga basin

The Ganga River originates from Gangotri glacier in Uttarakhand and is drained by tributaries viz. Yamuna, Bhagirathi, Alaknanda, Sharda, Ghaghra, Bagmati, Kosi, Gandak etc. and falls into Bay of Bengal through Bangladesh. Many of its tributaries originate in Nepal. Main features of the basin are as following:

- Catchment area in India: 861452 km^2 (Total: 1186000 km^2)
- Average annual runoff: 525.02 km^3
  - utilizable surface water resources: 250.00 km^3
  - estimated replenishable groundwater resources: 170.99 km^3
- Total of storage created, under creation & under consideration: 90.74 km^3
  - live storage capacity created so far: 42.06 km^3
  - live storage capacity under creation: 18.60 km^3
  - live storage capacity under consideration: 30.08 km^3
- No. of glaciers: 968
  - Area of glaciers: 2484 km^2
  - Volume of glaciers: 214 km^3
  - Equivalent water resources: 182 km^3 (considering a multiplying factor of 0.85)
- Co-basin States
  - Bihar - complete
  - Chattisgarh - partly (drains into Mahanadi basin also)
  - Delhi - complete
  - Haryana - partly (drains into Indus basin also)
  - Himachal Pradesh - partly (drains into Indus basin also)
  - Jharkhand - partly
  - Madhya Pradesh - partly
  - Rajasthan - partly (drains into Indus basin also)
  - Sikkim - partly
  - Uttar Pradesh - complete
  - Uttaranchal - complete
  - West Bengal - partly

6.2.1. Status of Irrigation Development

State-wise Irrigation Development status upto X Plan of the co-basin States along with State-wise Population supported by the water resources for drinking and other purposes is given in Table - 20.

Table - 20 Status of Irrigation development in Ganga basin

Thousand hectare

State	*Population as per 2001 census (Million)*	*Ultimate Irrigation Potential*		*Status upto X Plan (Major & Medium)*	
		Major & Medium	*Minor*	*Potential created*	*Potential utilised*
Bihar	83.00	5223.50	5663.50	2959	1896.18
Chattisgarh	20.83	1146.93	571	1810.68	1281.52
Delhi	13.85	-	-	-	-
Haryana	21.14	3000	1512	2191.36	1909.69
Himachal Pradesh	6.08	50	303	15.45	8.89
Jharkhand	26.95	1276.50	1183.50	603.97	440.70
Madhya	60.35	4853.07	11361	1451.90	917.88

State	Population as per 2001 census (Million)	Ultimate Irrigation Potential		Status upto X Plan (Major & Medium)	
		Major & Medium	Minor	Potential created	Potential utilised
Pradesh					
Rajasthan	56.51	2750	2378	2890.35	2611.60
Sikkim	0.54	20	50	0.00	0.00
Uttar Pradesh	166.20	12154	17481	8781.35	6926
Uttaranchal	8.49	346.00	518	289.65	191.49
West Bengal	80.18	2300.00	4618	1769.81	1583.36

6.2.2. Status of hydropower development

According to "Re-assessment of HE Potential of the country (1978-87)", carried out by CEA the HE Potential of Ganga River System is assessed as 10715 MW at 60% load factor from 142 HE Schemes. The total Probable Installed Capacity of these schemes is 20765 MW, with annual energy benefit of about 80,740 Gwh in 90% dependable year. The basin wise summary of HE Potential of Ganga River System is given in the Table - 21.

Table - 21 Hydropower potential in Ganga basin

Basin	No. of Schemes	Firm power (MW)	Probable installed capacity (MW)	Potential at 60% LF (MW)
Upper Ganga	50	3155	10669	5249
Upper Yamuna	32	799	2035	1331
Lower Yamuna	-	-	-	-
Chambal	4	138	392	224
Betwa & Sind	7	70	172	115
Gomti-Sarda-Ghagra	24	1825	5903	3041
Sone	17	347	1052	577
Gandak-Kosi-Mahananda	3	34	93	57
Lower Ganga	2	40	345	67
Damodar	3	32	104	54
Total	**142**	**6440**	**20765**	**10715**

At present out of assessed potential of 10715 MW at 60% LF, HE schemes with a potential of 1877 MW (17.52%) have already been developed, H.E schemes with a potential of 1368.05 MW (12.77%) are under various stages of development. The balance 69.71% of the assessed potential is yet to be harnessed.

Out of identified 142 schemes, 35 are storage type. Storage schemes like Rihand, Gandhi Sagar, RP Sagar, Ramganga, Tehri have already been developed. Some of the constructed major ROR Projects are Chibro/Khodri (Yamuna Stage-II; 360 MW), Tanakpur (120 MW) & Obra (99 MW) etc.

6.2.3. Status of flood management

The State-wise flood management status in this flood prone basin as of March 2006 is given in Table - 22.

Table - 22 Status of flood management in Ganga basin

Lakh hectare

State	Flood prone Area as assessed by RBA	Flood prone Area as reported by States for XI Plan	Area protected as reported by States upto March 2006
Bihar	42.60	68.80	29.49
Chattisgarh	-	-	0.00
Delhi	0.50	0.70	0.78
Haryana	23.50	23.50	20.00
Himachal Pradesh	2.30	2.31	0.12
Jharkhand	-	-	0.01
Madhya Pradesh	2.60	3.37	0.04

State	Flood prone Area as assessed by RBA	Flood prone Area as reported by States for XI Plan	Area protected as reported by States upto March 2006
Rajasthan	32.60	32.60	0.82
Sikkim	-	0.20	0.17
Uttar Pradesh	73.36	73.40	17.03
Uttaranchal	-	-	0.02
West Bengal	26.50	37.66	25.68

6.2.4. Status of water quality

Water quality position of Ganga is relatively not good particularly in the plains due to major cities like Delhi, Agra, Kanpur, Varanasi, Patna etc. situated on the banks of the river or its tributaries and discharging their waste including industrial waste into the rivers. The riverine length for different BOD values is as given below:

- Length of river for BOD > 6 mg/L (severely polluted): 1760 km (13.87%)
- Length of river for BOD 3-6 mg/L (moderately polluted): 3612 km (28.46%)
- Length of river for BOD < 3 mg/L (relatively clean): 7318 km (57.67%)
- Total length of the river including tributaries: 12690 km

6.2.5. Status of glaciers retreat

The sub-basin wise details of the glaciers have been tabulated in Table - 7. GSI has monitored the glaciers in Ganga basin and found that they are retreating, in general based on the long-term data ranging from 5 years to 150 years for different glaciers. The observed retreat in the glaciers is varying from 3.0 m/year to 48.8 m/year however, average annual retreat of the majority of the glaciers is about 0.30% of their total length. Retreat status of some of glaciers in the basin has been given in the Table - 23.

