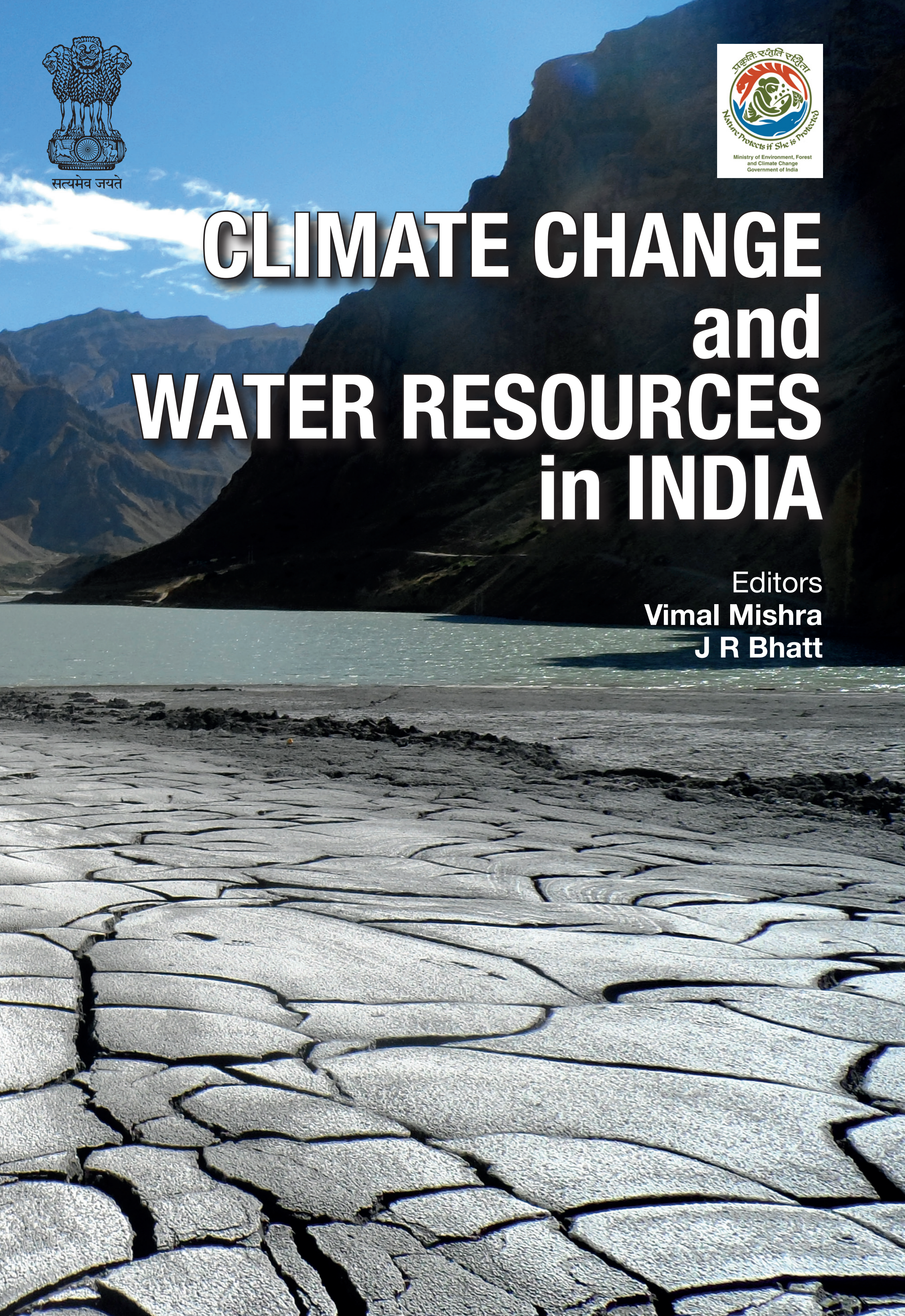

सत्यमेव जयते

प्रकृतिः रक्षति रक्षिता

Nature Protects if She is Protected

Ministry of Environment, Forest
and Climate Change
Government of India

CLIMATE CHANGE
and
WATER RESOURCES
in INDIA

Editors
Vimal Mishra
J R Bhatt

1. **Water Resources Under Changing Climate in India: An Overview**

2. **Impacts of Climate Change on the Indian Summer Monsoon**

3. **Climate Change Impacts on Streamflow in India**

4. **Water Availability Across India Under Observed and Projected Climate**

5. **Climate Change and Reservoir Storage in India**

6. **River Response to Climate Change: Geomorphic Approach to Understand Past Responses and River's Future**

7. **Impact of Climate Change on Drought Frequency over India**

8. **Impact of Climate Change on Water Resources, Irrigation Water Requirement**

9. **Water Use Projections in Industry Sector Under Different Climate Change Regimes**

10. **Implications of Climate Change on Water Quality: A Review on Perspectives and Challenges**

Climate Change and Water Resources in India

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and Climate Change
Government of India

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J R Bhatt

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Dr. Harsh Vardhan

सत्यमेव जयते

भारत सरकार
पर्यावरण, वन एवं जलवायु परिवर्तन मंत्री
GOVERNMENT OF INDIA
MINISTER OF ENVIRONMENT, FOREST &
CLIMATE CHANGE

MESSAGE

Climate change is one of the most profound challenges related to the environment and society. The impacts of climate change have been observed, and these are likely to be seen in the coming decades. The global mean temperature has increased significantly in the last few decades. The last few years ranked warmest in the instrumental record. The rise in global mean temperature affects all the aspect of society. The cost of adaptation to climate change has been rising along with the damage to infrastructure due to extreme events. The natural disasters have caused enormous economic damage that is likely to increase in the future. The Paris Agreement aims to holding the increase in the global average temperature to well below 2ºC above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5ºC above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.

India has witnessed the impacts of climate change as the frequency of heat waves has increased, flood events are on the rise, and the summer monsoon has become erratic over the last few decades. In view of all these visible effects of climate change, impacts on climate change on water availability and demands in India has great importance. A large fraction of the Indian population is associated with agriculture, and water availability directly affects crop production and livelihood of millions of people living in India.

This book titled "ClimateChangeandWaterResourcesinIndia" showcases our understanding of climate change impacts on water resources in India. The book covers a wide range of issues related to surface and groundwater resources, water availability and demands in agriculture and industry, droughts, the role of reservoirs, and water quality that are linked with the climate change.

I compliment the contributing authors for their thought-provoking essays on the impacts of climate change on water resources and in bringing out this valuable publication.

Date: 28.11.2018

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सत्यमेव जयते

सचिव
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पर्यावरण, वन एवं जलवायु परिवर्तन मंत्रालय
SECRETARY
GOVERNMENT OF INDIA
MINISTRY OF ENVIRONMENT, FOREST AND CLIMATE CHANGE

FOREWORD

"Climate Change and Water Resources in India" is a compilation of independent views and thoughts of eminent experts from India on the subject. In the spirit of the Paris Agreement, the Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India (GoI) has been facilitating the process of inclusive, participatory consultation on climate change. The present volume is one of the products of this process being brought out on the occasion of24th meeting of the Conference of Parties (CoP) to United Nations Framework Convention on Climate Change (UNFCCC).

Water is the most vital resource for human survival. India has around 18% of the global population and only about 4% of the renewable water resources. Climate change has directly affected the water cycle. The characteristics of the Indian summer monsoon rainfall has changed in the past few decades. Rainfall due to low-intensity rainy days has declined while the frequency of extreme rainfall events has increased. Both surface and groundwater resources in India face challenges due to climate change and rising population. Per capita, water availability has declined in India. A large part of the country has faced severe depletion in groundwater while water storage in major reservoirs in India declined. The demands of water have increased in agriculture as well as in industry. Therefore, the gap between water availability and water demand has increased, which is likely to worsen further under the warming climate.

Understanding the impacts of climate change on water resources in India is essential for water security of the vast developing country. India is a party to the Paris Agreement that aims to holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change. Limiting the global mean temperature below these targets will not eliminate the adverse effect of climate change. However, it is highly likely that the negative impacts of climate change will be substantially reduced if these targets are met. While India is aggressively tackling the issue of climate change at both the fronts—climate change adaptation and mitigation, it would be essential to reduce and manage the negative impacts of climate change on water resources.

The present book on "Climate Change and Water Resources in India" has a unique collection of chapters on a number of themes. The information related to surface and groundwater potential and observed changes in water availability in India are essential to anticipate and respond to the changes that may occur under the warming climate. Understanding the changes in the summer monsoon that provides about 80% of total annual rainfall and how these are linked with streamflow, water availability, reservoir storage, and drought is essential. The book provides comprehensive information on water demands in agriculture and industrial sectors.

The contribution of well-known Indian experts is valuable and appreciated. I compliment the contributing authors and appreciate the efforts put in by Dr. Arun Kumar Mehta, Additional Secretary and Dr. J. R. Bhatt, Scientist- G, Ministry of Environment, Forest and Climate Change in bringing out this book.

[C.K. Mishra]

Dated: **29th November, 2018**
Place: **New Delhi**

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EXECUTIVE SUMMARY

The warming of the atmosphere over the last century is attributed to the increase in emissions of greenhouse gases from anthropogenic activities like fossil fuel consumption, agriculture, and landuse change. Future changes in climate are expected to include additional warming leading to changes in precipitation patterns and amount, the frequency of extreme events, and sea level rise. The stakes associated with projected climate change are high especially in a developing country like India as it has lower adaptive capacity, and the uncertainties associated with the impacts may further widen the existing inequalities amongst its population.

India has reasons to be concerned about climate change. Vast population depends on climate-sensitive sectors like agriculture and forestry for livelihood. The adverse impact on water availability due to the recession of glaciers, changes in precipitation patterns, and extreme events of flooding and droughts in certain pockets would threaten food security, cause dieback of natural ecosystems including species that sustain the livelihood of rural households. The impacts of climate change are becoming increasingly evident in all the sectors of society and the environment. India has already witnessed profound implications of climate change in the form of extreme hydroclimatic events (droughts, floods, and heat waves), damage to infrastructure, and substantial economic losses in recent decades.

India is fast urbanizing, and it is projected that more than 50% of the population will be living in urban areas by 2050, adding another 375 million to the present 440 million residing in cities. India is investing more in infrastructure to provide sustenance to these and also to its rural people. As more than 60% of the population in India directly or indirectly relies on agriculture, the adverse impacts of climate change on food production raises concerns about the food security of the rising population in India. How will the food and fresh water security change under the warming climate in India, remains an area that needs wider attention. The hydrologic cycle has already altered considerably, and the impacts are visible on the key components (e.g., precipitation, evapotranspiration, and runoff).

Understanding the impacts of climate change on water resources in India is essential for future food and freshwater security. Water resources in India are currently facing multiple risks that are associated with climate change. For instance, the Indian summer monsoon has become erratic in the last two-three decades. There has been a significant decline in the monsoon season rainfall in one of the most fertile and productive regions of the world (i.e., Indo-Gangetic Plain). Climate change has affected the spatial and temporal variability of the summer monsoon, which has resulted in adverse impacts on water availability and water demands.

Moreover, the nature of the summer monsoon precipitation has significantly altered. The number of rainy days has significantly declined across the country with a more prominent reduction in the low-intensity rainy days. On the other hand, a few rainy days with intense and heavy rainfall have increased in large part of India. The changes in the rainfall intensity have affected water resources. For instance, low-intensity rainfall is a key contributor to the groundwater recharge during the monsoon season in India and the decline in the low-intensity rainfall has translated lesser groundwater recharge. The increase in the high-intensity rainfall resulted in frequent and devastating floods in large parts of the country. Our existing reservoirs have faced numerous challenges due to increased extreme precipitation, flood events, and siltation in India.

Climate change projections have uncertainties that are associated with climate models, emission scenarios, and initial conditions. Despite these uncertainties, the projections for the future climate provide some actionable information that can help policymakers and organizations working in the areas of climate change adaptation and mitigation. The monsoon season precipitation is projected to increase under the warming climate so is the air temperature. Therefore, India is likely to witness a wetter and warmer climate in the future. However, will this wetter and warmer climate be beneficial for the future food and freshwater security in India, or will reduce agricultural production?

The contributing chapters highlight that under the warming climate precipitation, runoff and streamflow are projected to increase in India. The increase in streamflow, mainly during the monsoon season, will pose pressure on the major reservoirs that may not be able to accommodate the additional flow generated due to extreme precipitation events. Moreover, increased precipitation during the monsoon season doesn't necessarily mean increased water availability. Due to warming climate, the atmospheric water demands in the form of potential evapotranspiration will also increase. Therefore, the dry season water demands are likely to increase in future in India. The frequency of droughts is also likely to increase along with the irrigation and industrial water requirements. Increasing urbanization will create additional stresses through enhanced water demand in cities. Moreover, climate change is also likely to affect the water quality of surface and groundwater resources in India.

The major challenges related to water resources in India in the context of climate change are the following:

- Changing nature of the Indian summer monsoon under climate change, which can result in both devastating floods and frequent droughts
- Changing characteristics of the monsoon rainfall with more heavy rain events and less low-intensity rain events
- Rapid depletion of groundwater in many parts of India that is driven by excessive pumping and climate variability

- Increasing temperature has a negative impact on agriculture and food production
- Water demands are going to increase under warming climate while water availability during the dry season is likely to get reduced
- Climate change as well as the anthropogenic influence may further reduce water quality of surface and groundwater resource in India

We find that climate change is projected to pose enormous challenges to water availability, water demands, as well as water quality for India. The studies made in this book suggest that their adverse impacts are likely to vary in distribution across regions, people, sectors, and times. Our country will, therefore, need a better strategy to maintain, manage, and sustain water resources by better measurements, improving efficiency, and by reusing and recycling. The contributing chapters in this book highlight some of these issues and provide state-of-the-art technical information.

Vimal Mishra, Associate Professor, IIT Gandhinagar
Amit Garg, Professor, IIM Ahmedabad
J R Bhatt, Scientist-G, Ministry of Environment, Forest and Climate Change

Acronyms

AET	Actual Evapotranspiration
APHRODITE	Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation
BAU	Business As Usual
BOD	Biological Oxygen Demand
CAC	Command and Control
CAD	Computer Aided Design
CGWB	Central Groundwater Board
CMIP5	Coupled Model Intercomparison Project Phase 5
CO_2	Carbon dioxide
CSO	Combined Sewer Networks
CWC	Central Water Commission
DEM	Digital Elevation Model
DO	Dissolved Oxygen
DSSAT	Decision Support System for Agro-technology Transfer
ENSO	El Niño Southern Oscillation
ES	Effluent Standards
ESACCI	European Space Agency Climate Change Initiative
ESS	Energy Snapshot
ET	Evapotranspiration
ET_c	Crop Evapotranspiration
ET_o	Reference Evapotranspiration
EVI	Enhanced Vegetation Index
FAO	Food and Agriultural Organisation
GCAM	Global Change Assessment Model
GCM	Global Climate model
GDP	Gross Domestic Product
GFDL	Geophysical Fluid Dynamics Laboratory
GLAS	Geoscience Laser Altimeter System
GRACE	Gravity Recovery and Climate Experiment

HadGEM	Hadley Centre Global Environment Model
ICESat	Ice, Cloud, and land Elevation Satellite
IGB	Indo-Gangetic Basin
IHA	Indicators of Hydrologic Alteration
IMD	India Meteorological Department
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institut Pierre Simon Laplace
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
ITCZ	Inter Tropical Convergence Zone
IWMP	Integrated Watershed Management Programmes
LGM	Last Glacial Maxima
LPAA	Lima-Paris Action Agenda
MAP	Mean Annual Precipitation
MBI	Market Based Instruments
MDGs	Millennium Development Goals
MIDC	Maharashtra Industrial Development Corporation
MIROC	Model for Interdisciplinary Research On Climate
MISO	Monsoon Intraseasonal Oscillations
MODIS	Moderate Resolution Imaging Spectroradiometer
MoEFCC	Ministry of Environment, Forest and Climate Change
MOUR	Ministry of Urban Development
MOWR	Ministry of Water Resources
NAPCC	National Action Plan on Climate Change
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCC	Norwegian Climate Centre
NCEP	National Centers for Environmental Prediction
NDVI	Normalised Differene Vegetation Index
NMSA	National Mission for Sustainable Agriculture
NOAA	National Oceanic and Atmospheric Administration
NorESM	Norwegian Earth System Model
NSIDC	National Snow and Ice Data
NWM	National Water Mission

PET	Potential Evapotranspiration
PMEL	Pacific Marine Environmental Laboratory
PRECIS	Providing REgional Climates for Impacts Studies
PVC	Polyvinyl chloride
RCM	Regional Climate Models
RCP	Representative Concentration Pathway
REMO	REgional MOdel
RFWR	Renewable Freshwater Resources
SDGs	Sustainable Development Goals
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
SRES	Special Report on Emissions Scenarios
SRTM	Shuttle Radar Topography Mission
SST	Sea Surface Temperatures
SWAT	Soil and Water Assessment Tool
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UNGA	United Nations General Assembly
UNICEF	United Nations International Children's Emergency Fund
VIC	Variable Infiltration Capacity
WHO	World Health Organisation
WTS	Wastewater Treatment Standards
WUE	Water Use Efficiency
ZLD	Zero Liquid Discharge

Units and quantities

^{0}C	Degree Celsius
BCM	Billion Cubic Meter
cm	Centimetre
GW	Giga Watt

hPa	Hectopascals
ka	Killoannual
km	Kilometre
Km^3	Cubic Kilometre
M	Million
m	Meter
m^2	Square Meter
m^3	Cubic Meter
m^3/Mwh	Cubic Meter Per Mega Watt Hour
m^3/s	Cubic Meter Per Second
m^3/t	Cubic Meter Per Tonne
mg/L	Milligram Per Litter
Mh	Million Hectares
mL	Million Litter
mm	Millimetre
Mm/yr	Millimeter Per Years
t/ha	Tonne per Hectares
W/m^2	Watt Per Meter Square

CONTENT

Chapter 1

Water Resources Under Changing Climate in India: An Overview

Nanditha J. S.[1] **and Vimal Mishra**[1*]

Abstract

In the background of the expanding population and dwindling water resources together with the risks posed by climate change, it is essential to quantify available and potential water resources of the country and the possible impacts of climate change on the existing resources. Here we provide a brief account of different water resources, their availability, potential, the implication of climate change on water availability, demands, and water use in various sectors. We also study the projected changes in precipitaton and air temperature under the warming climate in India and their potential implications. India is endowed with numerous surface water resources and groundwater aquifers. However, these resources are not effectively utilized leading to over exploitation in certain areas and under development in the rest. Climate change driven increase in extremes, droughts, and increased irrigation requirements, can further reduce the water availability in India. The existing reservoir capacity may not be suffieicnt to accomodate floods driven precipitation extremes under the warming climate. Similarly, groundwater storage is likely to get affected due to excessive pumping to meet increased irrigation water requirements. In the future, along with the agriculture sector, burgeoning water demand from the industrial sector and rapid urbanization may aggravate water stress in rapidly developing India. Moreover, a significant portion of our available water resources is severely polluted. To meet the future water demands, we need to come up with water-efficient technologies, reuse and recycling of wastewater, along with the strategies to sustainably use water resources.