Table - 23 Retreat position of glaciers in Ganga basin

Name of glacier	Period	Average retreat (m/year)
Bandarpunch	1960-1999	25.5
Jaundar Bamak	1960-1999	37.3
Jhajju Bamak	1960-1999	27.6
Tilku	1960-1999	21.9
Gangotri	1935-1996	18.8
Bhrigupanth	1962-1995	16.7
Dunagiri	1992-1997	3.0
Gl.no.3 (Arwa)	1932-1956	8.3
Bhagirathi Kharak	1962-2001	16.7
Chaurabari	1992-1997	11.0
Pindari	1958-2001	9.4
Chipa	1961-2000	26.9
Meola	1961-2000	34.6
Jhulang	1962-2000	10.5
Ramganga	1962-2002	48.8#
Nikarchu	1962-2002	9.2
Adikailash	1962-2002	12.8
Poting	1906-1957	5.1
Shankalpa	1881-1957	6.8
Milam	1848-1997	16.7
Burphu	1966-1997	4.8

Based on the SOI sheet. The snout of Ramganga glacier on aerial photographs were not discernible as it was snow covered.

6.2.6. Hydrological and hydro-meteorological data collection

Hydrological and hydro-meteorological data collection is being carried out by CWC, IMD, State Governments/Project Authorities on regular basis and by the Research or Academic Institutes for shorter duration for the purpose of specific study. CWC has a network of 317 no. hydrological observation sites which are distributed in the co-basin States. The details of the CWC observation sites are given in Table - 24. The dissemination of hydrological data to any other agency requires approval of MoWR.

Table - 24 Hydrological data collection sites of CWC in Ganga basin

State	*Parameter observed*				
	Gauge	*Gauge & Discharge*	*Gauge, Discharge & Water Quality*	*Gauge, Discharge & Sediment*	*Gauge, Discharge, Sediment & Water Quality*
Bihar	33	4	4	1	14
Chattisgarh	1	-	-	-	-
Delhi	-	-	1	-	-
Haryana	1	3	-	-	1
Himachal Pradesh	-	1	2	-	-
Jharkhand	9	12	-	1	2
Madhya Pradesh	-	10	3	1	6
Rajasthan	2	7	1	-	5
Sikkim	4	-	-	-	-
Uttar Pradesh	37	11	14 + 1 (no discharge)	-	31
Uttaranchal	11	13	4	4	5
West Bengal	19	12	6	2	18
Total	**117**	**73**	**36**	**9**	**82**

Parameter-wise details of the sites are summerised as following:

- Gauge sites: 317 no.
- Discharge sites: 199 no.
- Sediment observation: 91 no.
- Water Quality monitoring: 118 no.

In addition to above CWC is also operating two snow observatories at Jubbal in Sundlinala watershed of Yamuna basin since 1984. Another four snow sites are in the process of establishment.

6.2.7. Studies carried out on various aspects of water resources in Ganga basin

Various studies have already been undertaken by the related Government organizations, scientific/research organizations and academicians which are summarized as under:

6.2.7.1. Diurnal variations in hydrological parameters of the Gangotri Glacier

Singh et al (2005) studied diurnal variations in discharge and SSC, including runoff delaying characteristics, for the Gangotri Glacier, the largest glacier in the Garhwal Himalayas (glacierized area 286 km^2; drainage area 556 km^2), Hourly discharge and SSC data were collected near the snout of the glacier (~4000 m) at an interval of about 15 days for an entire ablation period (May-October 2001). Diurnal variability in SSC was found to be much higher than the discharge. A comparison of runoff-delaying parameters with discharge ratio clearly indicated that changes in time lag and time to peak are inversely correlated with variations in discharge.

6.2.7.2. Mapping dry/wet snow cover in the Indian Himalayas using IRS multispectral imagery

Gupta et al. (2005) used remote sensing data to differentiate between dry/wet snows in a glacierized basin. The present study has been carried out in the Gangotri Glacier, Himalayas, using IRS-LISS-III multispectral data for the period March-November 2000 and the digital elevation model. It is observed that there occur four water bearing zones in the glacierized basin: dry snow zone, wet snow zone, exposed glacial ice and moraine covered glacial ice, each of which possesses unique hydrology characteristics and can be distinguished and mapped from satellite sensor data.

6.2.7.3. Prevailing weather conditions during summer seasons around Gangotri Glacier

Singh et al. (2005) presented the meteorological data collected near the snout of the Gangotri Glacier. The average seasonal rainfall is observed to be about 260 mm. The rainfall distribution does not show any monsoon impact. Amount of seasonal rainfall is highly variable (131.4-368.8 mm) from year to year, but, in general, August had the maximum rainfall. Average daily maximum and minimum temperatures were 14.7 and 4.1°C respectively, whereas average mean temperature was 9.4°C. July was recorded as the warmest month. During daytime, wind speed was four times higher than that at night-time. The average daytime and night· time winds were 12.6 and 3.0 km/h respectively. Mean seasonal evaporation was 640.8 mm, which is high with respect to the high altitude. Average relative humidity and daily sunshine duration were also high throughout the melting season.

6.2.7.4. Hydrological Importance of an Unusual Hazard in a Mountainous Basin: Flood and Landslide

Haritashya et al. (2006) studied the unusual hazard in a proglacial melt water stream of the Gangotri Glacier. The upper part of the basin lies in the high altitude region of the Garhwal Himalayas and is extensively covered by glaciers. They provided hydro-meteorological insight into a severe storm that produced unusual high rains in June 2000 in the uppermost part of the Bhagirathi River. This storm was concentrated upstream of Gangotri town and triggered landslides/rockslides at several locations between the glacier snout and Gangotri town. One of the major rockslides blocked the Bhagirathi River at Bhujbasa, about 3 km downstream of the Gangotri Glacier snout, creating an artificial lake at this location. High stream flow in the river, generated by rapid runoff response from mountain slopes along with melt runoff from the glacier, quickly increased the level of water stored in the artificial lake. Daily rainfall in this region rarely exceeds 10 mm, while total rainfall during this 6-day storm was 131.5 mm. Sudden release of stored water generated floods that created havoc downstream of the artificially created lake.

6.2.7.5. Suspended sediment from the Gangotri Glacier: Quantification, variability and relation with other parameters

Haritashya et al. (2006) collected the suspended sediment samples and discharge data near the glacier snout (4000 m) for four melt seasons during the period 2000-2003. These data were used to estimate SSC, SSL, sediment yield and erosion rate in the glacier melt stream, (Bhagirathi). Maximum SSC in meltwater was observed in July followed by August. It was found that the cumulative percentage delivery of SSC precedes discharge throughout the melt season. Delivery response of SSL in terms of percentage of total load is less in the early part of the melt season than in the later stage in comparison to that of discharge. This may be due to the fact that in the beginning of the melt season low melt rate conditions prevails and thus, the low discharge velocity could not flush out stored glacial sediment. It has been observed that 59-64% of the sediment passed through the channel by the time 50% of the total discharge passed. The average suspended sediment yield for the whole melt season from the study area was estimated to be about 4834 ton/km^2 and corresponding erosion rate was 1.8 mm.