1.1. Introduction

India is a water-stressed country with currently estimated per capita water availability of 1,588 cubic meters per year (India-WRIS, 2012), which is well above 1000 cubic meter per year, the benchmark for designating a country as water scarce. Currently, India houses 18% of the world's population, but its share of renewable water resources is only 4% of the world. Of the total available water resources, roughly 50% is utilisable. With the increasing population and the projected increase in demand for water resources especially for ensuring the food security needs of the country, there is going to be tremendous pressure on our existing water resources. As of now, over 54% of the country suffers high

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to extreme water stress. Adopting proper conservation standards, facilitating replenishment, sustainable management, and maintaining the quality of available resources is critical to prevent our country from succumbing to water scarcity in the future. Apart from conservation, emphasis should be on reuse and recycling of existing water resources along with the development of new water resources to meet future demands (Gupta and Deshpande, 2004).

1.2. Surface Water Resources

Indian surface water resources are classified into 12 major and 8 composite basins by Central Water Commission (CWC). Different agencies in the country (e.g., CGWB, NCIWRDP, ISRO, India –WRIS) have come up with their classifications. Surface water contributes 37% of the irrigation requirements, which comprises 29% sourced from canals, 4% from surface water tanks, and the rest from other surface sources. These figures need to be read with the overall irrigation efficiency in the canal system of 38-40% to understand the water wastage (Dhavan, 2017). Canal irrigation is dominant in the plains of northern and northwestern India and tank irrigation—one of the most preferred and sustainable irrigation practice—is in vogue in the hard and rocky terrain of the peninsula.

1.2.1 Availability and Potential

The country receives annual average precipitation of 4,000 BCM, which contributes to the total annual flow of rivers of 1,869 BCM and the utilisable surface water resources further comes down to 690 BCM (India-WRIS, 2012). This disparity may be mostly attributed to the temporal variability in the availability of precipitation, most of the peninsular rivers receive around 90%, and the snow-fed Himalayan rivers receive 80% of their inflow during the monsoon season (June to September). Figure 1.1A shows the distribution of mean annual precipitation over the country for the period 1901-2012 (Shah and Mishra, 2016). Clearly, the northwestern regions, rain shadow zones of the Western Ghats, and Ladakh regions receive scanty rainfall in a year. Runoff generated (Fig. 1.1C) also follows the same regional distribution and spatial pattern. The mean annual temperature is greater than 25^0C in these arid regions of the nation with an increasing trend across the time span (Fig. 1.1E and 1.1F). Also, Mann Kendall trend values for the same time period indicates a decreasing trend in the amount of precipitation and runoff generated in regions receiving higher rainfall. This is of grave concern to our water security.

The regional disparity in the distribution of rainfall along with the temporal variations leads to simultaneous situations of floods and droughts in the country adversely affecting the quantum of utilisable water resources. Also, the storage capacity of our reservoirs is inadequate to hold the excess flow during monsoon. Reservoir capacity in Ganges and Brahmaputra basins is less than 12% (Table 1.1, India-WRIS, 2012) of their annual flow, which is insufficient

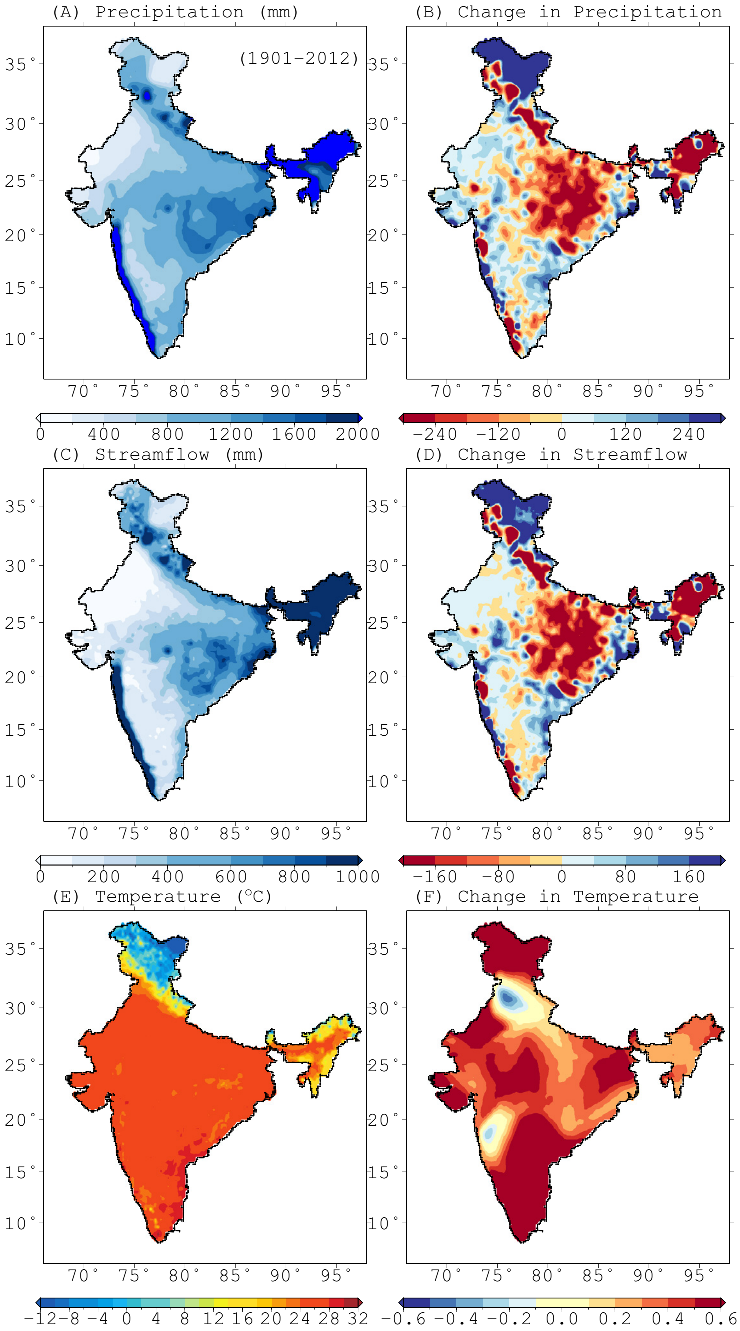

Figure 1.1 **Mean annual (A) precipitation, (C) streamflow and (E) Temperature from 1901-2012 (IMD Sheffield Datasets) and the corresponding Mann Kendall slope value is shown in figs (B), (D) and (F).**

to meet the needs of the population. Compared to other rivers, peninsular rivers have a relatively better reservoir storage capacity, which is greater than 50% of their mean annual flow. Water utilisation in the Ganga-Brahmaputra basin can be considerably increased by damming swift flowing inlet rivers in neighboring countries (Kumar et al., 2005). Major river basins, their potential water availability (average annual flow), utilisable water resources, and live storage capacity of completed and under construction projects are shown in Table 1.1.

Northern India is gifted with higher availability of surface water resources, which are predominantly perennial in nature. The perennial Himalayan Rivers and seasonal extra peninsular rivers together carry more than 70% of the total available water resources in the country leaving the available water resources in the peninsular region to 30%. However, while around 45% of the available water resources in peninsular India are utilisable, the corresponding percentage for north India is 33%. These figures are consistent with the reservoir storage capacity across the rivers in India. It implies around 67% of available water in the major north Indian rivers are drained into the ocean without being able to use. This fact underscores the tremendous scope of river linking proposals mooted by the government to connect surplus basins to deficient basins. However, linking rivers are always associated with substantial environmental consequences. Smart waterways, a method being suggested recently help in addressing many ecological concerns related to connecting rivers. In this method, rivers are connected on a flat plane facilitating two-way flow thereby eliminating the requirement of pumping which demands enormous amount of electricity.

Apart from the traditionally available sources, we need to emphasise on developing new and sustainable sources to meet our water demands. Currently, 80% of municipal and industrial discharge reaches our rivers without any treatment. If we can realise this potential by adequately treating and recycling grey water, it can provide a sustainable solution for our water crisis. Recycling industrial and municipal wastewater itself can provide 177 BCM of utilisable water per year (Gupta and Deshpande, 2004). Artificial recharge of groundwater sources is another strategy to maximise the utility of surface flow. Conservation using water harvesting systems and facilitating groundwater recharge can generate yearly additional water resources of 125 BCM (Gupta and Deshpande, 2004). Additionally, there is enormous scope in improving irrigation and water use efficiency in the agriculture sector, which consumes about 80% of the total available water resources in India.

Table 1.1: **Basin wise annual average streamflow, utilisable surface water resources, the live storage capacity of completed and conceived projects (Modified from India-WRIS, 2012)**

Sl No.	Major Basins and sub-basins	Catchment Area (KM^2)	Average annual flow (BCM)	Utilizable surface water resources (BCM)	Percentage of utilisable water resources (%)	The live storage capacity of completed projects (BCM)	The live storage capacity of projects under construction (BCM)	Total storage (BCM)	Percentage of available water that can be stored (%)
1	Indus	3,21,289	73.31	46.00	62.75	16.28	0.28	16.56	22.59
2	Ganga	8,61,452	525.02	250.00	47.62	42.06	18.6	60.66	11.55
3	Brahmaputra	1,94,413	537.24	24.00	4.47	2.33	9.35	11.68	2.17
4	Godavari	3,12,812	110.54	76.30	69.02	25.12	6.21	31.33	28.34
5	Krishna	2,58,948	78.12	58.00	74.24	41.8	7.74	49.54	63.42
6	Cauvery	81,155	21.36	19.00	88.95	8.60	2.7	11.3	52.90
7	Mahanadi	1,41,589	66.88	50.00	74.76	12.33	1.87	14.2	21.23
8	Narmada	98,796	45.64	34.50	75.59	16.98	6.62	23.6	51.71
9	Tapi	65,145	14.88	14.50	97.45	9.4	0.85	10.25	68.88
10	Sabarmati	21,674	3.81	1.9.00	49.87	1.31	0.06	1.37	35.96
11	Mahi	34,842	11.02	3.10	28.13	4.72	0.26	4.98	45.19
12	Subernarekha	29,196	12.37	6.80	54.97	0.67	1.65	2.32	18.76
13	Brahmani and Baitarani	51,822	28.48	18.30	64.26	4.65	0.88	5.53	19.42
14	Pennar	55,213	6.32	6.90	109.18	2.65	2.2	4.85	76.74
15	Barak and Others	41,723	48.36	--				0	0.00

Sl No.	Major Basins and sub-basins	Catchment Area (KM^2)	Average annual flow (BCM)	Utilizable surface water resources (BCM)	Percentage of utilisable water resources (%)	The live storage capacity of completed projects (BCM)	The live storage capacity of projects under construction (BCM)	Total storage (BCM)	Percentage of available water that can be stored (%)
16	West flowing rivers from Tapi to Tadri	55,940	87.41	11.90	13.61	11.27	3.46	14.73	16.85
17	West flowing rivers from Tadri to Kanyakumari	56,177	113.53	24.30	21.40	10.24	1.32	11.56	10.18
18	East flowing rivers from Mahanadi and Pennar	86,643	22.52	13.10	58.17	1.60	1.42	3.02	13.41
19	East flowing rivers between Pennar and Kanyakumari	1,00,139	16.46	16.50	100.24	1.84	0.07	1.91	11.60
20	West flowing rivers of Kutch and Saurashtra including Luni	3,21,851	15.10	15.00	99.34	4.73	0.8	5.53	36.62
21	Minor rivers draining into Myanmar and Bangladesh	31,000	31.00	----		0.31	0	0.31	1.00

1.2.2 Potential Impacts of Climate Change

The projected increase in the frequency of climate extremes due to anthropogenic warming (Mukherjee et al., 2018) may further reduce the potential of utilisable surface water resources. High-intensity precipitation in the catchment areas of storage reservoirs exceeds their capacity prompting the opening of shutters which causes accelerated flows downstream of the rivers and consequent wastage of water. The recent occurrence of floods in Kerala, Chennai, Gujarat, Hyderabad, Uttarakhand and so on are examples of surface water getting wasted without being able to conserve for drought period. The high temporal variability in precipitation triggering flash floods in urban as well as rural habitats and the occurrence of prolonged droughts affects predominantly south Indian basins with seasonal flow further accentuating water stress in these areas.

Fig 1.2-1.5 displays the projected percentage change in precipitation and increase in temperature in °C for different representative concentration pathways (rcps) in near (2010-2039), mid (2040-2069), and far (2070-2099) periods with respect to the historic period (1971-2000). Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012, 2007)Global Climate models (GCMs) were used to simulate projected future climate. All rcps projects increase in precipitation almost throughout the country even in the arid regions. The projected temperature shows a higher increase in Himalayan and Sub-Himalayan regions in particular and northern India in general.

Another significant threat to surface water resources is pollution from point and non-point sources. Climate change can exacerbate pollution of water resources. Urban floods can lead to mixing of sewage and industrial waste with surface water sources. Also, abstraction of more groundwater due to drought has led to contamination of groundwater by uranium in aquifers of Rajasthan and Gujarat. The uranium-rich granite of these aquifers undergoes oxidation due to reduced water level and lead to the release of uranium contaminating the groundwater (Supriya, 2018)

Snow and glacial melt play a significant role in the development of water resources in the Himalayan rivers. The importance of glacier melt is that it contributes more water during drought years and fewer waters during flood years thereby balancing and maintaining water availability in the basin (Mall et al., 2006). Available literature shows glaciers in the Himalayan regions has been retreating and experiencing negative mass balance since the mid-19th century, and the rate of loss has increased in the recent decades owing to temperature increase (Bolch et al., 2012).

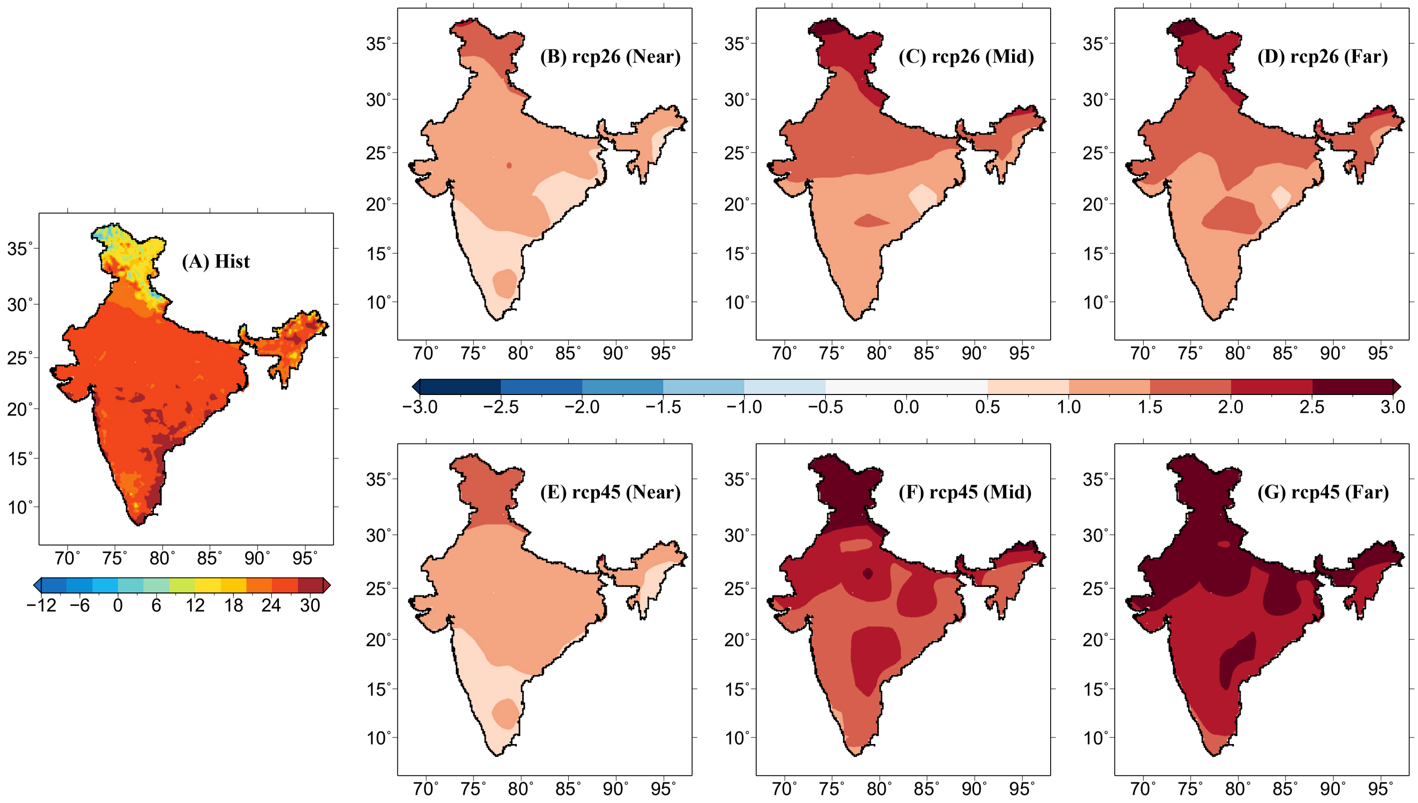

Figure 1.2 (A) Multi-model Ensemble mean of average annual temperature (°C) for the historical period (1971-2000) and (B-G) the change in temperature (°C) from the historical period to near (2010-2039), mid (2040-2069), and far (2070-2099) period in rcp 26 and 45 scenarios.

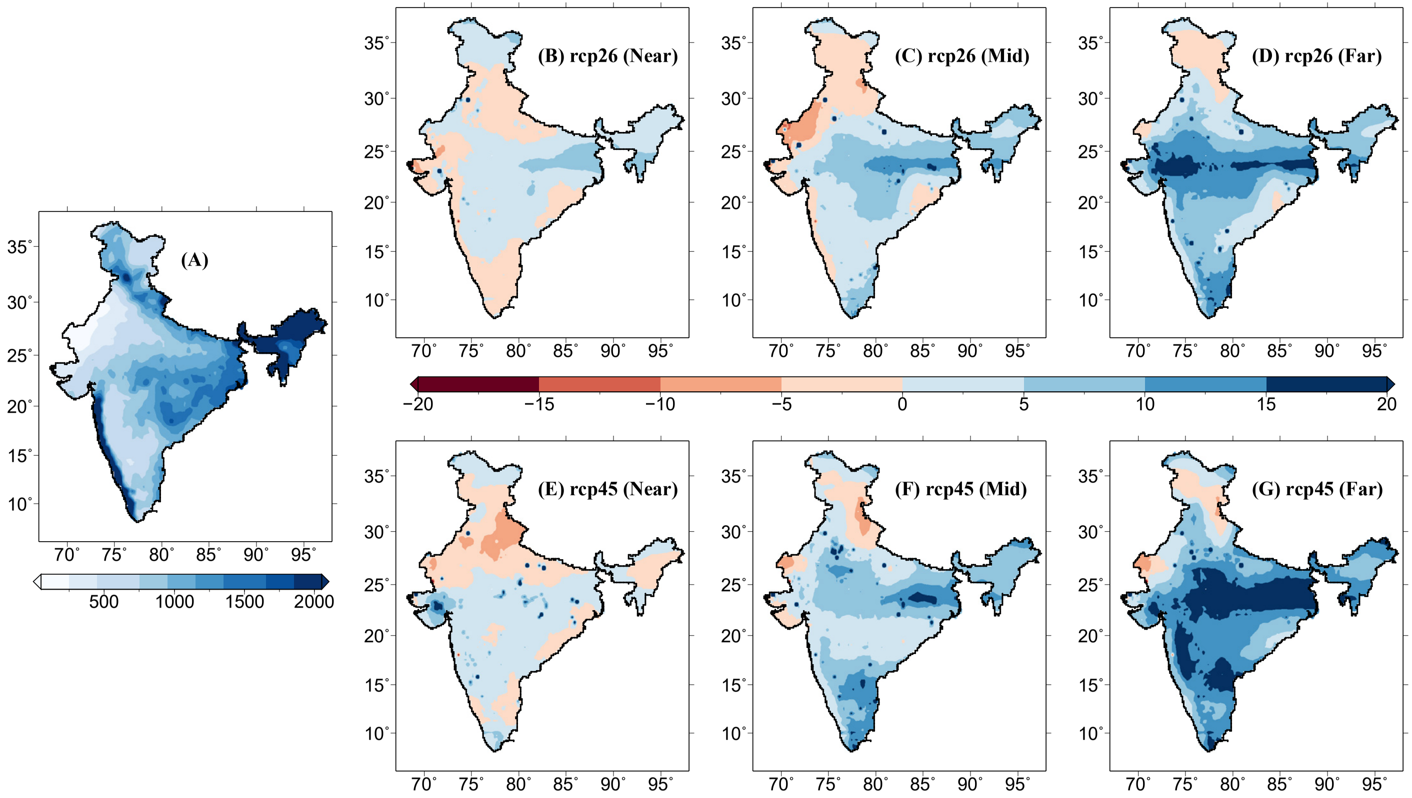

Figure 1.3 (A) Multi-model Ensemble mean of average annual precipitation (mm) for the historical period (1971-2000) and (B-G) the percentage change of precipitation (%) from the historical period to near (2010-2039), mid (2040-2069), and far (2070-2099) period in rcp 26 and rcp45 scenarios.