6.2.7.6. Meteorological study for Gangotri Glacier

Singh et al. (2007) made a comprehensive meteorological analysis for the Gangotri Meteorological Station (Bhagirathi Valley, Garhwal Himalayas) using data observed for four consecutive melt seasons (2000-2003) covering a period from May to October for each year. The collected meteorological data includes rainfall, temperature, wind speed and direction, relative humidity, sunshine hours and evaporation. The magnitude and distribution of temperature were found to be similar for different Himalayan regions, while rainfall varied from region to region. The influence of the monsoon was meagre on the rainfall in these areas. July was recorded to be the warmest month for all the regions and, in general, August had the maximum rainfall. For all the stations, daytime up-valley wind speeds were 3 to 4 times stronger than the nighttime down-valley wind speeds. It was found that the Gangotri Glacier area experienced relatively low humidity and high evaporation rates as compared to other parts of the Himalayas.

6.2.7.7. Hydrological characteristics of the Dokriani Glacier

Singh et al. (1995) gave a brief of observations of discharge, temperature and suspended sediment made at a gauging site established near the snout of the Dokriani glacier in the western Himalayan region. These observations were made during a scientific expedition to this glacier over 21 days (23.8.1992-12.9.1992). The minimum streamflow in the glacier melt stream was observed at 0700h whereas the maximum was observed at 1800h: the ratio of maximum to minimum flow was computed to be 1.81 from the continuous hourly observations. Based on an analysis of the recession of the hydrograph, it was found that the meltwater time lag from the accumulation zone of the glacier was more than seven times higher than that from the ablation zone. No specific relationship was observed between suspended sediment and discharge. The average values of the suspended sediment concentration and load were found to be 350 ppm and 180 t/day, respectively, for the study period. A high correlation coefficient (r=0.89) was found between the glacier specific runoff and the air temperature at the gauging site. It showed that temperature alone can represent the melting of the glacier and may be considered for the hydrological modeling of glacier melt runoff.

6.2.7.8. Correlations between discharge and meteorological parameters and runoff forecasting for Dokriani glacier

Singh et al. (2000) investigated the predictive significance of meteorological parameters for forecasting discharge for the Dokriani Glacier basin in the Himalayan region. Discharge autocorrelation was found to be very high for each individual summer month and for the melt season as a whole. This suggests substantial meltwater storage in the glacier, which results in a delayed response of runoff, and therefore discharge. A comparison of correlations between discharge and temperature, and discharge and precipitation shows that temperature has a better correlation with discharge during June and September, while precipitation has good correlation with discharge in July and August. A comparison of correlations for the Dokriani Glacier with those for the Z'mutt Glacier basin, Switzerland, has also been made. In general, for both glacier basins, maximum correlation is found between discharge and precipitation on the same day.

6.2.7.9. Degree-day factors for snow and ice for Dokriani Glacier, Garhwal Himalayas

Singh et al (2000), degree-day factors for snow and ice over Dokriani glacier located in the determined Garhwal Himalayas. The degree-day factor for clean ice was about 30% higher than that for clean snow. The presence of dust increased the degree-day factor for snow by about 12%, whereas for ice this factor was increased by about 9%. These observations suggest that the effect of dust on degree-day factor for snow is more pronounced than that for ice.

6.2.7.10. Suspended Sediment Transport from the Dokriani Glacier

Singh et al. (2003) undertook an assessment of suspended sediment concentration, load, yield and erosion rate for the Dokriani Glacier drainage basin located in the Garhwal Himalayas. About 60% of the total drainage area of this basin is glacierized. Data was collected for four ablation seasons (1995-1998). The mean daily suspended sediment concentration for June, July, August and September was 452, 933, 965 and 275 mg/L, respectively, indicating highest suspended sediment concentration in August, followed by July. Similar trends were also found for the sediment load and about 88% of the total suspended sediment load of the melt period was transported during the months of July and August. Sediment yield for the study basin was computed to be about 2,800 t/km-^{2}/yr, which is comparable with glacierized basins (10-30%) glacierized in the Pamir region. For the entire ablation period, the erosion from the Dokriani Glacier basin is estimated to be about 1.0 mm. There was a poor relationship between suspended sediment concentration and discharge.

6.2.7.11. Seasonal changes in meltwater storage and drainage characteristics of the Dokriani glacier

Singh et al. (2003) studied the storage and drainage characteristics of the Dokriani Glacier (9.66 km^2) located in the Garhwal Himalayas. In order to understand these characteristics, clear weather (non-rainy) days, data for three ablation seasons (1996-1998) were used. Results indicate that meltwater storage characteristics of the glacier lead to high discharges in the stream during the night. Consequently, night-time discharges are comparable with those observed during daytime throughout the melt season. Meltwater storage characteristics of the glacier are much stronger in the early part of the melt season and they weaken as the melt season progresses. Recession trends of the hydrographs with time suggested a similar hydrological response of the glacier in June and September, The basin behaved like a single conceptual linear reservoir for these two months, while for July and August it behaved like two conceptual linear reservoirs, namely, accumulation and ablation reservoirs.

6.2.7.12. Determination of snowmelt factor in the Himalayan region

Singh and Kumar (2006) computed SMF for a normal snow pack over a glacier at an altitude of about 4000 m in the Garhwal Himalayas. The effect of natural dusting on SMF is also examined.

6.2.7.13. Effect of climate change on runoff of a glacierized Himalayan basin

Singh et al. (2006) used the snowmelt model SNOWMOD to simulate the melt runoff from a highly glacierized small basin for the summer season. The model simulated the distribution and volume of runoff with reasonably good accuracy. Based on a 2-year simulation, it is found that, on average, the contributions of glacier melt and rainfall in the total runoff are 87% and 13% respectively. The impact of climate change on the monthly distribution of runoff and total summer runoff has been studied with respect to plausible scenarios of temperature and rainfall, both individually and in combined scenarios. The combined scenarios represented a combination of warmer and drier and a combination of warmer and wetter conditions in the study area. The results indicate that, for the study basin, runoff increased linearly with increase in temperature and rainfall. For a temperature rise of 2° C, the increase in summer streamflow is computed to be about 28%. Changes in rainfall by ±10% resulted in corresponding changes in streamflow by ±3·5%. For the range of climatic scenarios considered, the changes in runoff are more sensitive to changes in temperature, compared with rainfall, which is likely due to the major contribution of melt water in runoff.

6.2.8. Activities of MoWR

MoWR is setting up two chairs in IIT Kanpur and NIT Patna for taking up related studies in the basin in particular. It has also been decided that NIH would take up development of a model for Tehri dam as per the long-term action plan of the MoWR detailed at para-4.7. CWC is opening four snow hydrology sites in the basin out of which two are in Yamuna sub-catchment.

6.2.9. Discussion on status of water resources aspects and studies

The Ganga basin is the richest basin in terms of availability of utilizable surface water resources and replenishable ground water resources. The basin also has rich glacier wealth in India while many of its tributaries, which originate from Nepal are also fed by the glaciers. The stage of irrigation potential created in co-basin States is about 69% which is slightly less than potential created at national level of about 72%. Percentage of storage already created with respect to average annual flow of the basin is about 8% which is also less than the percentage at national level of about 11.7%. The stage of development of hydropower in the basin is better than the stage of development at national level. The basin is highly flood prone and about 20.4 MHa area (6.2% of geographical area of the country) of co-basin States is identified as flood prone by the RBA which has been further increased to 24.25 MHa as reported by the States for XI Plan finalization. The river water quality is also a concern as about 14% of river length is considered to be severely polluted and about 28.5% is moderately polluted. The Ganga and its tributaries also carry high silt load. The basin supports population of about 544 Million in its co-basin States.

The various studies carried out by for the Ganga basin also concentrated on meteorological, hydrological including glaciology and snow sciences as was the case with Indus basin. Some of the studies were carried out for sedimentation in rivers also. The summarized findings, in addition to the discussion made for Indus basin, have been listed below:

(i) There is a rising trend in temperature in the basin except minimum temperature in monsoon period which is showing falling trend. Further rise in temperature has been predicted. (*specific studies are further needed*);

(ii) Rainfall trend studies have been carried out by IITM and NIH. It has been observed that the results are varying if the data periods taken into consideration in the study are different. The results are also not consistent if the set of observation sites for which data has been considered in the studies are different. NIH has indicated rising trend in rainfall; falling trend in number of rainy days but rising trend in heavy rain events. IITM with DEFRA predicted a 12% rise in annual rainfall by 2071-2100 in the basin due to climate change. A similar rise has been predicted in the annual flows also. (*[A]More basin specific study for prediction for rainfall and flows are required and [B] the scientist and the organization should work in coordination and first decide upon period of dataset as well as set of observation sites to be considered for the study. Thereafter with the common dataset and observation stations possible studies can be taken up by the related organizations, in order to avoid any confusion as well as to reach at reliable conclusions.*);

(iii) Glaciers of the basin are also retreating with varying magnitude (GSI). (*Sub-basin-wise averaging of water equivalent of glacier melt runoff studies are needed for considering mitigation measures*);

(iv) Various Studies conducted in Ganga basin show similar type of findings as were recorded for Indus basin. Much of the work has been done on Gangotri and Dokriani glaciers. Some additional work has been done on *suspended sediment transport however further project specific works are needed.* (*Findings of the studies may be extended to the water resources facilities in the basin for optimizing the operation of the same*).

(v) Much of the upstream basin lies in the neighbouring country Nepal which is covered by snow and glaciers. Similar studies are needed for that catchment also. Government of Nepal and other scientists have done some studies (collected from web) and concluded almost on similar lines though the data considered for the studies was comparatively of lesser duration. No significant trend has been found in precipitation and river flows. GLOF has been identified as a problem to water resource development and proposed to adapt design considerations specific to GLOF.

Data inadequacy for the studies is also an issue in this basin. GoI stakes are highest in this basin as about half of the interlinking schemes are planned for transferring of water either to or from this basin. To have a better and optimized planning of schemes which are highly capital intensive, an accurate and validated database is essential. In fact, the directives of NWP, 2002 that "Water resources development and management will have to be planned for a hydrological unit such as drainage basin as a whole or for a sub-basin, multi-sectorally, taking into account surface and ground water for sustainable use incorporating quantity and quality aspects as well as environmental considerations" further gets strengthened due to such unpredictable threats of climate change. Since, the impacts of climate change are likely to vary from basin to basin, which would be beyond political boundaries, another directive of NWP, 2002 with respect to river basin organizations needs attention which quoted as "Appropriate river basin organisations should be established for the planned development and management of a river basin as a whole or sub-basins, wherever necessary. Special multi-disciplinary units should be set up to prepare comprehensive plans taking into account not only the needs of irrigation but also harmonising various other water uses, so that the available water resources are determined and put to optimum use having regard to existing agreements or awards of Tribunals under the relevant laws." *Accordingly, now it is again strongly felt that it is very important to have basin-wise approach to planning and development for which it is essential to create River Basin Organisations to take care of the unique needs and aspiration and mitigate/adapt to the threats of the basin.*

There is already a substantial increase of about 19% over flood prone area as assessed by the RBA in the co-basin States and the same as reported by the States for formulation of XI Plan. As the flood events and intensity are likely to increase due to climate change phenomenon the flood prone area is further likely to increase. The likely increased sediment flow may affect the morphology of the rivers. In the light of these observations *it is necessary (a) to review flood prone areas using modern technologies like remote sensing, satellite data and air-borne laser terrain mapping, (b) flood plain zoning bill be adopted and enforced, (c) flood hazard zonation maps be prepared and widely publicized, (d) flood forecasting and warning network be strengthened and modernized; (e) instrumentation for monitoring of glacial lakes and warning for outburst flood be mandated to appropriate organization and necessary institutional arrangement be setup with Nepal for this purpose, (f) special studies and mitigative measures for landslide events due changing weather conditions in the fragile and youngest mountain range of Himalayas be taken up, (g) Project hydrology alongwith dam safety aspects of the existing facilities be reviewed for GLOF events and (h) review the Indian Standards accordingly.*

6.3 Brahmaputra, Barak & other basins

Brahmaputra River starts its journey from Mansarovar in China and flows through the northeastern part of India before debouching in the Bay of Bengal through Bangladesh. Many of its tributaries originate in China and Bhutan. Main features of the basin including Barak and other rivers are as following:

- Catchment area of Brahmaputra in India: 236136 km^2 (Total: 580000 km^2)
- Catchment area of Barak River: 41723 km^2
- Average annual runoff: 585.60 km^3
  - utilizable surface water resources: 24.00 km^3
  - estimated replenishable groundwater resources: 35.07 km^3
- Total of storage created, under creation & under consideration: 52.94 km^3
  - live storage capacity created so far: 2.33 km^3
  - live storage capacity under creation: 9.35 km^3
  - live storage capacity under consideration: 41.26 km^3
- No. of glaciers: 610
  - Area of glaciers: 929 km^2
  - Volume of glaciers: 49 km^3
  - Equivalent water resources: 42 km^3 (considering a multiplying factor of 0.85)
- Co-basin States
  - Arunachal Pradesh - complete
  - Assam - complete
  - Manipur - partly
  - Meghalaya - complete
  - Mizoram - partly

- Nagaland - complete
- Sikkim - partly
- Tripura - partly
- West Bengal - partly

6.3.1. Status of Irrigation Development

State-wise Irrigation Development status upto X Plan of the co-basin States along with State-wise Population supported by the water resources for drinking and other purposes is given in Table - 25.