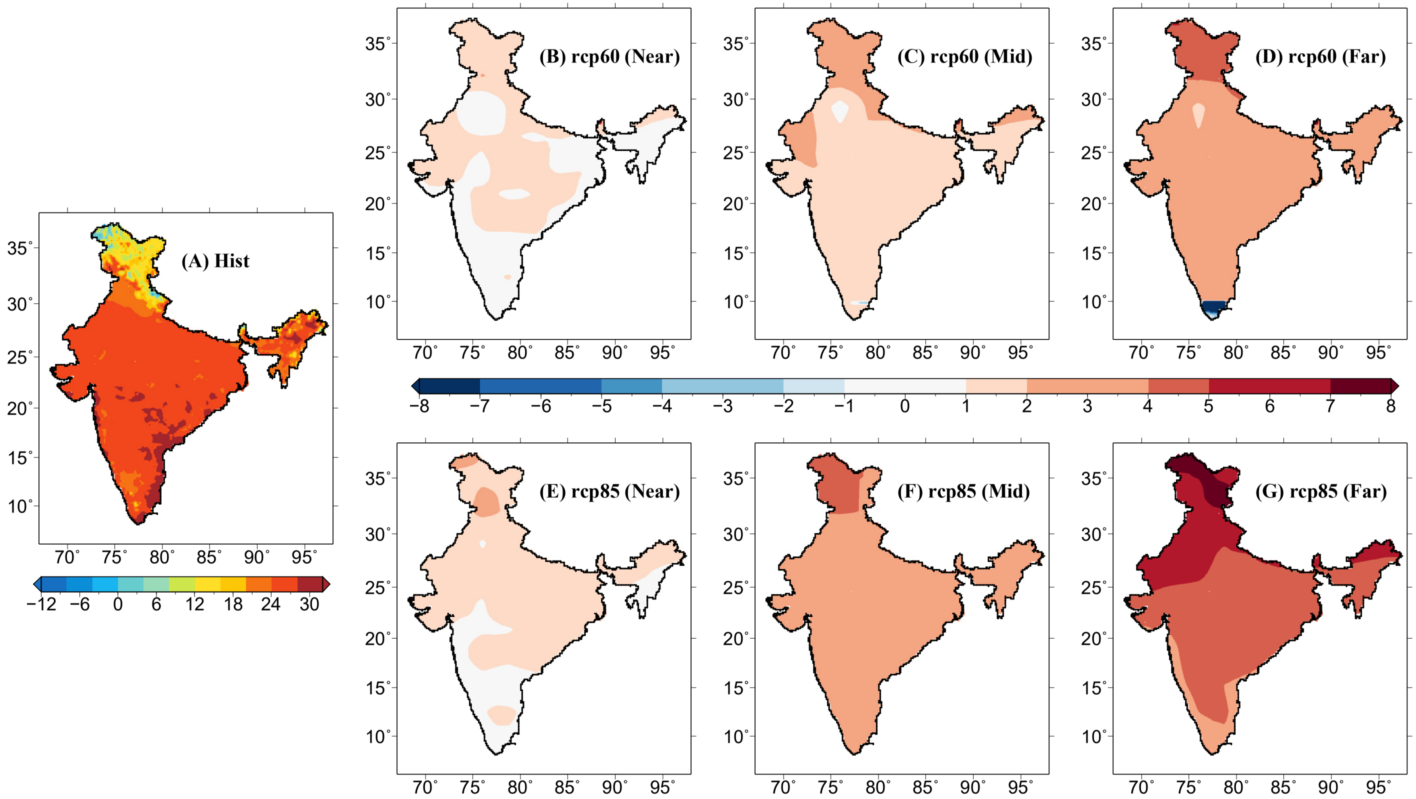

Figure 1.4 (A) Multi-model Ensemble mean of average annual temperature (°C) for the historical period (1971-2000) and (B-G) the change in temperature (°C) from the historical period to near (2010-2039), mid (2040-2069), and far (2070-2099) period in rcp 60 and rcp 85 scenarios

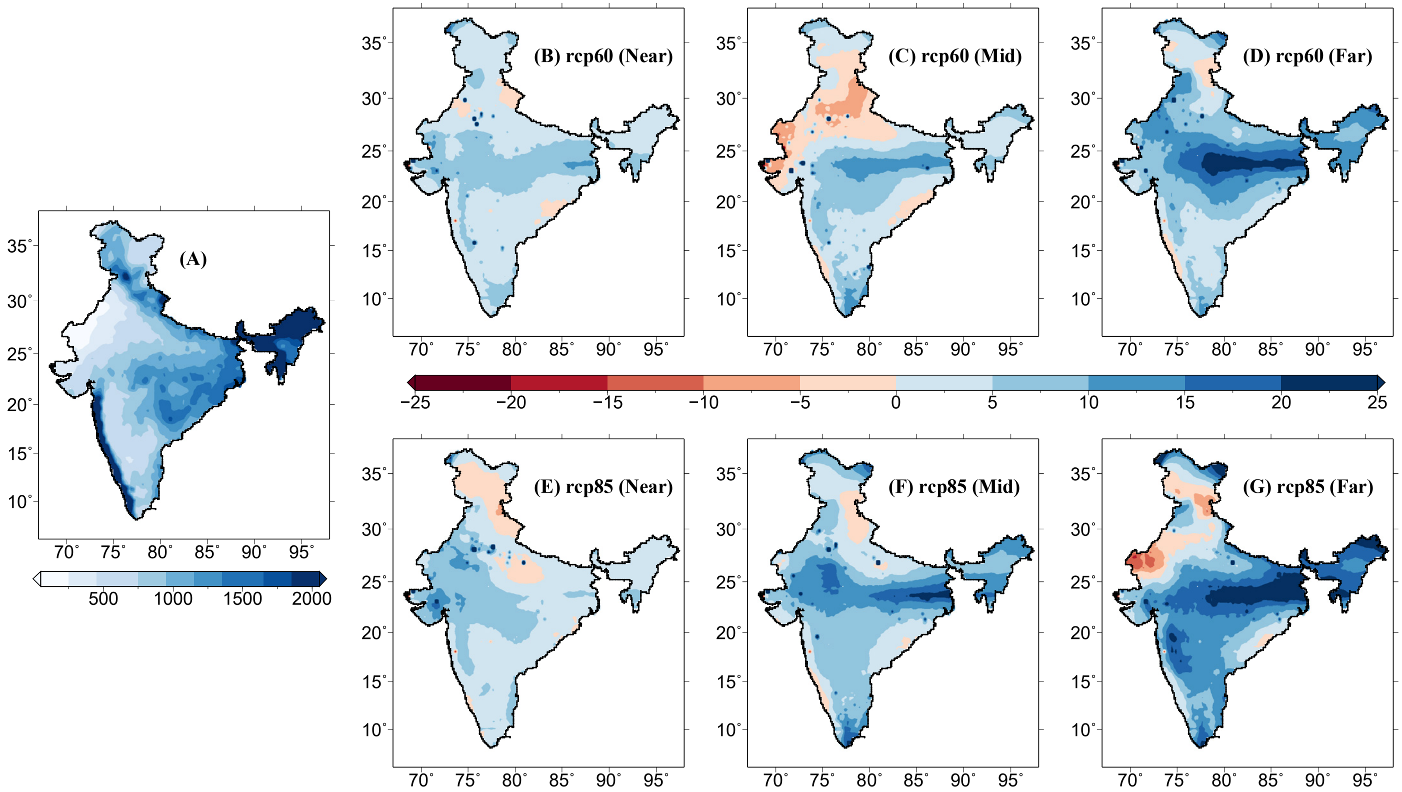

Figure 1.5 (A) Multimodel Ensemble mean of average annual precipitation (mm) for the historical period (1971-2000) and (B-G) the percentage change of precipitation (%) from the historical period to near (2010-2039), mid (2040-2069), and far (2070-2099) period in rcp 60 and rcp 85 scenarios

1.3. Groundwater Resources

Groundwater resources of the country are mainly consumed by the agrarian sector which amounts to a whopping 90% of annual groundwater draft, leaving the remaining 10% for domestic and industrial use. Groundwater contributes to 62% of the irrigation needs, 85% of rural and 45% of urban water supply systems(CGWB, 2014).

1.3.1 Availability and Potential

The total annual replenishable groundwater resources in the country as of 31st March 2013 is evaluated as 447 BCM, and the net yearly groundwater availability after deducting for 36 BCM for natural discharge is 411 BCM. For the reference year 2013, the yearly groundwater draft is estimated at 253 BCM. Rainfall contributes 67% to the replenishment of groundwater annually with monsoon season rainfall making up 58%. Canal seepage, irrigation return flow, recharge from water harvesting and conservation systems, tanks, and ponds contribute the rest (CGWB, 2014). Of the replenishable resources, Indo-Gangetic plains, Brahmaputra valley, northeastern states, deep south constituting Kerala, southern and eastern coast of Tamil Nadu, eastern coastal plains, and Saurashtra region is recharged with more than 50 cm groundwater. Aquifers in the arid regions in and around the Thar desert, central and eastern India, and rain shadow regions of Karnataka plateau are confined to a recharge of below 15 cm on an average (CGWB, 2014).

Figure 1.6 (Asoka et al., 2017) illustrates the groundwater anomaly obtained from the Gravity Recovery and Climate Experiment (GRACE) Mission from 2002-2013 for the months of January, May, August and November. The figure shows the alarming rate at which groundwater resources are depleting across the country with a positive change in the groundwater table observed in southern and western regions. Across the north Indian plains, the groundwater table is found to decrease, due to high abstraction for irrigation and a decrease in precipitation (Asoka et al., 2017). Even though positive anomaly is found in arid regions of the country, the aquifers in these regions have low recharge-value.

The property of aquifers and rock formations has a significant role in determining water recharge and hence the availability of groundwater resources in the country. The deep alluvial formations in Indo-Gangetic-Brahmaputra basin got high specific yield and higher recharge rate. Around 2/3rd of the country including the peninsula is made up of fissured formations, which are thin and underlain by hard rocks which restricts the recharge potential (CGWB, 2017). Asoka et al. (2017), has found high-intensity rainfall is vital in recharging southern rocky aquifers and low-intensity rainfall can better replenish northern and northwestern alluvial formations.

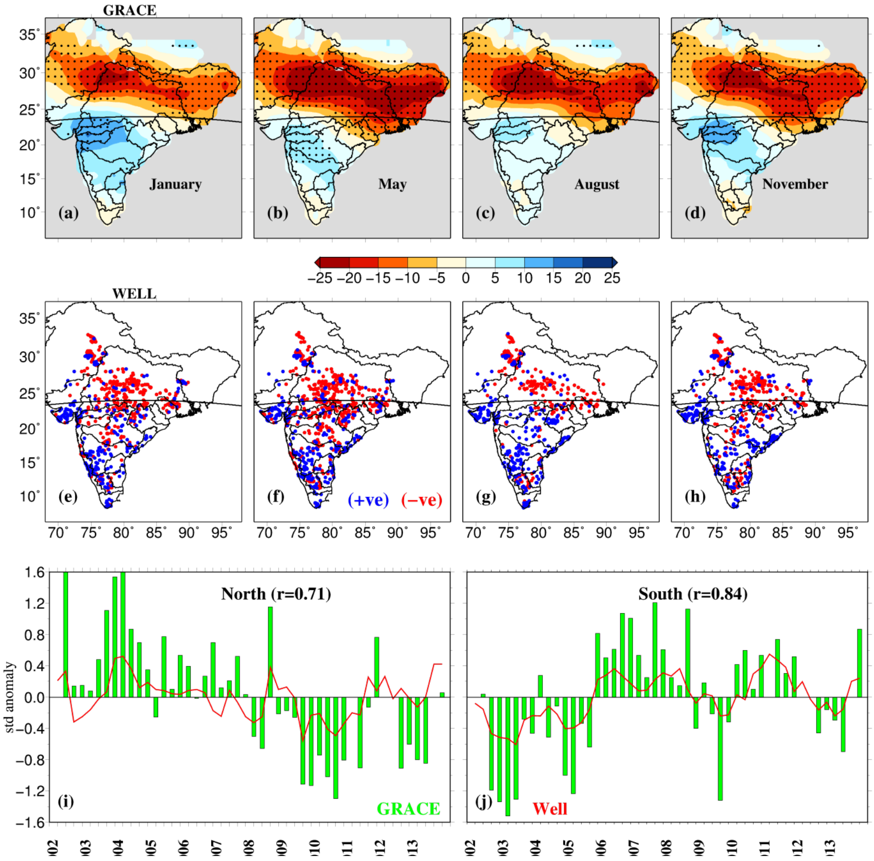

Figure 1.6 **Comparison of GRACE groundwater anomaly and in situ well level observations. Trend in GRACE groundwater anomaly (a-d) and well level (e-h) for the month of January, May, August and November. The standardized anomalies of GRACE groundwater and well level observations regionally averaged over northern and southern region (region above and below 23° N latitude shown as black line in a-h).(Asoka et al., 2017)**

Due to the uneven utilisation of groundwater along with the spatial disparity in replenishment, some regions end up being water stressed while some regions exhibit suboptimal stage of groundwater development. The Indo-Gangetic plains from Punjab to Uttar Pradesh due to massive demand for irrigation end up being over-exploited disregard of the high level of groundwater replenishment in the area. The western part of India, including Rajasthan and Gujarat, also forms over-exploited region owing to less recharge due to arid conditions (low rainfall). Other over exploited regions include states of Karnataka, Tamil Nadu, and some parts of Andhra Pradesh and Telangana, comparatively low recharge in these regions may be partially ascribed to the rocky terrain of the Deccan plateau regions (CGWB, 2014).

In a study that compared the dynamics of water use in the thick alluvial reservoirs of Punjab and shallow rocky reservoirs of Telangana (Fishman et al., 2011), they found the unsustainability of groundwater abstraction in Punjab due to greater availability and the limited use in Telangana due to the constraint offered by low capacity of shallow rock aquifers. Thick alluvial aquifers in northern India have been continuously exploited for meeting irrigation needs. Here, energy supply and land are the constraints to the extent of cultivable area and crop choice, which ultimately leads to depletion of water table beyond annual replenishment. This highlights the unsustainable abstraction of groundwater that is unprecedented elsewhere in the world. In Peninsular India, the low capacity shallow hard-rock aquifers act as the limiting agent that determines the variability in the yearly cultivable area. These aquifers are recharged annually, and the abstraction roughly equals the groundwater recharge by precipitation. Though this guarantees the long-term sustainability of the aquifers, it underlies the crucial dependence of the agrarian sector in this area to short-term variation in rainfall and thereby to the vagaries of climate change.

Groundwater storage variability across India mainly depends on precipitation variability and groundwater abstraction for irrigation. In north-west India, the latter is a more important cause while for north, central and south India precipitation is more significant (Asoka et al., 2017).

1.3.2 Potential Impacts of Climate Change

Climate change alters the frequency of climatic extremes which will affect soil moisture and groundwater recharge and finally the groundwater level in different regions. Fast withdrawal of water due to pressure from the rapidly growing population will reduce the recharging time of aquifers and further deteriorates water levels (Mall et al., 2006).

Recently due to El Nino effect, a decline in low-intensity precipitation in the north-west and north central India is observed which can adversely impact recharge in the alluvial aquifers. On the other hand, Sea surface temperature over the Atlantic ocean is favouring high-intensity precipitation over Southern India supporting groundwater recharge there (Asoka et al., 2018).

There have been several kinds of literature available that have carefully studied the variability in groundwater level in recent years. Studies based on the Gravity Recovery and Climate Experiment Mission (GRACE) data from 2002 and 2008 provides some conflicting results. Some of the studies have overestimated depletion rate in north-west India to be 17.7± 4.5 BCM/ year on an average (Rodell et al., 2009), higher than 13.2 BCM/year estimated by Ministry of Water Resources. Long et al. (2016) has confirmed this overestimation of groundwater depletion by GRACE in north-west India and reassessed the depletion to 14±0.4 BCM/year consistent with the ministry's data. Northern India comprising the Gangetic basin infamous for the high rate of groundwater abstraction for irrigation use is found to have depleted the resource at the rate of 54±9km^3/year from 2002 to 2008 (Tiwari et al., 2009). Another study by Asoka et al. (2017) provides a promising result of an increase in storage level in southern India by 1 to 2 cm/year from 2002 to 2008. However, the storage level decreased in northern India at the rate of 2cm/year for the same period. They also found that the groundwater abstraction across India increases with a deficit in precipitation.

Asoka et al. (2017) have found that more than the anthropogenic factors, climate change plays a significant role in deciding the groundwater table of a region. Even though, both north Indian plains and Saurashtra region depends on groundwater for irrigating 40 percentage of the land area; the positive trend in precipitation has led to an increase in groundwater table in the Saurashtra region while a negative trend in precipitation has led to a fall in groundwater table in the north Indian plains.

1.4. Water Demand

The total water usage in 2010 in the country is estimated as 761 BCM, of which 688 BCM (90%) used for irrigation, 56 BCM for municipal and 17 BCM for industrial use. It includes surface water withdrawal of 396 BCM and groundwater abstraction of 251 BCM. The corresponding figures for 1990 were 362 BCM of surface water and 190 BCM of groundwater. When surface water withdrawal increased by 9.4% in 2 decades, groundwater withdrawal more than trebled (32.1%) (FAO, 2011).

The reliance on groundwater resources by various sectors are increasing day by day compared to dependence on surface water sources. The stage of GW development in the country is almost 62%, with northwestern states vis Punjab, Delhi, Haryana and Rajasthan having development stage greater than 100% implying groundwater abstraction greater than the annual replenishment level. Groundwater development stage is below 70% in rest of the country except for Tamil Nadu, Uttar Pradesh, Puducherry and Daman & Diu, where the stage of development is greater than 70% (CGWB, 2014).