Table - 25 Status of Irrigation development in Brahmaputra, Barak & other basin

Thousand hectare

State	*Population as per 2001 census (Million)*	*Ultimate Irrigation Potential*		*Status upto X Plan (Major & Medium)*	
		Major & Medium	*Minor*	*Potential created*	*Potential utilised*
Arunachal Pradesh	1.09	0	168	1.20	0.79
Assam	26.65	970	1900	312.90	219.21
Manipur	2.29	135	469	103.05	82.39
Meghalaya	2.31	20	148	0	0
Mizoram	0.88	0	70	0	0
Nagaland	1.99	10	75	1	0.65
Sikkim	0.55	20	50	0	0
Tripura	3.19	100	181	18.70	13.47
West Bengal	80.18	2300	4618	1769.81	1583.36

6.3.2. Status of hydropower development

Brahmaputra basin has immense hydropower potential which has been assessed as 34919 MW at 60% load factor from 226 Schemes. The total probable installed capacity of these schemes is 66065 MW, with annual energy benefit of about 267852 Gwh in 90% dependable year. The basin wise summary of hydropower Potential of the basin is given in Table - 26 below:

Table - 26 Hydropower potential in Brahmaputra, Barak & other basin

Basin	*No. of Schemes*	*Firm power (MW)*	*Probable installed capacity (MW)*	*Potential at 60% LF (MW)*
Dihang-Dibang	28	8048	25032	13615
Lohit	11	2491	7456	4152
Subansiri	25	4036	13767	6892
Upper Brahmaputra	19	474	1203	789
Kameng	34	1189	3896	1982
Kalang (Kopili)	16	306	924	510
Teesta	30	1795	7046	3021
Lower Brahmaptura	3	30	62	50
Barak & other Neighbouring Rivers	60	2345	6679	3908
Total	**226**	**20714**	**66065**	**34919**

Out of total of assessed potential of 34919 MW in the basin, potential of 537 MW (1.54 %) has already been developed, 428 MW (1.23 %) is under development and 669 MW (1.92%) is in various stage of clearance as on 01.09.01. Hydropower schemes having 33285 MW potential (95.32%) are yet to be harnessed in the Brahmaputra Basin.

6.3.3. Status of flood management

The Assam State is most flood prone amongst the co-basin States of the basin. The State-wise flood management status in this flood prone basin as on March 2006 is given in Table - 27.

Table - 27 Status of flood management in Brahmaputra, Barak & other basin

Lakh hectare

State	*Flood prone Area as assessed by RBA*	*Flood prone Area as reported by States for XI Plan*	*Area protected as reported by States upto March 2006*
Arunachal Pradesh	-	0.82	0.55
Assam	31.50	38.20	16.42
Manipur	0.80	0.80	1.32
Meghalaya	0.20	0.95	0.01
Mizoram	-	0.54	0
Nagaland	-	0.09	6.32
Sikkim	-	0.20	0.17
Tripura	3.30	3.30	0.33
West Bengal*	26.50	37.66	25.68

** Figures of West Bengal include area due to other rivers also*

6.3.4. Status of water quality

Water quality position of Brahmaputra basin is the best among all other basins of the country. All the riverine length of 5013 km, including tributaries, is having BOD < 3 mg/L which is considered to be relatively clean.

6.3.5. Status of glaciers retreat

The retreat analysis of the glaciers in Brhamputra basin has not been reported so far.

6.3.6. Hydrological and hydro-meteorological data collection

CWC has a network of 132 no. hydrological observation sites which are distributed in the co-basin States. The details of the CWC observation sites are given in Table - 28. The dissemination of hydrological data to any other agency requires approval of MoWR.

Table - 28 Hydrological data collection sites of CWC in Brahmaputra, Barak & other basin

State	*Parameter observed*				
	Gauge	*Gauge & Discharge*	*Gauge, Discharge & Water Quality*	*Gauge, Discharge & Sediment*	*Gauge, Discharge, Sediment & Water Quality*
Arunachal Pradesh	12	3	-	7	-
Assam	42	2	5	1	19
Manipur	1	-	-	-	-
Meghalaya	1	-	5	1	-
Mizoram	2	2	2	2	-
Nagaland	-	-	-	-	-
Sikkim	-	5	-	7	-
Tripura	4	-	4	-	5
West Bengal	-	-	-	-	-
Total	**62**	**12**	**16**	**18**	**24**

Parameter-wise details of the sites are summerised as following:

- Gauge sites: 132 no.
- Discharge sites: 70 no.
- Sediment observation: 42 no.
- Water Quality monitoring: 40 no.

6.3.7. Studies carried out on various aspects of water resources in Brahmaputra, Barak & other basin

Unlike other two Himalayan basins viz. Indus & Ganga scientific studies for this basin have not been reported particularly in the field of glaciology or snow hydrology and related meteorological parameters. Reasons may be harsh terrain and lack of related data. However, Sikkim has started data collection for taking up related studies. One related study on regional flow duration modeling of ungauged Himalayan catchments is briefed below:

6.3.7.1. Regional flow duration models for ungauged Himalayan catchments for planning microhydro projects

Singh et al. (2001) developed models for 1200 ungauged watersheds of the Lower Himalayas. To this end, the region, comparatively larger in size than the catchment, is assumed to be hydro- meteorologically homogeneous in its behavior. It is found that the statistical approach of quantile estimation (non-dimensional) performs satisfactorily in calibration as well as in validation. The simple power relation for mean flow-estimation, as well as the complete model, performs well in calibration and less satisfactorily in validation because of the short length of data.

6.3.8. Activities of MoWR

MoWR is setting up two chairs in IIT Kharagpur and IIT Guwahati for taking up related studies in the basin in particular. It has also been decided that CWC would setup a small network of snow observatories in snowfed Teesta and Kameng basins on behalf of Brahmaputra Board which would later on be transferred to Brahmaputra Board for operation. After sufficient data collection NIH would take up development of model for Kameng project and Teesta stage II project as per the long-term action plan of the MoWR detailed at para-4.7.

6.3.9. Discussion on status of water resources aspects and studies

The basin has glacier wealth in India but large part of the glaciers lie in China and Bhutan. Almost all water resources development indicators show relatively less development including irrigation potential created in co-basin States; storage already created; development of hydropower etc. This basin is also highly flood prone like Ganga basin and about 3.58 MHa area of co-basin States (except West Bengal) is identified as flood prone by the RBA which has been further increased to 4.49 MHa as reported by the States for XI Plan finalization. The entire Brahmaputra river length comes under relatively clean status. The rivers in the basin carry high silt load like other basins in the Himalayas. The basin supports population of about 39 Million in its co-basin States (except West Bengal).

Related studies are required to be taken up for this basin as has been done for Indus and Ganga basins. However, by and large the discussions summarized for Ganga basin holds good for this basin also.

Data inadequacy for the studies is a serious issue in this basin. GoI stakes are also very high in this basin as it is richest in terms of hydropower potential and proposed interlinking schemes are planned for this basin. Accordingly, the need described for creation of river basin organizations for all the river basins in the country is further strengthened. Other flood management related issues are similar to those of Ganga basin.

6.4 Peninsular & other basins

This report has tackled more on the Himalayan basin due to their higher vulnerability to climate change owing to sizeable catchment covered with glaciers and snow. As the behaviour of the three Himalayan basins is different from each other, the peninsular basins would also need separate detailed attention. IITM has predicted an increase in annual rainfall by 21-23% and in annual flows by 12-18% in Krishna and Godavari basins by 2071-2100. In peninsular India one of the major impacts may be on rise in sea level which may induce inundation of coastal areas and erosion at increased scale. Comprehensive studies are required to be carried out for coastal areas considering impacts on coastal erosion not only at vulnerable areas but updrift and downdrift areas also. Some ongoing studies for peninsular and other basin areas are briefed as following:

6.4.1. Assessment of water resources under climate change scenarios at river basin scale

Details of the study and outcomes/findings, so far, have already been detailed in para 5.2.3, 5.3.1 and 5.3.2.

6.4.2. Collaborative studies with Columbia university/IISc, Bangalore

A collaborative research proposal with Columbia University through IISc, Bangalore is under process, which also aims at knowledge transfer due to rapidly changing economy, population demographics, water use patterns and climate.

6.4.3. Activities of MoWR

Besides above studies MoWR has decided to develop an appropriate model for predicting flow series under varying conditions as per the long-term action plan of the MoWR detailed at para-0. *Inputs and collaborations with Academicians would also be useful for conducting and developing basin specific research programmes for different basins of peninsular India and other remaining basins as being done for the Himalayan basins by way of setting up of chairs in IITs & NITs, therefore similar arrangement may be considered for peninsular India and other remaining basins also.*

7. Adaptation Strategies

In order to minimize the adverse impacts of climate change on country's water resources and attaining its sustainable development and management, there are needs for developing rational adaptation strategies and enhancing the capacity to adapt those strategies. Thus, due considerations are required to be given to the effect of climate change while planning, designing and operating the water resources projects. Accordingly, the present practices being followed in the water resources sector are required to be reviewed and revised considering the change in climate for different agro-climatic zones of India. It would provide the means for alleviating the negative impacts of climate change. The risk, reliability and uncertainty analysis must be carried out before deciding the adaptation strategies.

7.1 Assessment of water resources

Climate change would significantly affect the temporal and spatial availability of the water resources in the country. It may lead to the re-allocation of the water for meeting the demands of the different sectors. As the climate change may change the rainfall characteristics in time and space, the surface runoff and rainfall recharge to the groundwater would also be significantly affected. Further more, because of adaptation in other sectors due to climate change; there may be other physical changes in the basin which would influence the hydrological cycle considerably. Thus, the methodologies for the assessment of surface water as well as Groundwater resources are required to be modified considering all the changes expected in the basin because of climate change.

Many a times data collection networks are reviewed by the Government with a view to reduce the network after considering adequacy of data colleted. For proper understanding the issues like climate change for various sectors it is very important to have continued data collection from a well designed network for much longer duration with regular technological updation. There are WMO recommendations for hydrological and hydro-meteorological data collection network but for Indian conditions having monsoon phenomenon and to capture increasing localized extreme rainfall events the network should be denser then WMO recommendations.

7.2 Hydrological design practices and dam safety

The flood control structures, railway and highway bridges, cross drainage works and other minor hydraulic structures are designed for specific return period floods following the recommended hydrologic design criteria. The floods for a specific return period are estimated for gauged catchments using the site specific flood frequency analysis of the historical annual maximum peak floods data. At site regional or wider regional flood frequency analysis approaches are used for the estimation of floods for the catchments with limited data or for ungauged catchments respectively. In the existing methodologies, the effect of climate change on annual maximum peak floods are not considered for carrying out the flood frequency estimates.

For design of medium and major water resources projects, SPF and PMF respectively are considered. For SPF and PMF, SPS and PMP are used along with the specific time distributions and critical sequencing to provide design storm values. For the computations of SPS and PMP, the climate change is not considered in the methodology. The design storm values are transformed to design flood estimates utilizing the basin response as transfer function. However, due to climate change the basin response transfer function itself would be modified. Thus, in view of the above facts, the existing methodologies for the computations of SPS, PMP, design storms, basin response and other design parameters are required to be reviewed and, wherever it is necessary, those are required to be suitably modified.

Scenarios of future climate indicate the possibility of sharpening of extremes & changes of seasonality. This would have a significant impact on river flow, one of the most important hydrological variables. Beran and Arnell (1995) have found that a ten percent increase of the mean would cause a ten-year flood to occur on an average every seven years. If such circumstances of a significant increase in the severity of hydrological extremes in the 'warmer' world, the consequences for design codes could be severe (Kundzewicz and Kaczmarek, 2000). It would be necessary to design bigger water storage volumes at higher costs to accommodate larger flood waves and to fulfill the growing demand for water during the prolonged and more frequent droughts of increasing severity.

In view of intensification of hydrological cycle, the parameters for dam safety review for the existing structures should also be modified and put into practice. Inflow warning systems need to be developed supported by well designed data collection network.

7.3 Operation policies for water resources projects

The operation policies for operating the water resources projects are developed considering the inflow to the reservoirs as major input. These inflow values are computed either using stochastic method or deterministic method. In stochastic method, time series models are fitted with the historical time series data and a suitable fitted time series model is utilized for generating the synthetic sequences of the inflow time series. In this process, the time series is considered to be stationary and the estimated parameters are considered to be applicable for the future predictions. But, due to climate change, the time series of inflow is no longer stationary and hence the methodology for time series analysis under non-stationary conditions is required to be evolved. For computing the inflows using deterministic methods, the hydrological models, capable of considering all changes in the basin due to climate change, have to be developed. The demand patterns are also likely to be affected because of climate change. Thus, in the operation policies for the conservation purposes, due considerations may have to be given to the changed demand patterns. The policies are also developed for real time operation of the reservoirs for mitigating the floods. As the characteristics of the flood are likely to be affected due to climate change, hence this aspect will also have to be considered while formulating the policies for real time operation of the reservoir for flood control.

7.4 Flood management strategies

Structural and non-structural measures are normally adopted for flood management in the flood prone areas. The change in climate may result in change in the flood characteristics of the rivers. Hence the long term flood management strategies should be re-examined and accordingly actions may be taken. All the methodologies involved for the computations of flood characteristics need to be modified considering the various factors affecting the floods in the basin due to the impact of the climate change in addition to the various other factors responsible for generating the floods. Flood hazard maps are required to be prepared for advising on flood plain zoning for the flood prone areas.

7.5 Drought management strategies

The strategies of drought management require the necessary measures to increase supplies and decrease demands in the drought prone areas. Due to climate change, the patterns of supply and demands are likely to change in time and space. Thus, the impact of climate change on the supply and demand is required to be properly considered for evolving the drought management strategies. For mitigation of drought, various drought indices are developed and the drought vulnerability maps are prepared analyzing the historical data. Drought response plans are prepared as a drought management strategy. Predictions about the occurrence of drought are made based on these plans and analysis which require further investigations in view of the predicted climate change. *Many of the adaptation to impacts of climate change relate to management of water resources. Related managerial inputs and collaborations would be useful for developing suitable managerial skills and strategies for which capacity building programme need to be initiated with reputed management institutes like IIMs. Technologies transfer programme may also be identified.*

7.6 Temporal & spatial assessment of water for Irrigation

Due to predicted climate change, it is expected that the availability of water would be significantly affected in time and space. Accordingly, in long run, cropping pattern and other land uses are likely to change. Thus, the revised assessment of water for irrigation has to be made in view of these changes. The long term planning for the development of irrigation systems (surface water and groundwater) should consider the variation in the availability of surface water and groundwater resources under changed climatic scenarios. Improving the methods of surface irrigation, increasing irrigation efficiency by reducing the water losses from main canals, distributaries and water courses and sowing of less water consuming crops may be very much helpful for extending the irrigation in additional areas under the command. Conjunctive use of surface water and groundwater needs to be planned for irrigation under changed climatic scenarios for sustainable developments in the basins.