1.4.1 Agriculture

The agriculture sector is the primary consumer of water resources of the country; it uses up around 83% of the total available water resources. Imparting irrigation efficiency by adopting techniques like sprinkler and drip irrigation, and complete elimination of flood irrigation is critical in reducing growing demands from the sector. The government policy that emphasises on 'per drop, more crop' initiative is a commendable effort to achieve water use efficiency. However, efficient irrigation technologies need to be offset by water policies that incentivise conservation efforts like water pricing and de-subsidising pumping cost, to reduce groundwater use for irrigation (Fishman et al., 2015).

The current irrigation penetration in the country is less than 50%. A higher penetration is inevitable for ensuring food security in the context of climate change. A higher irrigation penetration will multiply water demand for agriculture at present irrigation efficiency. Achieving high water and land productivity is key to sustaining future food security for developing countries like India. We need to consider aspects like green and blue water and their proportional share in our agricultural products and agro-exports to optimise water usage (Falkenmark, 2006).

Other than inefficient irrigation methods, unscientific cropping pattern followed in the country where water-intensive crops are cultivated in critically stressed areas accentuates water demand. Shift to paddy cultivation in northwestern India since the green revolution era has led to the indiscriminate extraction of groundwater resources in north Indian plains. Also, India is a net water exporter; we export water-intensive crops and import less water-intensive crops thereby increasing the count of virtual water embedded in our economy. India exports water-intensive crops like cotton, rice, sugar and soybean, amounting to a net water export equivalent to 1% of the total available water every year (Dhavan, 2017).

1.4.2. Domestic and Industrial Use

The estimated water requirement for meeting the drinking, industrial and energy needs of the country are 43 BCM, 37 BCM and 19 BCM respectively as of 2010 (Bhat, 2014). Currently, many Indian cities are unable to cater to the increasing demand. Government data reveals 22 out of 32 major cities in India faces water shortage and Jamshedpur leads the list with a demand-supply gap of 70%. Inefficiencies in the water supply network further accentuate the demand-supply gap. Poor engineering works and lack of maintenance of the water supply network create substantial distribution losses which amount to 40% of the water supply in Delhi.

1.4.3. Future projections

With our population expected to cross 1.7 billion by 2050 and a possible shift from an agrarian to an industrial or service-oriented economy, the demand for water resources in India will leapfrog in the future. Along with food security needs, demand for water resources from rapid urbanisation and industrialisation will further exacerbate pressure on water resources. Indian water demand is expected to rise by over 70% by 2025 and India is projected to suffer severe water stress by 2050 (OECD,2014). The alarming rate of groundwater depletion, the variability of precipitation coupled with the uncertainty brought in by climate change, inefficient irrigation water use and deteriorating water quality on the one hand and burgeoning water demand on the other side depicts the grim reality of water crisis in our country.

The water availability projected for the year 2025 is 1,434 cubic meter per year per capita (India-WRIS, 2012) which will further dwindle to 1,140 cubic meters per year per capita by 2050, the year by which our population is expected to stabilise. The total water demand is expected to meet availability by 2025, and the absolute water requirement by 2050 is assessed to be 1,450 BCM (Gupta and Deshpande, 2004).

According to recent studies, at least 21 Indian cities are moving towards zero groundwater level by 2020, and about 40 per cent people in India may not have water to drink by 2030 (Shukla, 2017). Apart from falling quantity, quality of our available resources is also poor. The UN has ranked India 120th of 122 countries for water quality. Only 20% of the municipal and industrial water is treated in India, and hence about 70 per cent of the supply is contaminated (Iyer et al., 2018).

1.5. Summary

Availability of freshwater resources is rapidly falling across the world. India which will supersede China to be the world's most populated country by 2025 will be placed at a disadvantageous position if we fail to manage our water resources properly. Integrated management of resources at a basin scale instead of the currently followed state wise management practices is key to achieving long-term sustainability.

India is blessed with many rivers and alluvial aquifers with high specific yield. However, there is much spatial disparity in the distribution of these resources. In north India availability has led to indiscriminate use of groundwater, on the other hand, we are unable to utilise the full potential of available surface water in the same region. This disparity needs to be catered into for balancing the supply-demand conundrum. We have to build up more possibilities to maximise the utilisation of surface water which is currently much less than 50% of the available water resources.

Maintaining the quality of water is another critical area. Currently, 70% of our water resources are contaminated. If we fail to act timely in this regard, our future water security will be severely impacted. Apart from traditional water resources, their proper conservation and maintenance, we need to look into the development of new sources simultaneously. This can include appropriate recycling of grey water, artificial recharge of aquifers and desalination of seawater by taking advantage of our long coastal line.

Imparting futuristic technology, especially in agriculture is inevitable to improve our water and land productivity. In the future, we have to produce more crops consuming limited water and land resources. High yield and low water-intensive crops, efficient agronomic practices and intelligent irrigation methods need to be developed and implemented on the field for ensuring food and water security for future India.

If we can synchronise different departments and undertake integrated planning, we will be in a position to address the impending water crisis. Sustainability of our limited resources depends mainly on proper usage and management of our existing resources. Larger availability leads to indiscriminate usage and consequent wastage of resources.

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Chapter 2

Impacts of Climate Change on the Indian Summer Monsoon

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Abstract

Variability of the Indian summer monsoon has increased significantly since the 1950s. For several regions across India, this means an increase in long dry periods with low or no rainfall, intermittent with short, intense spells of rainfall. These changes are particularly significant for the western, central and eastern states of India where more than 55% of the cultivated area is largely rainfed and where the adaptive capacity is the lowest. The large-scale secular changes in monsoon rainfall are attributed to the increase in global emissions of greenhouse gases and air pollutants. At the same time, local changes through urbanization, land use changes and deforestation have brought in a non-uniform response in these rainfall trends. Changes in the onset, duration and intensity of the rainfall call for a reassessment of the crop calendar and climate resilient measures for the food-water-energy sectors of the country. Global warming has also altered the relationship between sea surface temperatures and other predictors of monsoon rainfall, introducing increasing challenges and uncertainties in the monsoon forecasts. Climate projections indicate a further increase in the monsoon variability and a shortening of the rainy season in the future, though there is considerable disagreement between model simulations.

2.1. Introduction

Every year during the summer from June to September, the southwesterly monsoon winds bring about 848 mm of rain for the 1.3 billion population of India. Considering the total area of India as 3 trillion m^2, the quantum of rain received during this season would equate to roughly 2,700 trillion litres, which translates to about 2 million litres of water per person. Almost half of this rainwater goes into the rivers, out of which half of the river water flows via the Ganges-Brahmaputra river basins at a rate of 37 million litres per second (Kumar et al., 2005). The summer monsoon rains bring more

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than 78% of annual rainfall to the Indian subcontinent. As such, any slight deviation in the rainfall could set off a cascade of events which can break or make the backbone of the society because the food, water and essentially the gross domestic product (GDP) of the subcontinent largely depend on these rains. The Indian summer monsoon exhibits variability on sub-daily and subseasonal to interannual and multi-decadal to centennial timescales. In this chapter, we will explore the monsoon variability along these timescales and how climate change is interacting among these scales. Human activities leading to increased greenhouse gas emissions, air pollution and deforestation are found to dominate the observed and projected changes in the monsoon, on sub-daily to multi-decadal timescales.

2.2. Changes in the Monsoon Variability on Subseasonal Timescales

The subseasonal variability, known as the monsoon intraseasonal oscillations (MISO), manifests as the active (wet) and break (dry) phases of the summer monsoon season. These intraseasonal oscillations originate as an ocean-atmosphere coupled event in the tropical Indian Ocean, propagate northward and depending on the phase of the oscillation, results in the wet and dry spells of the monsoon. The active phases are generally accompanied by heavy rainfall events while the break phases are characterised by low rainfall or occasionally long dry periods without any rains. This means that even if the seasonal mean rainfall is normal, the subseasonal variability can impact the food-water-energy sectors of the country. Generally, moderate rainfall is more useful for agriculture than very heavy rainfall—which has an adverse effect on the crops (Revadekar and Preethi, 2012). Recent studies show that the occurrence of prolonged breaks or heavy rains during a normal monsoon season can cause a reduction in kharif (summer) food grain yield (Preethi and Revadekar, 2013). In fact, most of the normal (and above normal) monsoon seasons years are associated with heavy-to-extreme rainfall activities while drought years are not associated with such intense rainfall activity (Preethi and Revadekar, 2013).

Since the initiation and propagation of MISO are tied to the ocean-atmospheric coupled evolution of sea surface temperatures (SST), winds and convection (Jiang et al., 2004; Roxy and Tanimoto, 2007; Zhou and Murtugudde, 2014), the basin-wide warming in the Indian Ocean has an impact on its characteristics in the recent decades. Recent studies using observations and atmospheric general circulation model experiments (Sabeerali et al., 2014b) indicate that the rapid increase in SST during the past decade (2001-2011) has changed the northward-propagating characteristics of the MISO, relative to the 1978-1988 period. They found that the MISO variance has increased in the recent period due to the SST rise. The warming of the equatorial region is also found to slow down the northward propagation, resulting in prolonged convection over the equatorial Indian Ocean (Sabeerali et al., 2014b).

Heavy-to-extreme rainfall events occur during active phases of the monsoon, and several studies point out a significant increase in the frequency of heavy and extreme rains across several regions of India (Singh et al., 2019). The rise in heavy rains coincides with a decrease in low or/and moderate rains (Goswami et al., 2006; Mishra et al., 2018; Rajeevan et al., 2008; Roxy et al., 2017; Singh et al., 2014), similar to the rainfall changes observed in other parts of the tropics (Lau and Wu, 2007) (Fig. 2.1). The increasing trend in extreme rainfall is homogenous across some regions like the central Indian region where the modulation of the monsoon westerlies is largely governed by global change (Roxy et al., 2017). However, there is a large regional variability over other regions across the country (Ghosh et al., 2012; Ghosh et al., 2016), and also localised changes in rainfall due to changes in land use land cover and urbanization (Ali and Mishra, 2017; Mondal and Mujumdar, 2015; Shastri et al., 2015).

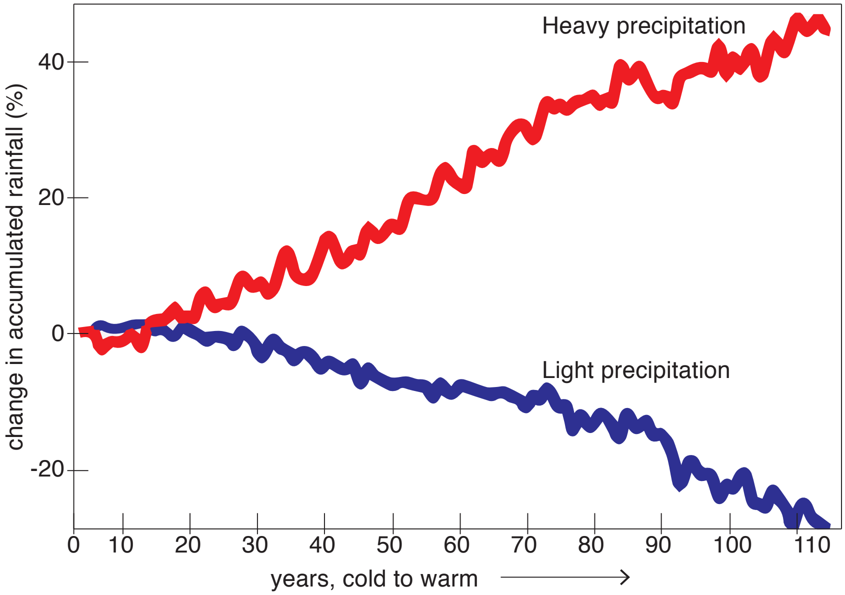

Figure 2.1. Seasonal changes in accumulated precipitation for heavy and light precipitation as a function of regional temperature over India, arranged from coldest to warmest years. Figure adapted from Mishra et al. (2018).

Rainfall data from the India Meteorological Department (IMD) for the period 1901-2014 shows a 12% increase in the number of active spells in the second half (1958-2014) (Pai et al., 2016). This increase in the active spells are mainly due to a shift towards more frequent occurrence in the short duration (3–6 days) spells compared to the long duration (≥13 days) spells (Dash et al., 2011; Pai et al., 2016; Singh et al., 2014). Meanwhile, another study using the IMD rainfall data for the period 1951–2013 suggests a decreasing trend in the strength of MISO (in the 20-60 days’ timescale) over India (Karmakar et al., 2015), possibly attributed to a weakening of the local monsoon circulation. The study finds that the increase in extreme events is relatively more pronounced in the break phases than the active phases of MISO, which is suggestive of a flattening of the MISO during the past six decades (Karmakar et al., 2015). The changes in monsoon sub-seasonal variability are also felt in the major river basins over India. Analysis indicates that river basins located in central India show a significant increase in the intensity and area covered by heavy rains (Deshpande et al., 2016). At the same time, dry spells (days with no rainfall) are increasing in all the river basins except some parts of the Krishna and Peninsular river basins.

Analysis using IMD rainfall data for the period 1950-2015 indicate a threefold rise in extreme rainfall events which are widespread, covering a large area across the central belt of India, and last for a duration of about 3 days (Roxy et al., 2017). These widespread rainfall events are found to result in largescale floods and catastrophic loss for life and property across central and northern India–Gujarat, Maharashtra, Madhya Pradesh, Chhattisgarh, Telangana, Odisha, Jharkhand, Assam and parts of Western Ghats–Goa, north Karnataka and South Kerala (Roxy et al., 2017) (Fig. 2.2). There have been 285 reported flooding events in India over 1950-2017 affecting about 850 million people, leaving 19 million homeless and killing about 71,000 people (according to the International Disaster Data Base). The total damage during this period is about $60 Billion. Changes in the drainage patterns due to land use and land cover changes and increased settlement in low lying areas have raised the vulnerability to extreme rainfall events which, in turn, increases the devastation and economic loss every year. During the last decade, the damage due to floods alone has been about $3 Billion per year.

The largescale, widespread changes in extreme rainfall over the Indian subcontinent are largely dominated by dynamic responses of the atmosphere rather than thermodynamic factors. The trend in extreme events shows a negative correlation with the local temperatures over the central Indian region (Ali and Mishra, 2017; Roxy et al., 2017; Vittal et al., 2016). This is interesting because, across most of the tropics, the increase in local temperatures plays a major role in the rising frequency of the extreme rainfall events (Wang et al., 2017). The rise in widespread extremes is associated with increased variability of the low-level monsoon westerlies over the northern Arabian Sea driving surges of moisture supply, leading to extreme rain episodes across the entire central Indian belt (Mishra et al., 2018; Roxy et al., 2017). This is attributed to the increased warming north of the Arabian Sea which results in increased moisture and also large fluctuations in the monsoon westerlies (Roxy et al., 2017). The increased ocean warming is, in turn, a result of human activities leading to increased carbon dioxide emissions (Dong et al., 2014). Meanwhile, urbanization has also impacted the local rainfall distribution, inducing

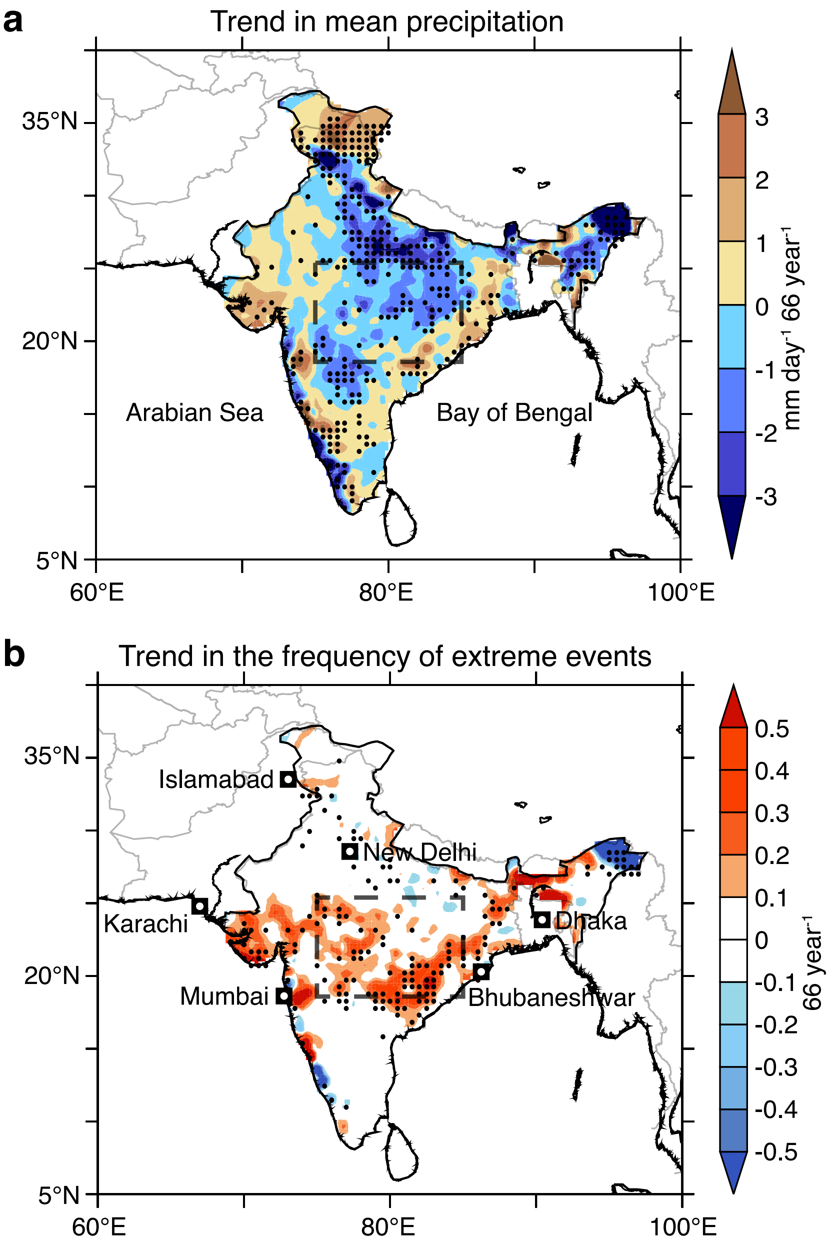

Figure 2.2. The observed trend in summer (a) mean precipitation anomalies (mm day^{-1} 66 year^{-1}) and (b) the frequency (66 year^{-1}) of extreme precipitation events (precipitation ≥ 150 mm day^{-1}). Stippling indicates trend values significant at 95% confidence level. Mean precipitation for the season is 8.1 mm day^{-1}. Figure adapted from Roxy et al. (2017).

nonuniformity in the observed changes of these extremes across India (Shastri et al., 2015). The impact of urbanization is visible in the southern, central, and western India. For example, urbanization has intensified the extreme rainfall in the metropolitan city of Mumbai, which is not visible in the nearby coastal town of Alibaug (Shastri et al., 2015).

Climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) project an increase in the monsoon variability at daily timescales, throughout the 21st century under the RCP 8.5 scenario, with a 13% to 50% increase by the end of the century (Menon et al., 2013). The active and break spells are projected to be more intense in the future climate, with an expansion in the area covered (Sharmila et al., 2015). These projections indicate an enhanced propensity towards short active and long break spells in the future. Short duration precipitation extremes, at sub-daily (3-hour timescales), are also projected to increase in the future. A rise of 1.5°C in the global mean temperatures (with respect to pre-industrial levels) is projected to results in a 20% increase in the sub-daily rainfall extremes, while a 2°C increase may result in a 25% increase (Ali and Mishra, 2018). However, the large spread among the CMIP5 monsoon simulations suggests low confidence in the projected changes in the monsoon and requires further investigation.

2.3. Changes in the Interannual and Multidecadal Variability of Monsoon

Though the year-to-year variability of the monsoon is generally within 10% of the average rainfall, the regional variabilities can be large, occasionally resulting in large-scale droughts. The onset and withdrawal dates are also different for each region and differ from year to year. El Niño Southern Oscillation (ENSO), characterised by a see-saw of ocean temperatures in the eastern Pacific, is a major factor influencing the monsoon variability by modulating the atmospheric circulation and the monsoon winds (Rasmusson and Carpenter, 1983). Hence generally, during El Niño conditions when the central-east Pacific temperatures are warmer than average, the monsoon circulation and winds are weak, and the rainfall over India is relatively low; and during La Niña conditions when the ocean temperatures are cool, the monsoon is strong. During 1901-2018, 12 out of the 25 monsoon droughts co-occurred with the El Niño events while 6 out of the 14 flood years were associated with the La Niña events (Fig. 2.3). This means that almost 50% of the monsoon drought and flood years are associated with the ENSO conditions in the Pacific Ocean. ENSO also influences the onset and withdrawal of the summer monsoon and in turn the length of the rainy season. An evolving El Niño reduces the tropospheric temperature gradient over the monsoon region and shortens the rainy season by delaying the onset and advancing the withdrawal (Goswami and Xavier, 2005).

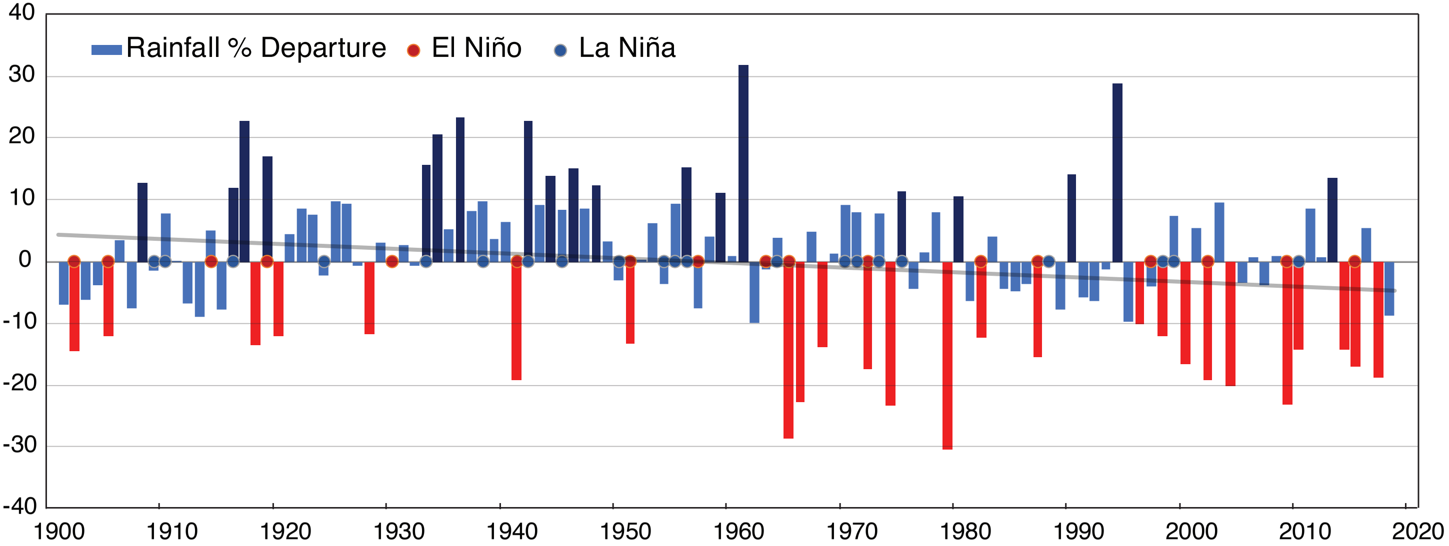

Figure 2.3. Percentage departure of summer monsoon rainfall over central India (76-86°E, 19-26°N, box in Fig.2) during 1901-2018. Wet years (above 10% departure) are marked in dark blue colour and drought years (below -10% departure) are marked in red colour. El Niño and La Niña conditions for the summer season are marked using red and blue dots.

However, during the last several decades, the frequency and intensity of monsoon droughts have increased, and some of these droughts were not linked to the El Niño (Fig. 2.3). Also, the El Niño-monsoon relationship exhibits a multi-decadal variability (Krishna Kumar et al., 1999), and may also depend on the temporal and regional evolution of El Niño in the Pacific (Ashok et al., 2007). Other than ENSO, the Atlantic also plays a role in influencing the monsoon interannual and decadal variability (Pottapinjara et al., 2014; Sankar et al., 2016; Yadav et al., 2018).

Nevertheless, the role of climate change is obvious in the observed changes in the interannual and multi-decadal variability of the monsoon. Observations show that Indian monsoon rainfall, particularly that over central and north India, has undergone a statistically significant weakening since the 1950s (Fig. 2.2). The secular decline in the mean rainfall is associated with a weakening of the local monsoon Hadley circulation. Several factors are attributed to the observed changes in the monsoon rainfall, one of them being the rapid warming in the Indian Ocean. It is suggested that the rapid warming in the Indian Ocean during the past six decades have reduced the meridional tropospheric temperature gradient, dampening the monsoon circulation (Gnanaseelan et al., 2017; Jin and Wang, 2017; Mishra et al., 2012; Roxy, 2017; Roxy et al., 2015). Deforestation, including conversion of forest land to cropland, have also contributed to the weakening of the monsoon, by decreasing the evapotranspiration and thereby the recycled component of rainfall (Paul et al., 2016). It is also argued that increased air pollution has played a role in changing the monsoon characteristics by reducing the meridional thermal gradient and by interacting with the convective processes (Guo et al., 2015)—though there is large uncertainty in these results due to lack of consistent, continuous observations and improper representation of aerosol effect in the models. Meanwhile, a recent analysis (Jin and Wang, 2017) suggests that enhanced land surface warming in the recent decade (2002-2014) has strengthened the meridional tropospheric temperature gradient, indicating a possible short-term revival of the monsoon.

Other than a weakening monsoon circulation, the onset of the monsoon over India has also experienced a delay in the recent decades (Sahana et al., 2015). The delay in the onset is attributed to a net decrease of moisture supply form the Arabian Sea in the post-1976 period. Hence, while the mean summer monsoon onset date was 1 June during 1948-1976, this has shifted to 5 June since 1976, suggesting a re-assessment of the crop calendar in India which depends on the monsoon onset dates. Global warming has also altered the predictor-predictand relationship in terms of monsoon forecasts. As a result, the skill in Indian monsoon seasonal forecasts has also reduced in the recent decades (Wang et al., 2015).

On a large scale, the rainfall over the northern hemisphere has shown substantial intensification during 1979-2011, with a striking increase of rainfall by 9.5% per degree of global warming (Wang et al., 2013). CMIP5 models project this to increase in the future, though there is low confidence in the simulations over the Indian monsoon region, due to large inter-model spread and coarse resolution of the model simulations (Sabeerali et al., 2014a; Saha et al., 2014). A study using selected CMIP5 models, which simulate the monsoon and Indian Ocean conditions, suggest a shortening of the rainy season in the future (Sabeerali and Ajayamohan, 2017). They attribute this to the rapid warming of the Indian Ocean which in turn dampens the meridional tropospheric temperature gradient. Another study indicates a weakening of the monsoon circulation due to a reduction in the large-scale meridional temperature gradient at upper tropospheric levels (200 hPa) over the Asian monsoon region, associated with increased heating over the equatorial Pacific in the future climate (Sooraj et al., 2015).

2.4. Changes in the Monsoon on Centennial Timescales

Centennial variability of the monsoon is inferred mainly from geological proxies such as stalagmites, stalactites, corals, marine and lake sediments (Chakraborty et al., 2012; Sinha et al., 2018; Zhisheng et al., 2015). A multi-centennial trend to drier and possibly cooler conditions in the Indus Valley region started around 4100 years ago. This coincided with a considerable decrease in the Northern Hemisphere temperature and Indus Valley deurbanization phase (about 3850–3300 years before present), as inferred from the speleothem oxygen isotope records from the Sahiya caves in north India (Kathayat et al., 2017). Oxygen isotope records based on stalagmite proxies from Kadapa caves in peninsular India also capture the wet and dry periods of the monsoon on decadal to centennial timescales (Fig. 2.4) (Sinha et al., 2018). These stalagmite records indicate an abrupt climate change, characterised by the decline of monsoon around 2800 years before the present time. This decline coincides with a sudden rise in the atmospheric carbon isotopes, indicative of reduced solar activity. It is noted that the declining trend of the monsoon follows the northern hemispheric summer insolation, which is known to influence the location and strength of the Inter Tropical Convergence Zone (ITCZ).

Studies show that the South Asian Summer Monsoon began to show a weakening trend from the mid-13th century, reaching a minimum in the mid-15th century and then peaking in the early 17th century. Upwelling proxy record from the Arabian Sea indicates that the monsoon strength reached a minimum around the year 1600 (Anderson et al., 2002). This weakening of the monsoon upwelling is reflected as drying over the subcontinent, especially over western-peninsula India during the period of 1580–1630 (Shi et al., 2018). Thereafter, the monsoon strengthened rapidly during 1630-1670. Following this, there has been a declining trend until the present (Shi et al., 2017; Shi et al., 2014). Such centennial variations may be partially attributed to changes in solar activity before the 19th century (Hiremath et al., 2015; Shi et al., 2017; Shi et al., 2014). Increased variability in solar radiation can increase the thermal contrast between land and sea (Hiremath et al., 2015), and lead to a northward shift of the intertropical convergence zone (Tierney et al., 2010) causing the monsoon to strengthen. Even though the solar radiation during four out of five of the solar activity sequences showed an increasing trend through the late 19th century, the monsoon continued to weaken (Shi et al., 2017). These mismatches may be related to the increased anthropogenic emissions in the 19th century (Bollasina et al., 2011; Guo et al., 2015; Krishnan et al., 2013; Roxy et al., 2015) because after the industrial era, the effect of natural forcings have decreased and that of anthropogenic emissions have increased (Bollasina et al., 2011).

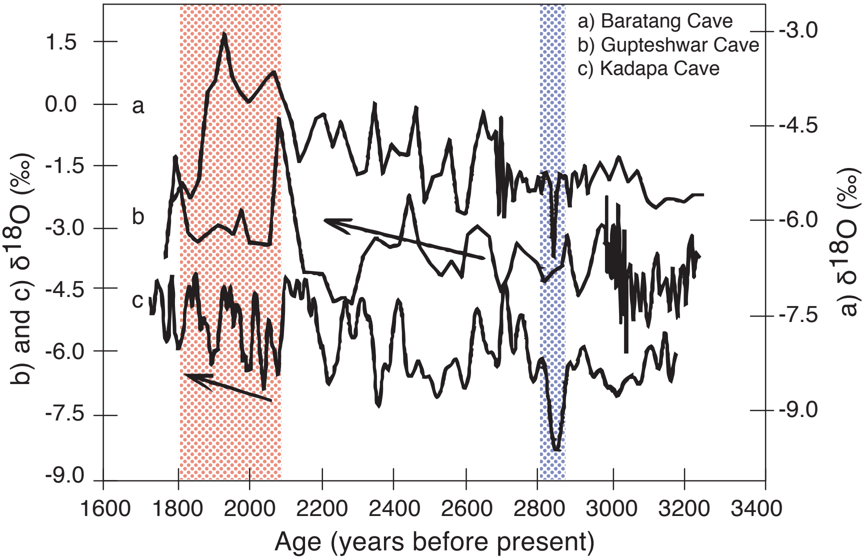

Figure 2.4. Variation of Oxygen isotopes at different caves across India, (a) Baratang Cave, (b) Gupteshwar cave and (c) Kadapa cave. The arrow shows an average declining trend in rainfall in all the records, during the warming period (red stippling) in Europe and the North Atlantic that ran from approximately 250 BC to AD 400. The blue stippling indicates the signature of enhanced monsoonal rainfall for a short period (about 2900–2850 years before present). Figure adapted from Sinha et al. (2018).

The Holocene age (the recent 10,000 years) saw large changes in the Earth's climate on a centennial scale. Weak summer monsoon winds correlate with reduced solar output—the variability as seen when going from a multidecadal scale to a centennial one. Studies indicate that over the past 11,100 years, the multidecadal to a centennial-scale decrease in summer monsoon intensity can be attributed to the intervals of reduced solar output and an increase in elevated solar output (Gupta et al., 2005). This link between the solar cycle and the monsoon appears to be via direct solar influence on the ITCZ that controls the monsoonal precipitation (Kodera, 2004). Meanwhile, it is indicated that the positive relation between monsoon rainfall and solar activity is mainly due to the effect of the Atlantic Multidecadal Oscillation, which is influenced by the changes in solar activity (Malik and Brönnimann, 2018). Also, it is argued that the strength of the relationship between monsoon rainfall and ENSO on interannual to centennial timescales is modulated by solar activity from 3 to 40 year timescales (Malik and Brönnimann, 2018).

2.5. Conclusion

Global changes resulting in warmer tropical oceans and local changes in land development, forest cover and air pollution have led to increased Indian summer monsoon variability during 1950-2018. Though non-uniform, the increase in variability is prominent with a significant weakening of the local monsoon circulation and rainfall, along with an increase in the frequency of short-duration extreme rainfall events. These changes are projected to increase further in the future, along with increased anthropogenic emissions. Using long-term data and high-resolution climate models, our understanding of these changes in monsoon rainfall has improved in recent decades. These observed and projected changes may be useful for the long-term management of the agricultural-irrigation sectors and efficient planning of the food, water and energy sectors of the region.

Short, extended range and seasonal monsoon forecasts have improved during the past decade due to advancement in monsoon research and development but more importantly due to the National Monsoon Mission which significantly raised the investment on high-performance computing, trained human resources and international participation (Abhik et al., 2017; Ramu et al., 2016; Sahai et al., 2013). However, state-of-the-art climate models still do not skillfully simulate the observed long-term climatic changes in monsoon rainfall, and there is low confidence in the projected changes in monsoon over South Asia. Besides, global warming has also introduced increasing challenges and uncertainties in the seasonal monsoon forecasts, which needs to be addressed (Wang et al., 2015). Hence, there is an urgent need to comprehensively understand the interactive roles of the land, ocean, atmosphere and biosphere on the observed changes and to incorporate them into the models for predicting the future changes (Swapna et al., 2015).

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Chapter 3

Climate Change Impacts on Streamflow in India

Harsh L. Shah[1] and Vimal Mishra[1*]

Abstract

Sustainability of water resources is vital for agricultural and socio-economic development in India. In the recent decades, India has witnessed erratic summer monsoon that accounts for more than 80% of the total annual rainfall. There is considerable uncertainty in the precipitation projections during the summer monsoon from the regional and global climate models; hence it is imperative to understand the sensitivity of water resources in the Indian River basins under the projected future climate. This is particularly important considering India's status as the most populated country in the world, after China. We evaluated changes in total runoff (TR) and streamflow in the 18 Indian River basins under the projected future climate using the Variable Infiltration Capacity (VIC), a macroscale hydrologic model, and a stand-alone routing model. We used downscaled and bias-corrected data from five General Circulation Models (GCMs) for two Representative Concentration Pathway (RCPs). We find that despite the intermodal variation, Indian River basins are projected to experience wetter and warmer climate by the end of the 21st century. Moreover, results indicate positive changes in TR under the projected future climate. Streamflow is also projected to increase in the majority of the river basins except for the Indus basin. However, a majority of the increase in total runoff and streamflow can be due to extreme precipitation events during the monsoon season. Therefore, despite the increase in runoff and streamflow in the monsoon season, water availability during the dry season may not increase substantially.

3.1. Introduction

India receives 80% of the annual rainfall during the monsoon from June to September. The variation in monsoon rainfall may lead to flood and drought conditions. India witnessed major floods (Kerala 2018, Gujarat 2017, and Madras 2015) and droughts (Gujarat 2016, and Maharashtra 2013) events in recent years. The monsoon variability has a significant impact on surface water availability. For instance, one of the scientific reasons behind the drying up of the Saraswati River was weak monsoon (Giosan et al., 2012). Moreover, climate change can further accentuate surface water availability in Indian River basins

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(Immerzeel et al., 2010). For instance, Immerzeel et al. (2010) reported that climate change would reduce the meltwater availability in the Himalayan Rivers, which are most vulnerable to a reduction of flow under the projected climate change.

General Circulation Models (GCMs) are designed to project climate variables using the concentration of greenhouse gases in the atmosphere (Intergovernmental Panel on Climate Change (IPCC), 1999). Climate models produce the future climate projections based on experiments under the time series of emission and concentrations of CO_2 (IPCC, 1999) from four (e.g., 2.6, 4.5, 6.0 and 8.5) Representative Concentration Pathway (RCPs) scenarios (Moss et al., 2010). Immerzeel et al. (2010) studied projected changes in water availability for Asian water towers using GCMs (A1B SRES scenario) over the period 2046 to 2065 and reported a decline in upstream water supply from the upper Indus (-8.4%) and Ganga (-17.6%) River basins. The main reason for a possible decrease in flow in the Indus and Ganga basin might be due to the decline in precipitation and snowmelt water.

Many previous studies related to climate impact assessment have been conducted for Ganga, Brahmaputra and Indus basins. Apart from these river basins, Godavari, Krishna, Cauvery, Coastal basins, Mahanadi, Narmada, Sabarmati, Mahi, Tapi, and Subarnarekha play a substantial role in the country's water security and development. In this chapter, we used the calibrated set up of the Variable Infiltration Capacity (VIC) model over 18 Indian River basins from Shah and Mishra (2016). For the future projections, we used bias-corrected data from five GCMs and two RCP scenarios (van Vuuren et al., 2011) to study changes in streamflow in Indian River basins.

3.2. Datasets, Model and Analysis

3.2.1 Dataset

We obtained 0.25° daily observed precipitation data from 1951 to 2012 from the Indian Meteorological Department (IMD) (Mishra et al., 2014; Pai et al., 2015; Rajeevan et al., 2006). IMD developed daily gridded precipitation data using 6995 stations (Pai et al., 2015). Gridded 1° maximum and minimum temperature data were obtained from the IMD, which are based on 395 stations across India. We regridded 1° temperature to 0.25° using a lapse rate and digital elevation model (DEM) as described by Maurer et al. (2002). We obtained daily wind speed data from the NCEP-NCAR reanalysis dataset, which are available at 0.25° spatial resolution. We selected 233 gauge stations across India from CWC and simulated daily streamflow from 1951-2099 using the routing model.