7.7 Land use & cropping pattern

Any perturbation in agriculture can considerably affect the food systems and thus increase the vulnerability of the large fraction of the resource poor population. We need to understand the possible coping strategies by different sections and different categories of producers to global climatic change. Such adaptation strategies would need to simultaneously consider the background of changing demand due to globalization and population increase and income growth, as well as the socio-economic and environmental consequences of possible adaptation options (Aggarwal et al., 2004; Easterling et al., 2004). Developing adaptation strategies exclusively for minimizing the negative impact of climatic changes may be risky in view of large uncertainties associated with its spatial and temporal magnitude. We need to identify 'no-regrets' adaptation strategies that may anyway be needed for sustainable development of agriculture. These adaptations can be at the level of individual farmer, society, farm, village, watershed, or at national level. Some of the possible adaptation options are discussed below:

a) Changes in land use and management: Small changes in climatic parameters can often be managed reasonably well by altering dates of planting, spacing and input management. Development of alternate cultivars and farming systems (such as mixed cropping, crop-livestock) that are more adapted to changed environment can further ease the pressure.

b) Development of resource conserving technologies: Recent researches have shown that surface seeding or zero-tillage establishment of upland crops after rice gives yields similar to those when planted under normal conventional tillage over a diverse set of soil conditions. In addition, such resource conserving technologies restrict release of soil carbon thus mitigating increase of CO_2 in the atmosphere. Greater emphasis on water harvesting and improving the efficiency of regional as well as farm water use efficiency could help to face uncertain rainfall.

c) Improved land use and natural resource management policies and institutions: Adaptation to environmental change could be in the form of crop insurance, subsidies, pricing policies and change in land use. Necessary provisions need to be included in the development plans to address these issues of attaining twin objectives of containing environmental changes and improving resource use productivity. Policies are needed that would encourage farmers to conserve water, energy and soil resources. For example, financial compensation/incentive for enriching soil carbon, and increasing the efficiency of irrigation water uses through drip and sprinkler methods could encourage farmers to improve soil health, manage with less water and assist in overall sustainable development.

d) Improved risk management though early warning system and crop insurance: The increasing probability of floods and droughts and other uncertainties in climate may seriously increase the vulnerability resource-poor farmers to global climate change. Early warning systems and contingency plans can provide support to regional and national administration, as well as to local bodies and farmers to adapt. Policies that encourage crop insurance can provide protection to the farmers in the event their farm production is reduced due to natural calamities.

e) Reducing dependence on agriculture: Although the share of agriculture in gross domestic product in India has declined to 20% but 58% population continues to remain dependent on this. Such trends have resulted in fragmentation and decline in size of land holdings leading to inefficiency in agriculture and rise in unemployment, underemployment, and low volume of marketable surplus and therefore increased vulnerability to global change. Institutional arrangements, such as cooperatives and contract farming that can bring small and marginal farmers together for increasing production and marketing efficiencies are needed (Aggarwal et al., 2005).

7.8 Coastal zone management strategies

With the likely rise in sea level the coastal hydrology is also likely to be affected considerably. The facilities along the coasts need to work out and examine the possible adaptive measures. As far as coastal erosion is concerned, comprehensive studies need to be taken up for optimized planning of the protection measures, both soft as well as hard. Coastal processes are very complex and to understand as well as to simulate them requires consistent long term data base of related parameters. Therefore, a data collection network should be designed for observing the related parameters on continuous basis. The exercise of preparation of State-wise coastal zone management plans to take care of possible impacts of climate change in coastal areas need to be taken up.

8. Future Directions

It is quite clear that even if countries do undertake immediate and rapid action to reduce their emissions, some degree of climate change is inevitable. Abilities to deal with weather extremes in the present day are considered to be very limited, the situation may get worse in the future. Therefore, the need is to significantly improve ability to plan and adapt to extreme events such as floods, droughts, cyclones and other meteorological hazards. Any robustness that we build into the system in this regard will always stand us in good stead, no matter what climate change actually transpires. In spite of the uncertainties about the precise magnitude of climate change and its possible impacts particularly on water resources at regional or basins scales, measures must be taken to anticipate, prevent or minimize the causes of climate change to mitigate its adverse effects. The possible future directions on various related issues are detailed as under:

8.1 Data collection

Data collection of all the constituents of hydrological cycle including precipitation in all the forms, surface flow in rivers & storage/withdrawal from rivers, sub-surface/ground water flow including return flows and evapo-transpiration should be at adequate locations in the basin by the national agencies concerned for generating information at basin level with high degree of confidence level. The data on water uses and requirement side should also be collected and compiled on basin scale by the national agencies concerned. For coordination amongst the different National and State agencies an Authority need to be considered at the highest level which can help in data pooling in WRIS as a by-product. A data collection network should be designed for observing coastal processes along the coast line of the country and the related national agencies be mandated for data collection and storage.

8.2 Scientific studies

Scientific studies, mainly academic have been carried out for various aspects of hydrological cycle in Indus and Ganga basins with different objectives. Studies are required to be taken up for Brahmaputra basin and peninsular & other basins also in addition to continued efforts in Indus and Ganga basins. The studies now should be need based and focused towards application on the operation of the projects as well as management of water resources by different stake-holders and users. A coordinating and guiding body should be created to give direction to the studies.

8.2.1. Networking of the Institutions

The output of the studies depend on the period of database, selection of sites/network and methodology adopted for the study and many a times results vary substantially due to which confusion arises and decision makers are unable to reach to a conclusion. Therefore, need is to first firm up the above parameters before taking up the studies which requires discussions and exchange of information amongst the engineers and scientists. Networking of the institutes is necessary to facilitate in carrying out credible and guided studies. After firming up the parameters, the related institutes may carry out different studies as proposed in above para.

8.2.2. Watch on impacts on other sectors

Water resources is one of the many sectors which are being impacted by climate change phenomenon in one way or the other but impacts on other sectors would further affect the water resources, particularly demand side of it. Socio-economic factors like migration of people due to excessive heat conditions in some areas, change in cropping pattern due to change in weather condition etc. would change water requirement scenario and therefore institutional interaction about information amongst the engineers and scientists is warranted. Therefore, networking of the related Agencies is necessary and need to develop.

8.2.3. River basin-wise studies

As the Indian River basins differ from each other in various aspects, their response to climate change phenomenon would also be different with respect to water resources. It is therefore important to take up studies at basin scale. The development in modelling approach should be continued to down-scale GCM to RCM and then to basin/project scale coupled with hydrological model to suite Indian conditions. The basin/project models should be periodically reviewed and updated/modified with the field data collected. Some of the areas suggested for the further works at basin scale are as following:

(i)	Trend analysis of temperature and prediction for different scenarios with degree of confidence;
(ii)	Prediction for meteorological extreme events, including heavy one-day or short period rainfall and localised cloud burst;
(iii)	temporal shift of precipitation;
(iv)	Trend analysis of precipitation and prediction for different scenarios with degree of confidence;
(v)	Analysis of river flows on 10-daily basis after including extractions by the projects in the basin and return flows and likely future scenarios;
(vi)	Different what-if analysis scenarios need to be generated for predicted combinations of rise in temperature and change in precipitation for the water resources facilities in the basin for optimizing the operation of the same;
(vii)	snowmelt characteristics and glacier retreat;
(viii)	Sub-basin-wise averaging of water equivalent of glacier melt runoff studies are needed for considering mitigation measures;
(ix)	Effect of de-glaciation on sedimentation for the water resources facilities in the basin;
(x)	inventory of glacial lakes and their vulnerability for outburst due to increase in temperature;
(xi)	Effect on irrigation water requirement and other consumptive uses eg. on demand side;
(xii)	Effect on hydropower projects;
(xiii)	Effect on water quality; and
(xiv)	Effect on groundwater resources.

8.2.4. Mitigation measures

Work should also be initiated on the mitigation measures including ideas like creation of reservoir(s) for such a capacity which can accommodate the predicted glacier melt in the basin/sub-basin and to operate in such a manner so as to simulate the melt pattern of glacier as well as of snow so that the projects and ecology at downstream are not affected.

8.3 River basin organisation

At the cost of reiterating, it is to again emphasize that it is very important to create River Basin Organisations to take care of the unique needs and aspirations and mitigate/adapt to the threats of the basin.

8.4 Flood management

In the wake of impacts of climate change on flood sector it is suggested to review (a) flood prone areas using modern technologies like remote sensing, satellite data and air-borne laser terrain mapping; (b) flood plain zoning bill be adopted and enforced; (c) flood hazard zonation maps be prepared and widely publicized; (d) flood forecasting and warning network be strengthened and modernized; (e) instrumentation for monitoring of glacial lakes and warning for outburst flood be mandated to appropriate organization and necessary institutional arrangement be setup including in neighbouring countries Bhutan and Nepal for this purpose, (f) special studies and mitigative measures for landslide events due to changing weather conditions in the fragile and youngest mountain range of Himalayas, (g) Project hydrology alongwith dam safety aspects of the existing facilities be reviewed for GLOF events and (h) review the Indian Standards accordingly.

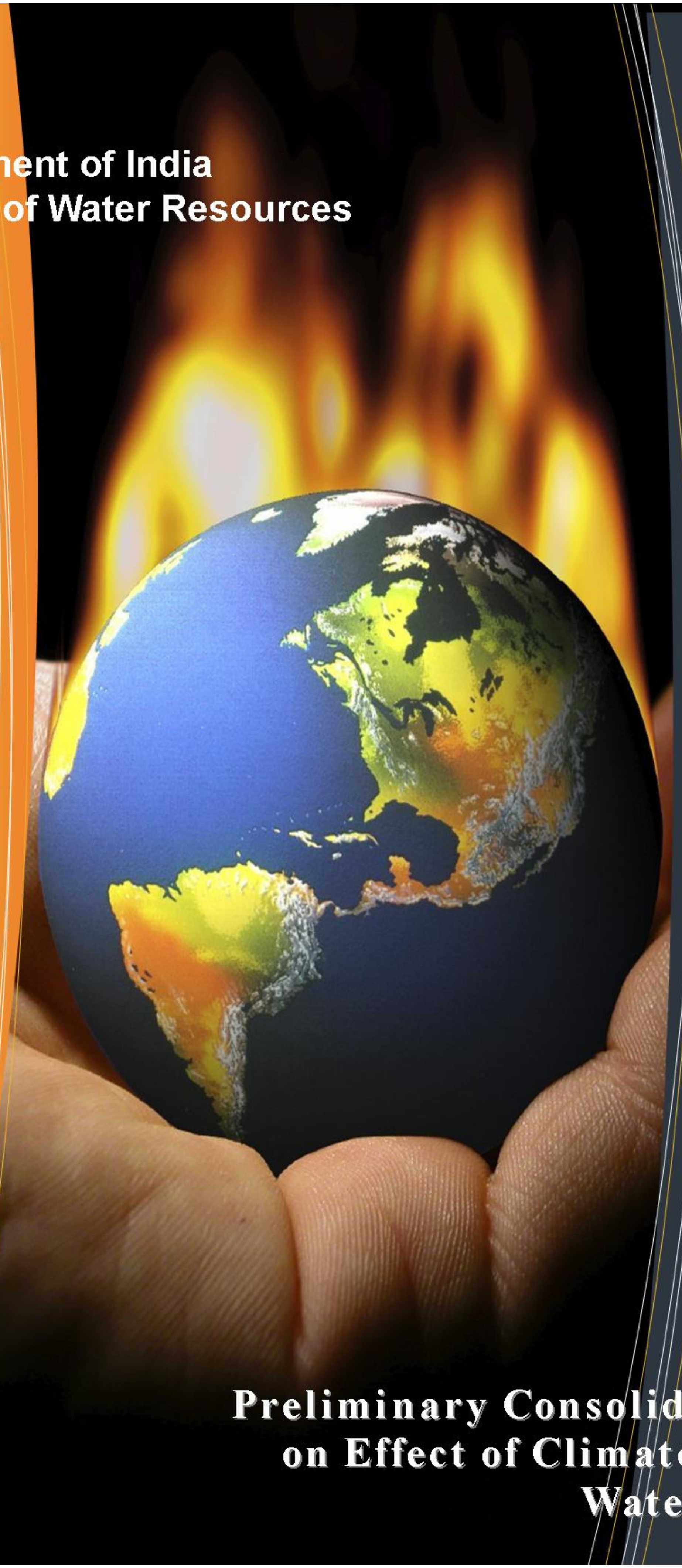
8.5 *Involvement of academicians and capacity building*

There are developments and studies being carried out worldwide on the climate change issues and its impacts on water resources including adaption techniques. The Indian administrators, engineers and scientists need to be exposed to the technological, managerial and scientific developments in other countries so as to adopt them judiciously for the national benefit.

8.6 *Awareness programme*

There are various reports in the different media on climate change issues which create anxiety in the public. Many a times these reports are based on the analysis of scanty data or half the story or twisted facts for merely creating sensation. In this regard, it would be necessary and in wider public interest to share the findings of the various studies being carried out by the Research Organisations or reputed Individuals and be publicized through different media to make the people aware of the unbiased picture.

Government of India
Ministry of Water Resources



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