We used two RCP scenarios: RCP2.6 and RCP8.5; and five GCMs: GFDL-CM3, GFDL-ESM2M, MIROC-ESM, MIROC-ESM-CHEM, and NorESM1-M. In RCP2.6 (RCP8.5), radiative forcing assumed to increase by 2.6 (8.5) Watt/m^2 by the end of 21st century. Description of all CMIP model acronyms is available in Table 3.1 and more detail available from http://cmip-pcmdi.llnl.gov/cmip5/docs/CMIP5_modeling_groups.pdf (Su et al., 2013). We bias corrected daily precipitation and temperature data from the five GCMs and two RCPs from 1951 to 2099 to evaluate streamflow change in projected future climate using the methodology of Hempel et al. (2013). Hempel et al. (2013) method is based on trend-preserving statistical bias correction, which was developed within the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). IMD daily precipitation and temperature data for the period 1951-2012 was used to bias correct the climate projections. Recently, Ali et al. (2018) used bias-corrected climate projections to evaluate the changes in hydropower production of Nathpa Jhakri, Bhakra Nangal, Srisailam, Nagarjuna Sagar, Hirakud, Sardar Sarovar and Indira Sagar dams.

Table 3.1 Information about the CMIP5 climate models used for IPCC.

Institute	Nation	Modeling Center	Model Name
GFDL	USA	NOAA Geophysical Fluid Dynamics Laboratory	GFDL-CM3
GFDL	USA	NOAA Geophysical Fluid Dynamics Laboratory	GFDL-ESM2M
MIROC	Japan	National Institute for Environmental Studies	MIROC-ESM
MIROC	Japan	National Institute for Environmental Studies	MIROC-ESM-CHEM
NCC	Norway	Norwegian Climate Centre	NorESM1-M

3.2.2 The Variable Infiltration Capacity (VIC) and Routing Model

The Variable Infiltration Capacity (VIC: (Cherkauer et al., 2003; Cherkauer and Lettenmaier, 1999; Liang et al., 1994; Liang et al., 1996) uses an aerodynamic representation of the latent and sensible heat fluxes at the land surface. The infiltration algorithm for the upper layer is essentially the same as for the single layer VIC model, while the lower layer drainage formulation is of the form previously implemented in the Max-Planck-Institute GCM. It is a macroscale hydrology model, which simulates daily/sub-daily water and energy fluxes at each grid cell. The VIC model represents the sub-grid variability of elevation, soil, and vegetation which makes hydrologic processes more realistic in the heterogeneous topographic regions (Gao et al., 2010). Apart from these characteristics, the VIC model has a better representation of drainage (lower soil layer as a nonlinear recession) and topography (orographic precipitation and temperature lapse rates). We used the calibrated and evaluated VIC setup from Shah and Mishra (2016). They evaluated simulated streamflow against observed data from Central Water Commission (CWC) and Global river discharge database-SAGE at different gauge stations; evapotranspiration (ET) with NASA's satellite product MOD16, soil moisture with European Space Agency Climate Change Initiative (ESACCI) soil moisture v1 for 18 Indian River basins: Brahmani, Brahmaputra, Cauvery, Ganga, Godavari, India east coast, India northeast coast, India south coast, India west coast, Indus, Krishna, Mahanadi, Mahi, Narmada, Pennar, Sabarmati, Tapi, and Subarnarekha. More information about the model, model calibration/validation and datasets are available in Shah and Mishra (2016).

We used a stand-alone routing model (Lohmann et al., 1996) to simulate streamflow. Shah and Mishra (2016) calibrated streamflow at observed gauge locations over the Indian River basins. The routing model uses daily surface runoff and baseflow simulated by the VIC to route daily flow at a desired location over the basin. The routing model is based on the unit hydrograph method, and the channel routing uses the linearised Saint-Venant equation. The river routing model assumes all runoff exits a cell in a single flow direction. We prepared flow direction, flow accumulation and station location files for the routing model using the Shuttle Radar Topography Mission (SRTM) elevation data. Please refer to Lohmann et al. (1996) for more details on the routing model.

3.2.3 Analysis

To calculate the change in precipitation (%), temperature (°C), TR (%) and streamflow (%), we selected historic (1970-99) period as a reference and estimated changes in near (2010-2039), mid (2040-2069), and end (2070-2099) period. We calculated the trend in TR in the observed period using a nonparametric Mann-Kendall trend test (Mann, 1945) and Sen's slope (Sen, 1968) at the 5% significance level. The Mann–Kendall method has been widely used for trend detection of water budget components at regional and global scales (Mishra and Lettenmaier, 2011; Shah and Mishra, 2016). Shah and Mishra (2016) used Mann-Kendall trend test and found precipitation and TR significantly decreased, and air temperature significantly increased in Ganga basin from 1948-2012.

3.3. Results

3.3.1. Historical Water Budget

Figure 3.1 shows the historical mean annual total precipitation and mean air temperature from 1970 to 1999 using the ensemble mean of five bias corrected GCMs. Mean annual total rainfall is higher (more than 2500mm/year) in the Western Ghats and northeastern regions; whereas lower (less than 400mm/year) mean annual precipitation is received in the Indus and upper part of Sabarmati basin (Fig. 3.1a). We find mean air temperature for the majority of the river basins is above 25ºC excluding the northern parts of the Indus and Ganga basins (Fig. 3.1b).

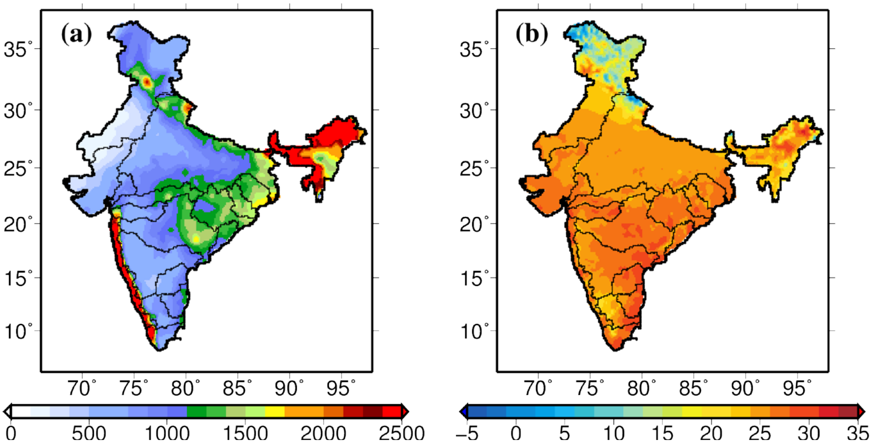

Figure 3.1. Ensemble historical mean of five GCMs (a) mean annual total precipitation (mm/year) and (b) mean air temperature (ºC/year) over Indian River basins from 1970-99.

We estimated trends in VIC-simulated mean annual TR during the periods of 1970–99 (Fig. 3.2). Mean annual TR varied between 100 and 1500mm from the arid and semiarid west (lower Indus basin and upper Sabarmati basin) to the eastern region (e.g., Brahmaputra basin). Moreover, lower TR in the upper Sabarmati basin and southern Indus basin can be attributed to low monsoon season precipitation in these regions (Fig. 3.2a). We find an increase in TR in East coast basins (e.g., Brahmaputra, Brahmani, Cauvery, Mahanadi, and Subarnarekha) during the period of 1970–99 (Fig. 3.2b), which may be due to increased precipitation. The decline in mean annual TR was noticed in parts of the Ganga, West coast, Indus, Krishna, Mahi, Pennar, Sabarmati and Tapi basins during the period of 1970–99 (Fig. 3.2c), which is consistent with the observations (Shah and Mishra, 2016).

3.3.2. Projection of Total Runoff (TR) and Streamflow

We considered 1970-99 as the reference period and estimated ensemble mean projected change in mean annual TR and mean streamflow for near, mid and end periods of the 21st century with respect to the reference period using bias-corrected data from the five GCM for RCP2.6 and RCP8.5.

In the RCP2.6 scenario, 2-10% decline in TR is projected in Indus basin, and up to 30% increase in TR is projected in the rest of the basins by the end of the 21st century (Fig. 3.4 and Table 3.2). These changes (decline and increase in TR) can be attributed to the projected decline in precipitation in the Indus basin

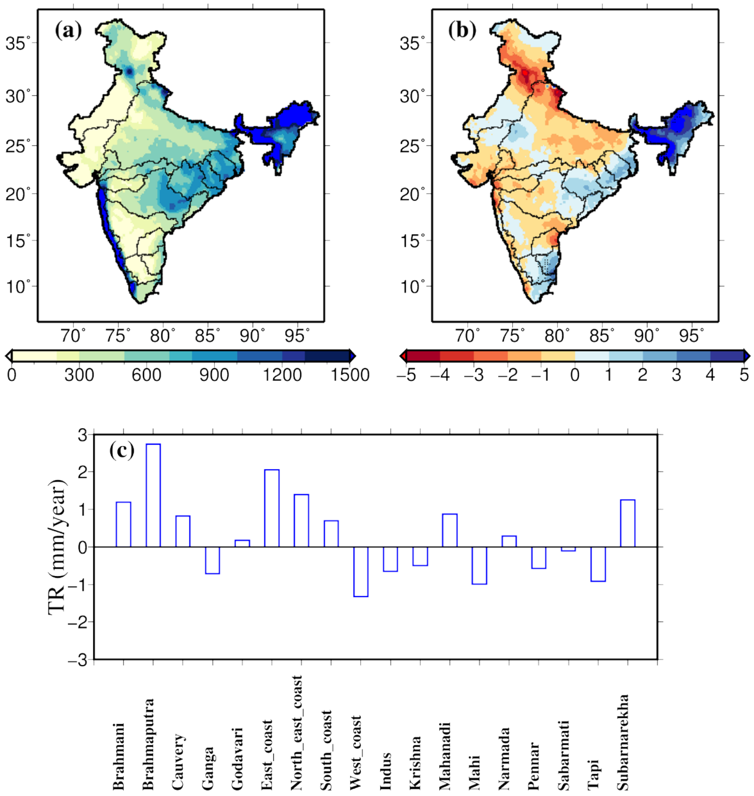

Figure 3.2. Ensemble historical mean of five GCMs (a) mean annual total runoff (mm/year), (b) trend in total runoff (mm/year) estimated using Mann-Kendall test; and (c) basin averaged change in total runoff (mm/year) from 1970-99.

by 5% while the projected increase in precipitation by 20% in the rest of the basins (Fig. 3.3). Moreover, the temperature is projected to increase by 0.8 to 2°C in all the basins by the end of the 21st century. In Krishna and Brahmaputra basins, TR is projected to increase by 8% in the near term climate (2010-2039). TR is projected to decrease (increase) in the Indus basin (in central and southern India) by the mid-period of a 21st century. More than 20% increase in TR is projected in Cauvery, East coast, South coast, Subarnarekha, Mahi, and Narmada basins by the end of the 21st century. However, the Indus basin is projected to face a decline in TR by 10% under the warming climate under RCP2.6.

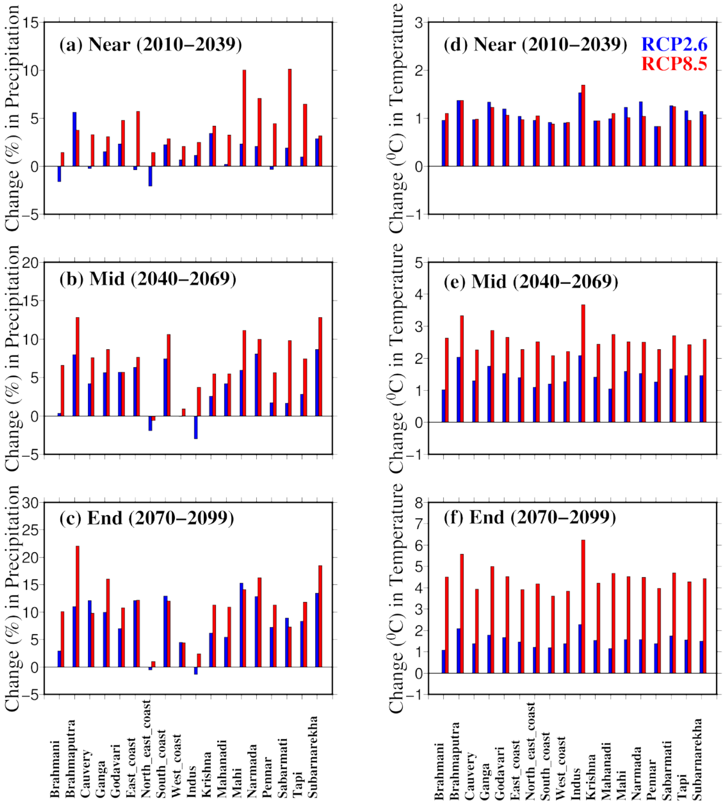

Figure 3.3. Basin-averaged projected change in (a, b, c) precipitation (%) and (d, e, f) air temperature (°C) calculated for near (2010-2039), mid (2040-2069) and end (2070-2099) period against the base period (1970-99). The blue bar shows the RCP2.6 scenario, and the red bar shows the RCP8.5 scenario.

Figure 3.5 shows the projected change in TR under the RCP8.5 scenario. Ensemble mean TR is expected to increase by 2-40% by the end of the 21st century under the high emission scenario of RCP8.5. Annual mean Precipitation is projected to increase by 10%, 12% and 20% in the near, mid and end period, respectively. India is projected to experience warming of up to 7°C by the end of the 21st century under the high emission scenario of RCP8.5 (Fig. 3.3). A higher increase in precipitation and warm days are projected in the RCP8.5 scenario than that of the RCP2.6 scenario. TR is projected to increase by 20% in the Peninsular and the basins located in western India by near period. North India (some part of Indus basin) is projected to experience a decline in TR. We find except in the North east coast, Indus basin, and along the west coast; TR is projected to increase more than 10% in the mid and end periods of the 21st century (Table 3.2). Therefore, based on our downscaled and bias-corrected projections we find that a majority of India is projected to experience a wetter and warmer future climate, which is consistent with the findings of Mishra and Lilhare (2016).

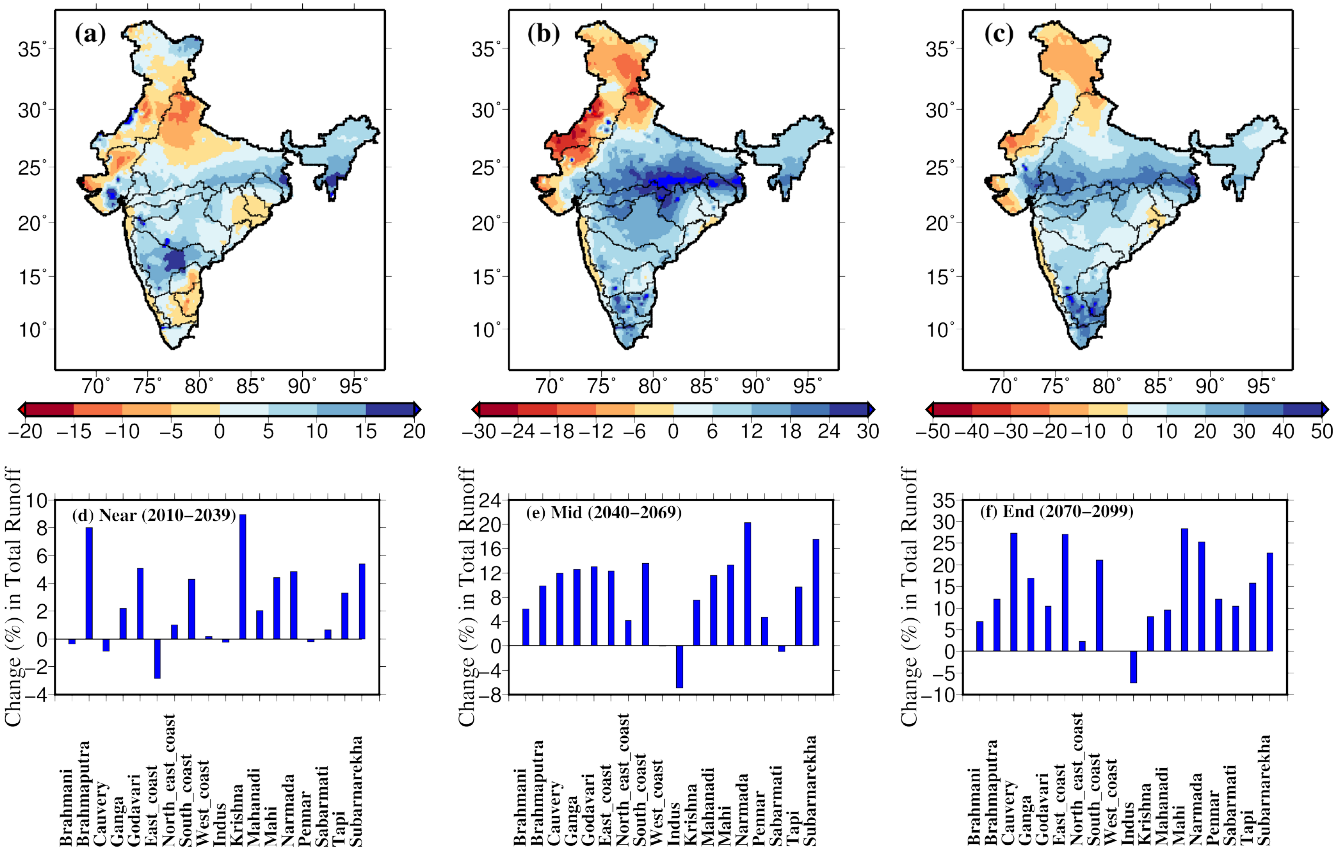

Figure 3.4. Change in total runoff (%) calculated for (a, d) near, (b, e) mid and (c, f) end period using the RCP2.6 scenario.

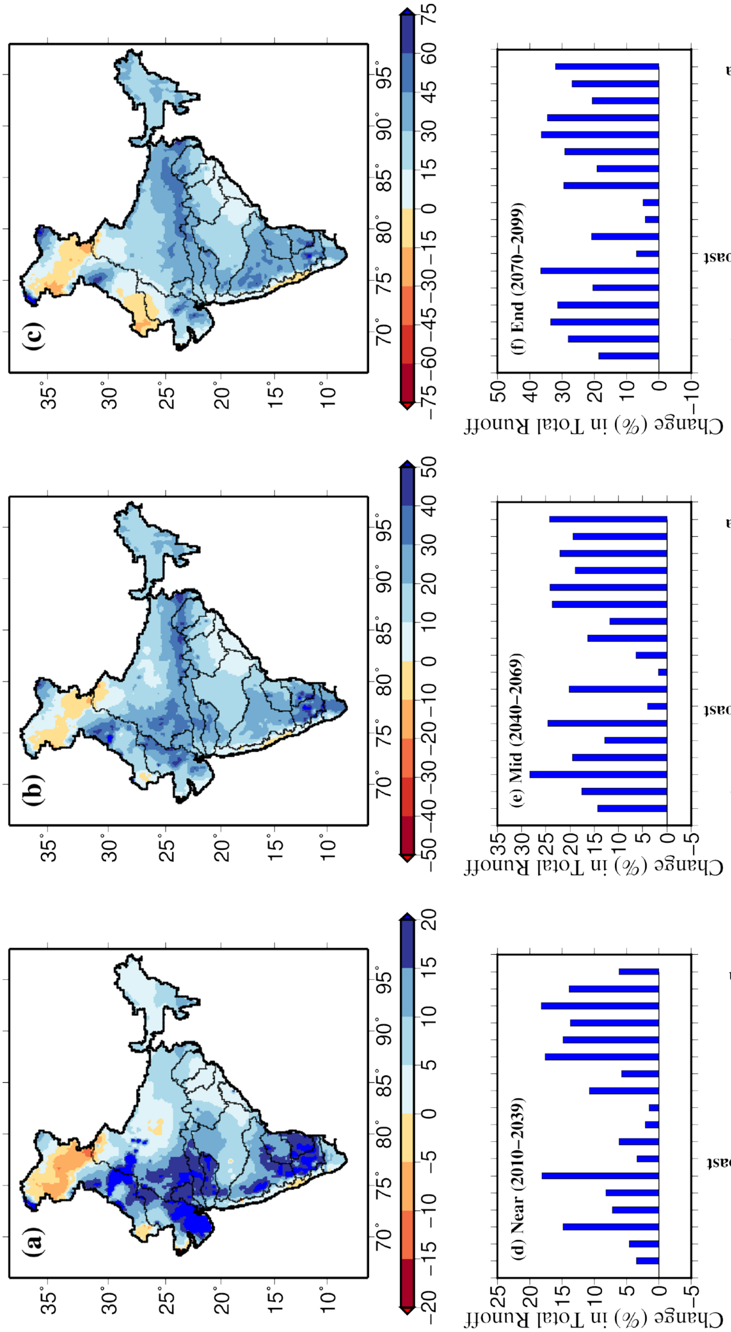

Figure 3.5. Same as Figure 3.4 but for the RCP8.5 scenario.

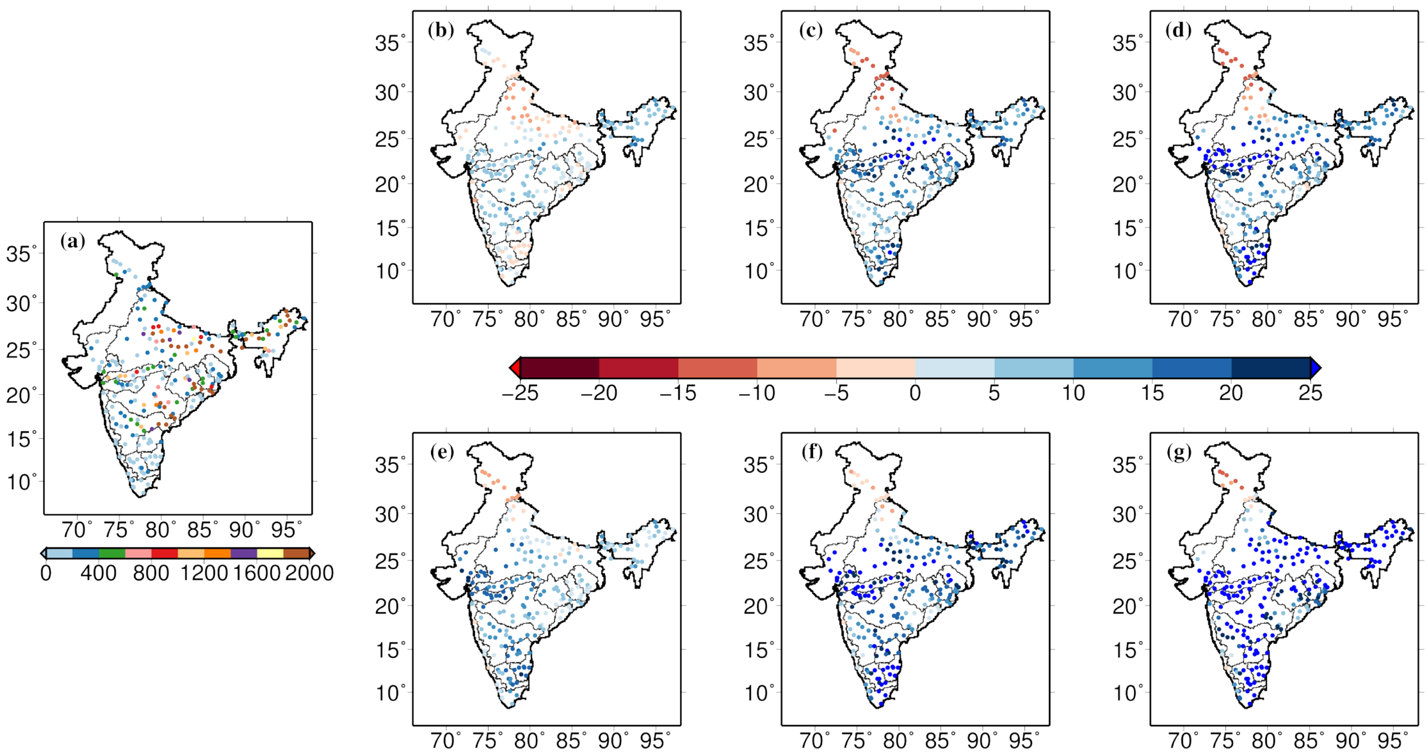

Figure 3.6. (a) Annual mean streamflow (m^3/s) at gauge stations across Indian River basins for the period of 1970-99. Change in streamflow (%) calculated for the (b, e) near, (c, f) mid and (d, g) end period for two (RCP2.6, RCP8.5) scenarios, respectively.

We estimated projected changes in mean annual streamflow simulated using the VIC model at 233 gauge stations for both RCP2.6 and RCP8.5 scenario (Fig. 3.6). In the RCP2.6 scenario, streamflow is projected to decrease in Ganga, Indus, coastal basin's gauge stations and more than 20% increase in streamflow is projected in central and peninsula river gauge stations (Fig. 3.6 b, c, d). We find more than 10%, 20%, and 25% projected increase in mean annual streamflow during the near, mid, and end periods over the majority of gauge stations under the RCP8.5 scenario, respectively. In both RCP2.6 and RCP8.5 scenario; streamflow is projected to increase at the majority of locations, which is consistent with the runoff projections.

3.4. Conclusions

India has the 2nd highest irrigated land area (more than 68.2 million hectares) and population (more than 1.34 billion) in the world although our irrigation penetration is less than 50%. Increasing population and growing demand for irrigation, along with new challenges posed by climate change will further exacerbate the water demand (Vorosmarty, 2000). Therefore, it is important to understand the availability of water for better management. We studied the projected change in total runoff and streamflow using the bias-corrected data from five GCMs and two RCPs scenarios. As per GCMs projections: temperature and precipitation are projected to increase in most of the basins (excluding Indus, the upper part of Ganga and Sabarmati basins), which leads to a projected increase in TR under both the RCPs. Moreover, streamflow is projected to increase more significantly during the end period and under the higher emission scenario than the early 21st century and low emission scenario. However, streamflow is projected to decline in the Indus basin.

Despite the projected increase in total runoff and streamflow in India under the warming climate, the water availability may not increase due to seasonal and regional variability. For instance, most of the increase in streamflow is projected during the monsoon season while the water demands will rise in response to future warming during the dry season (October to May). Moreover, the existing capacity of reservoirs may not be sufficient to accommodate the increased streamflow that can be used during the dry season. Therefore, future studies can evaluate the impacts of increased precipitation and air temperature on the overall water availability in India.

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Chapter 4

Water Availability Across India Under Observed and Projected Climate

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Abstract

Quantifying the spatiotemporal variability of water availability is crucial for decision making related to water management. Here, we estimate water availability over India under the historically observed climate and projected future climate. We estimate three indicators of water availability and associated variability: long-term renewable freshwater resources, the frequency of low flows, and the frequency of high flows. These indicators are estimated using two forms of the Budyko model, a physically based parsimonious model that relates available energy in a region to available water. The first form uses a probabilistic framework to estimate long-term water availability while the second form is a dynamic model that estimates daily water availability. Although we find a general agreement between various climate models on an expected increase in long-term water availability across India, considerable uncertainties exist and are mainly attributed to the choice of climate model and specific location within India.

4.1. Introduction

Availability of adequate water resources is essential for the environmental and socio-economic well-being of any region. In recent times, growing population and water-intensive lifestyles have increased the pressure on available freshwater resources, and several parts of the world have to deal with water scarcity either perennially or seasonally (Mekonnen and Hoekstra, 2016). India, in particular, has been facing long-term water scarcity in some regions along with frequent reoccurrences of floods and droughts in others (Mall et al., 2006). Therefore, efficient water management necessitates understanding and quantifying the spatiotemporal variation of water availability over India at decision-relevant scales.

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The expected change in future climate resulting from the anthropogenic increase of carbon dioxide and other greenhouse gases in the atmosphere is going to alter the spatiotemporal distribution of water resources in India further. Several efforts attempt to assess how water availability over India will change under future climatic conditions. Recent analyses suggest that surface water availability (runoff) may increase in most parts of India (Meenu et al., 2012; Mishra and Lilhare, 2016; Narsimlu et al., 2013; Whitehead et al., 2015). Some others surmise that uncertainties in future estimates of precipitation are likely to confound quantification of possible changes in water availability, as sometimes climate models do not agree even on the direction of precipitation change (Jeuland et al., 2013; Singh and Kumar, 2015). In addition to studies that focus on India, there are several global assessments, which also provide projections of future water availability over India. Notable among them is the work by Schewe et al. (2014) that estimate likely changes in future runoff for a 2°C increase in global mean temperature. Their estimates indicate that there is a strong agreement between several climate and hydrologic models regarding an increase in surface runoff over most parts of India spanning the Deccan plateau.

Similarly, climate and hydrologic model combinations also agree on likely reductions in runoff over the western coastal regions. However, models do not agree on whether there will be an increase or decrease in runoff over parts of the northern Himalayas and western desert regions; which is partly due to large uncertainties in climate models' precipitation estimates over the Himalayan regions (Mishra, 2015). Despite these general indications, it is important to note that each study can analyse only a limited number of climate and hydrologic models. In addition, state-of-the-art general circulation models (GCMs) may not be able to estimate precipitation change over India reliably, possibly due to their limited ability in capturing the dynamics of the Indian monsoon (Saha et al. 2014; Mishra, 2015). Finally, although many studies focus on understanding the impact of climate change on long-term water availability, relatively fewer efforts focus on the impacts on intra-annual water availability (Gosain et al., 2011; Mishra and Lilhare, 2016).

In this study, we assess water availability and associated uncertainties over India using three indicators: long-term renewable freshwater availability, the frequency of low flows and the frequency of high flows. We estimate these indices for observed historical climate and under expected changes in future climate using several GCMs and emission scenarios. As complex hydro-climatic processes determine how much water will be available in a region in the form of surface or groundwater sources, we generally resort to hydrologic models of varying complexity to quantify water availability. Here, we assess water availability using two recently developed models based on the same fundamental principles of water and energy balance in a region: the Budyko framework. The Budyko framework relates the available energy to available water in the region and provides a physically consistent framework to predict long-term water availability in a region. We employ a probabilistic version of the Budyko framework (Greve et al., 2015) that allows us to estimate long-term renewable freshwater resources in a region using satellite-based actual evapotranspiration data. Also, we use the dynamic Budyko model (Biswal, 2016) that uses the Budyko concept to simulate continuous daily time series of available water in a region and use them for analysing the frequency of low and high flows.

4.2. Modelling Frameworks

4.2.1. Probabilistic Budyko Framework for Estimation of Long-term Water Availability

The probabilistic Budyko approach allows us to estimate long-term water availability using only observed long-term climate (precipitation and temperature) data and satellite-based actual evapotranspiration (Singh and Kumar, 2015). The Budyko function relates a climate indicator, the aridity index (ratio of long-term potential evapotranspiration to long-term precipitation) to a water availability indicator, the evaporation ratio (ratio of long-term actual evapotranspiration to long-term precipitation). Here, we employ a form of the Budyko curve with a firm physical basis (Zhang et al., 2004):

$$\frac{AET}{P} = 1 + \frac{PET}{P} - \left(1 + \left(\frac{PET}{P}\right)^{\omega}\right)^{\left(\frac{1}{\omega}\right)} \tag{1}$$

where AET is the long-term actual evapotranspiration, P is the long-term precipitation, PET is the long-term potential evapotranspiration estimated from temperature data, and ω is a parameter inferred using historical data. The probabilistic approach groups ω inferred from smaller regions to obtain uncertainty ranges for larger regions. We estimate ω for each district of India using historical climate and satellite evapotranspiration (AET) data. Note that using AET data to calibrate the Budyko curve allows us to choose arbitrary control volume for the analysis. Thus, we chose to carry out the analysis at the district level, which are fine scale political divisions in India. The calibrated district-level values of ω are pooled together to obtain the regional distribution of ω over India. Regions are defined after Kampman et al. (2007). Renewable freshwater resources (RFWR) are estimated as the difference between long-term precipitation and actual evapotranspiration, assuming changes in storage over multi-decadal time scales are negligible (Singh and Kumar, 2015).

4.2.2. Dynamic Budyko Model for Projecting Intra-annual Changes

The dynamic Budyko model (Biswal, 2016) is based on the concept of *instantaneous aridity-index* or dryness-index. Unlike the original Budyko model, the dynamic Budyko model is designed to simulate discharge at small time-steps (daily). The model has a two-stage partitioning scheme for water balancing. In stage one, rainfall has to satisfy the evapotranspiration demand of the catchment, which is assumed to be equal to the potential evapotranspiration. The remaining rainwater (*W*) then enters into stage two. W at any time can thus be expressed mathematically as: $W(t)=Max(P(t)-PET(t),0)$. Note that the volume of water transforming into evapotranspiration is also the volume of water that absorbs solar energy or PET. Thus, the remaining energy (*H*) that enters into the second stage can be expressed as: $H(t)=Max(PET(t)-P(t),0)$. In the second stage, *W* and *H* interact with each other to produce effective rainfall (ER), the fraction of *W* that ultimately transforms into discharge, and rainfall loss (RL), the fraction of *W* that ultimately transforms into evapotranspiration: $(t)=ER(t)+RL(t)$. In other words, rainfall first gets stored in the catchment and then exits the system as streamflow and evapotranspiration.

The partitioning of *W* into *ER* and *RL* is determined by the dryness state of the catchment. Rainfall wets the catchment, whereas solar energy dries it. It is assumed that the effects of rainfall and solar energy on catchment dryness decay with time following an empirically derived decay function by Biswal (2016) as $x(t+\tau)=x(t)/(1+c\tau)$, where $x(t)$ is the effect of input $x(t)$ on catchment dryness remaining after time τ (in days), and c is a constant fixed at 0.4 based on previous application of the model. One can thus express functional volumes of water (*FW*) and energy (*FH*) from all the antecedent inputs affecting catchment dryness at any point of time:

$$FW(t) = \int_{t-N}^{t} W(\tau).\frac{1}{1+c(t-\tau)}\,d\tau \tag{2}$$

$$FH(t) = \int_{t-N}^{t} H(\tau).\frac{1}{1+c(t-\tau)}\,d\tau \tag{3}$$

, where N is the time period for which rainfall or solar energy will significantly influence catchment dryness, which is considered as 365 days (Biswal, 2016). Just like the definition of aridity-index, one can now express instantaneous aridity index (ϕ) as $\phi(t) = (FH(t)/(FW(t))$. Partitioning *W* into *ER* and *RL* is then expressed as:

$$ER(t) = W(t) \cdot \left[1 - \left(\varphi \cdot tanh\left(\frac{1}{\varphi}\right) \cdot (1 - e^{-\varphi}) \right)^{0.5} \right] \tag{4}$$

Since effective rainfall decays to produce discharge, it is also assumed that the same decay function can be used to obtain discharge from effective rainfall.

$$Q(t) = -\frac{d}{dt}\left[\int_0^t \left(-ER(\tau) \cdot \frac{1}{1+0.4(t-\tau)} \right) \cdot d\tau \right] \tag{5}$$

In this study, we employ this dynamic model to predict renewable freshwater at daily time-step using the daily rainfall and potential evapotranspiration time series data as model inputs. Based on these daily estimates, the frequency of high and low flows is quantified (described below in Section 2.3). The detailed procedure to apply the model equations at discrete time-steps can be found in Biswal (2016).

4.2.3. Indicators of water Availability

Three indicators of water availability are assessed in this study. The first indicator is related to long-term water availability and is estimated as the difference between long-term precipitation and the probabilistic Budyko model estimated actual evapotranspiration. We term this water as 'renewable freshwater resource' (RFWR) of a region on lines similar to Mishra et al. (2017). RFWR includes all flowing surface water as well as hydrologically active groundwater. Two indicators assess possible intra-annual changes in RFWR: the frequency of high and low values of RFWR (Olden and Poff, 2003; Singh et al., 2014). The high RFWR frequency indicator estimates the number of annual occurrences during which RFWR remains above three times the median daily RFWR value. The low RFWR frequency indicator counts the number of annual occurrences where RFWR remains below 5% of the mean daily RFWR values in the data period. The total number of occurrences of low RFWR is divided by record length in years to get an average estimate.

4.3. Study Area and Data

Historically observed climate data was obtained from the Indian Meteorological Department (IMD), Pune. The precipitation data was available in two formats. The first format was available at a monthly resolution from 1901-2000 at a spatial resolution of fine scale political divisions (districts) (Figure 4.1a). The second format was available at a daily temporal resolution but at a coarser spatial resolution of 0.25°x0.25° from 1901-2015. Daily maximum and minimum temperature time series were available at a spatial resolution of 1°x1° from 1951-2000. The temperature data was used to estimate potential evapotranspiration (PET) using the Hargreaves equation (Figure 4.1b; Hargreaves and Samani, 1985). Remote sensing based monthly actual evapotranspiration at a resolution of 0.073° was obtained from Zhang et al. (2009). Water availability was estimated only for those districts, which had at least 10 years of overlapping data for all three hydro-climatic variables.

The projections of future precipitation and temperature were obtained for five general circulation models (GCMs) belonging to the Coupled Model Intercomparison Project-5 (CMIP-5) database and were available from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP2a; Warszawski et al., 2014). The five GCMs, representing climate model structural uncertainty are GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M. The GCM based precipitation and temperature datasets were bias corrected using a trend-preserving approach following the observation (WATCH-forcing) dataset (see Hempel et al., 2013 for more details). GCMs use time series of radiative forcings as input to simulate global climate. These are termed representative concentration pathways (RCPs) and characterize the socio-economic settings that impact concentrations of carbon dioxide in the atmosphere in the future. Two RCPs are used in this study, RCP2.6 and RCP8.5, that represent different trajectories of radiative forcing, culminating in 2.6 W/m^2 and 8.5 W/m^2 of radiative forcing by 2100. End-of-century (2081-2099) projections of precipitation and temperature were used in the analysis.

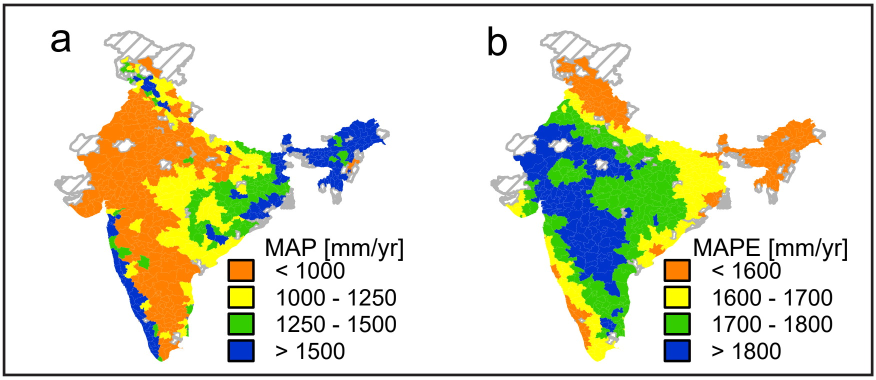

Figure 4.1. Study area covering entire India using political boundaries (district-level) to assess water availability. (a) Mean annual precipitation (MAP), and (b) mean annual potential evapotranspiration (MAPE) across the districts estimated for the historical time period of 1983-2000.

The dynamic Budyko model was applied to four selected districts so that the intra-annual variations in their water availability could be studied in detail. For estimating the changes in the frequency of high and low RFWR values, the dynamic Budyko model was forced with a time series of future climate generated by the delta change approach. In this approach, the projected relative change in the long-term value of a climatic variable is applied to historically observed time series data. These are in turn used to simulate daily values of RFWR. Four districts are selected to showcase the likely changes in indicators that estimate the intra-annual variability of water availability. The four districts are selected such that they represent diverse hydro-climatic and physiographic conditions (Table 4.1). The aridity index ranges from 0.5 to 2.4.

Table 4.1. A brief description of districts used for simulation by the dynamic Budyko model. Long-term means for climate variables is estimated for the time period 1983-2000.

SNo.	District Name (State name)	Latitude (N)	Longitude (E)	Area (km2)	Mean annual P (mm/yr)	Mean annual PET (mm/yr)
1	Cachar (Assam)	24°48′40″	92°51′23″	4100	3114	1419
2	Dhar (Madhya Pradesh)	22°29′50″	75°06′14″	8145	804	1820
3	Hassan (Karnataka)	12°59′43″	76°06′32″	6801	1171	1616
4	Sonepat (Haryana)	29°03′42″	76°52′46″	2158	711	1678

4.4. Results

4.4.1. Projections of Climatic Variables

Five GCMs from the CMIP-5 database were identified for assessing possible changes in future precipitation and potential evapotranspiration. The long-term average values of these climatic variables were estimated for historical (1983-2000) and end-of-century (2081-2099) time periods for two RCPs. The relative change in future estimates of mean annual precipitation (MAP) varies considerably more across GCMs than across RCPs (Figure 4.2). The mean value of the projected relative change in MAP across all districts and GCMs is 8.8% and 19.2% for RCP2.6 and RCP8.5, respectively. Therefore, in general, RCP2.6 projects relatively lower values of MAP when compared to RCP8.5. However, this increase varies significantly across GCMs. The mean value of relative change in MAP across all districts of India for GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M are -7.1% (-7.8%), 25.5% (47.4%), 8.8% (25.8%), 6.3% (10.7%), 10.4% (19.9%) for RCP2.6 (RCP8.5), respectively.

The spatial variability of projected changes in MAP is also evident in Figure 4.2. The percentage of districts with reductions in MAP for GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M are 64.9% (58.2%), 3.5% (2.0%), 21.2% (11.9%), 19.2% (21.7%), and 3.6% (1.9%), for RCP2.6 (RCP8.5), respectively. Thus, overall, GFDL-ESM2M projects a reduction in MAP over most parts of India. On the other hand, the percentage of districts with greater than 25% relative increase in MAP for GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M are 0.0% (0.0%), 42.5% (80.2%), 2.4% (48.7%), 1.9% (14.8%), and 1.4% (33.5%), for RCP2.6 (RCP8.5), respectively. This shows that HadGEM2 projects strong increase in MAP for relatively large parts of India. We conclude that there are significant uncertainties in future precipitation projections with some GCMs projecting moderate reductions, while others are projecting strong increases in MAP under RCP8.5.

Projections of mean annual potential evapotranspiration (MAPE) reveal greater spatial agreement than those of MAP. The mean value of projected relative changes in MAPE across all districts and GCMs is 2.8% and 11.0% for RCP2.6 and RCP8.5, respectively. This is expected as greater temperature increases are projected for RCP8.5, which in general has a greater radiative forcing. Also, the spatial variability of changes in MAPE is significantly greater under RCP8.5, when compared to RCP2.6. This is evident in the increase in standard deviation of projected MAPE across all districts and GCMs from 2.4% to 5.4% for RCP2.6 and RCP8.5, respectively. As with the case of MAP projections, MAPE projections vary across GCMs. The mean change in MAPE across all districts of India for GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M are 1.8% (10.1%), 4.1% (10.9%),4.3% (11.3%), 2.3% (13.8%), 1.8% (8.8%) for RCP2.6 (RCP8.5), respectively.

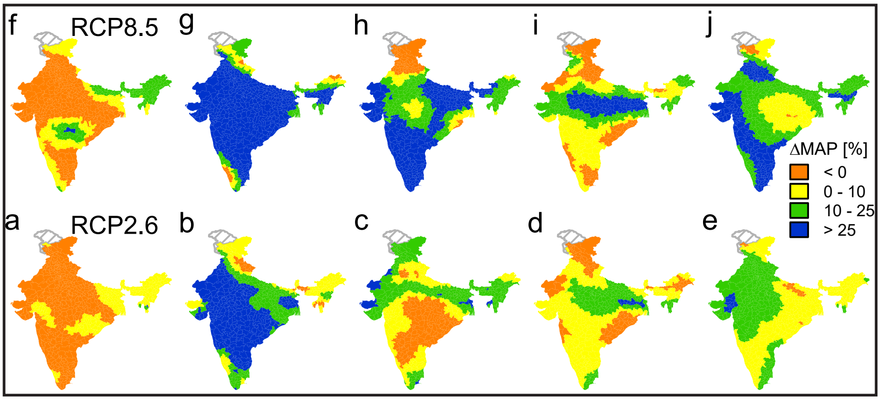

Figure 4.2. Projected relative changes in mean annual precipitation (MAP) across India for five GCMs under two RCPs: (a-e) RCP2.6 and (f-j) RCP 8.5. Each panel presents projections from a different GCM: (a,f) GFDL-ESM2M, (b,g) HadGEM2-ES, (c,h) IPSL-CM5A-LR, (d,i) MIROC-ESM-CHEM, and (e,j) NorESM1-M. Relative change in MAP corresponding to the future period of 2081-2099 are estimated with respect to the historical reference period of 1983-2000.

Although the spatial variability of the projected changes in MAPE is lesser than those for MAP, considerable variations do exist across GCMs and RCP realizations. The percentage of districts with less than 10% increase in MAPE for GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M are 100.0% (53.3%), 98.3% (47.6%), 99.5% (48.4%), 98.0% (28.5%), and 99.8% (87.9%), for RCP2.6 (RCP8.5), respectively. Thus, the spatial variability of projected changes in MAPE is much smaller under RCP2.6 when compared to RCP8.5. In addition, IPSL-CM5A-LR and MIROC-ESM-CHEM project greater than 15% increase in MAPE for a large percentage of districts (27.0% and 35.4%). Most of these districts are in northern India for IPSL-CM5A-LR projections (Figure 4.4h) but are distributed between northern and southern India under MIROC-ESM-CHEM projections (Figure 4.4i).

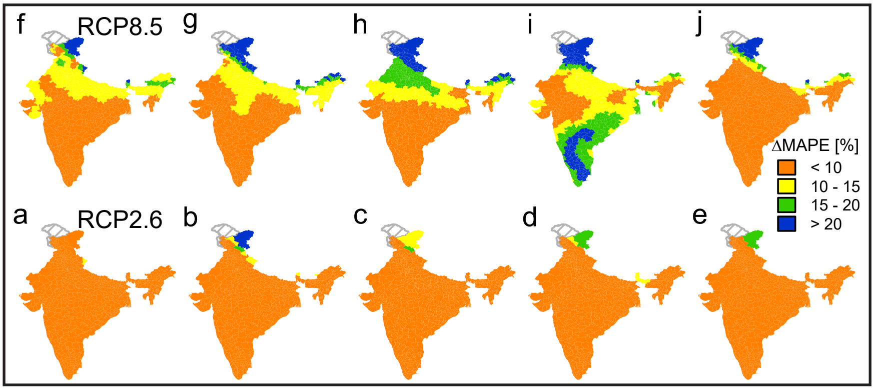

Figure 4.3. Same as Figure 4.2 but for mean annual potential evapotranspiration (MAPE).

4.4.2. Long-term Water Availability under Historically Observed Climate

Before understanding how water availability may change in the future, it is useful to assess the spatial variability of water availability and its drivers under observed historical climate. We use the historically observed estimates of MAP and MAPE within the probabilistic Budyko framework to estimate the median values and associated inter-quartile range of long-term RFWR (Figure 4.4). The median values of long-term RFWR range from 87 mm/yr to 5391 mm/yr, averaging at 749 mm/yr across all districts (Figure 4.4a). Regions with high median values of long-term RFWR include northeastern, western coastal, and northern districts of the east coast. Altogether, 23% of the districts have a median long-term RFWR greater than 900 mm/yr. A large fraction (44%) of the districts have low (<500 mm/yr) values of median long-term RFWR. These districts generally fall in the northwestern desert regions, part of the Indo-Gangetic plains, and plateau regions of Southern India. The desert regions and the plateau regions of southern India also have lower values of MAP as seen in Figure 4.1(a). Combined with high values of MAPE (Figure 4.1b), these districts generally have the lowest long-term RFWR. The Indo-Gangetic plain has quite a variation in long-term RFWR with generally lower median values of long-term RFWR in the upstream plain regions, and moderate to high values in the coastal regions.

The inter-quartile range of long-term RFWR also exhibits quite a variation from 28 mm/yr to 310 mm/yr (Figure 4.4b). Around 36% (34%) districts have an inter-quartile range of long-term RFWR less than 125 mm/ yr (greater than 175 mm/yr). Higher values of inter-quartile ranges are generally accompanied by higher median estimates of long-term RFWR. Thus, higher inter-quartile ranges are found in northeastern regions. However, high values of inter-quartile ranges are found for many districts in southern India along the eastern coast. These districts have low values of median long-term RFWR, and therefore, the relative uncertainty in estimates of RFWR is greater for southern Indian districts. Higher relative uncertainty in estimates of long-term RFWR is also observed in several districts belonging to the Indo-Gangetic plains. Regions with lowest relative uncertainties in RFWR include the northwest, western coastal districts, and central India. Overall though, the inter-quartile ranges are much smaller than the variability of long-term RFWR across the country. Thus, while there is uncertainty in these estimates, they present a distinct spatial variation of water availability across India.

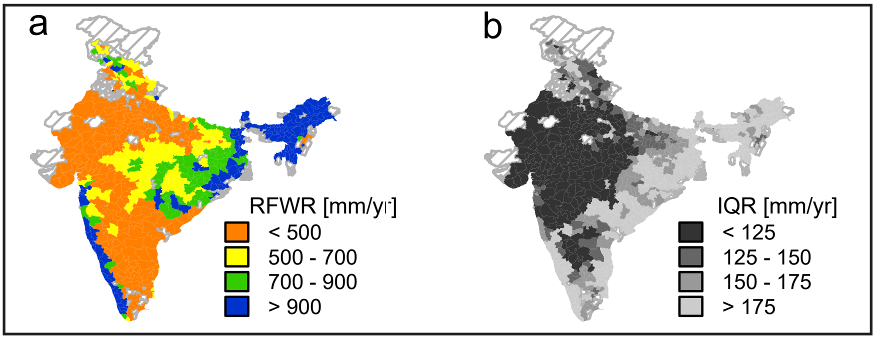

Figure 4.4. **Spatial variation of long-term renewable freshwater resources (RFWR) across India estimated using historically observed climate data for the time period 1983-2000.**

4.4.3. Long-term Water Availability under Projected Climate

We derive future estimates of water availability by using projections of precipitation and potential evapotranspiration from five GCMs for two RCPs within the probabilistic Budyko framework. The projected relative changes in the long-term values of median RFWR for each GCM and RCP combination is shown in Figure 4.5. Recall that the probabilistic Budyko framework provides both median and inter-quartile range of long-term RFWR. In the remaining section, we focus on relative changes in median values of long-term RFWR, termed hereafter as Δ_{med}RFWR. For entire India, Δ_{med}RFWR was estimated using area averaging of long-term median RFWR values for each district. All India estimated Δ_{med}RFWR for GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M are -3.0% (-2.5%), 40.9% (71.1%), 2.1% (27.4%), 7.1% (11.4%), and 6.2% (16.6%) for RCP2.6 (RCP8.5), respectively. Similarly, the mean values of Δ_{med}RFWR across all districts for GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M are -8.1% (-10.9%), 51.6% (88.9%), 1.7% (31.2%), 8.9% (10.4%), and 7.4% (18.4%) for RCP2.6 and RCP8.5, respectively. Thus, if GCM, and RCP related uncertainties are neglected, water availability is expected to increase at an all-India scale for four out of five GCMs for both RCPs. However, this gross estimate is complicated due to the significant spatial variation of Δ_{med}RFWR along with variations across GCMs and RCPs.

The disagreement between GCMs is spatially variable and more in some regions than others. For example, for northern India that includes the Himalayan regions as well as the Indo-Gangetic plains, three out of five GCMs project an increase in long-term RFWR with the area-averaged Δ_{med}RFWR ranging from 3.4% to 21.2% under RCP2.6. Two GCMs project Δ_{med}RFWR of -3.1% and -22.6% under RCP2.6. Under RCP8.5, three GCMs project a reduction in the area-averaged Δ_{med}RFWR ranging from -3.4% to -18.9%, indicating a reduction in long-term RFWR. On the other hand, for eastern India comprising of all northeastern regions, delta regions of Ganga-Brahmaputra basins, and Mahanadi river basin, GCMs project area average Δ_{med}RFWR ranging from 4.7% (5.0%) to 20.7% (41.4%) for RCP2.6 (RCP8.5), respectively. Similarly, for southern India, four out of five GCMs agree on increases in long-term values of median RFWR for both RCP2.6 and RCP8.5. For the remaining parts of India, three (four) out of five GCMs project a positive area averaged Δ_{med}RFWR for RCP2.6 (RCP8.5). Thus, even across relatively large regions, there are considerable differences regarding the future projections of water availability for each GCM.

When finer spatial variations are accounted for, there are significant disagreements among GCMs regarding the direction of change. GFDL-ESM2M projects reduction in long-term values of median RFWR for 62% and 61% districts across India for RCP2.6 and RCP8.5, respectively. On the other hand, HadGEM2-ES projects an increase in median values of long-term RFWR for 94% and 95% districts for RCP2.6 and RCP8.5, respectively. In general, HadGEM2-ES, MIROC-ESM-CHEM, and NorESM1-M project an overall increase in long-term values of median RFWR over the majority of districts of India for RCP2.6 as well as RCP8.5. Projections of IPSL-CM5A-LR are an exception as it projects a reduction in long-term values of median RFWR for half of the districts under RCP2.6 but relatively fewer districts (20%) for RCP8.5. Thus, there is disagreement between GCMs on whether water availability will increase or decrease in the future under RCP2.6. Barring projections from IPSL-CM5A-LR, there is agreement across RCPs for each GCM on the direction of change.

It is worth quantifying the variations in projections of long-term values of median RFWR across GCMs and RCPs. The standard deviation Δ_{med} RFWR across GCMs is 30.2% and 53.7% for RCP2.6 and RCP8.5, respectively. On the other hand, the standard deviation of Δ_{med} RFWR across RCPs is 20.2%, 63.3%, 36.0%, 17.3%, and 13.6% for GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M, respectively. Thus, in general, the variation across GCMs is greater than that across RCPs, indicating that model structural uncertainties dominate the uncertainty in projections of long-term RFWR when compared with the uncertainty regarding future carbon dioxide emissions.

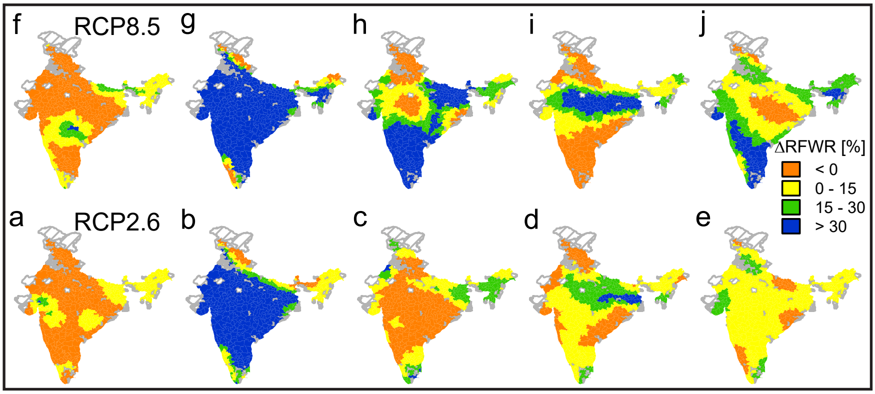

Figure 4.5. Same as Figure 4.2 but for the median long-term renewable freshwater resources (RFWR).

4.4.4. Changes in Intra-annual Indicators

Our results show how climate change may affect the long-term availability of water resources, albeit in an uncertain manner. In addition to these long-term changes, climate change may also induce changes in the temporal distribution of water within a year. Such intra-annual changes are likely to be equally important from the perspective of water management. For example, if the long-term estimates of water availability do not change, but the frequency of extremes such as floods and droughts increases, greater investments in infrastructure will be needed to cope with the increased variability of water availability. Here, we quantify the expected changes in two indicators of water availability: frequency of low and high values of RFWR.

In general, we find that the frequency of low values of RFWR reduces across majority of GCMs for both RCPs across all districts. The mean relative change in the frequency of low values of RFWR across all GCMs and RCPs is -24.5%, -22.0%, -13.0%, and 3.0% for Cachar, Dhar, Hassan, and Sonepat, respectively. Thus, for three out of four districts, the frequency of low values of RFWR is projected to reduce, except for Sonepat where a slight increase is expected. Similarly, the frequency of high values of RFWR is projected to increase for three out of four districts when average estimates across all GCMs and RCPs are considered for each district. For Cachar, Dhar, Hassan, and Sonepat, the mean of the relative change in frequency of high values of RFWR is 18.4%, 17.7%, 7.9%, and -2.9%, respectively. A reduction in frequency of low values of RFWR combined with an increase in frequency of its higher values is projected, on an average, for Cachar, Dhar, and Hassan districts, indicating that the overall variability of water availability may remain the same. On the other hand, a reduction in the frequency of high values of RFWR combined with an increase in the frequency of low values of RFWR is projected for Sonepat. We, therefore, conclude that there are significant spatial variations in relative changes in the frequency of high and low values of RFWR.

Table 4.2. Ranges of projected relative change in frequency of low and high values of RFWR for four selected districts across India as estimated by the dynamic Budyko model. The relative change is calculated as a percentage from historical baseline for each GCM and RCP combination.

SNo.	District Name	ΔLow flow frequency		ΔHigh flow frequency [%]	
		RCP2.6	RCP 8.5	RCP 2.6	RCP 8.5
1	Cachar	(-32.7, -4.1)	(-49.0, -20.4)	(5.5, 31.7)	(8.9, 46.7)
2	Dhar	(-43.9, -2.4)	(-70.7, 4.9)	(0.9, 47.4)	(-17.4, 74.7)
3	Hassan	(-15.9, 1.6)	(-85.7, 11.1)	(-9.1, 12.9)	(-22.1, 74.3)
4	Sonepat	(-1.9, 22.2)	(-20.4, 16.7)	(-49.0, 25.2)	(-72.3, 38.5)

The intra-annual changes estimated above conceal considerable uncertainties in the projections of relative changes in the frequency of low and high values of RFWR. As with the projections of long-term water availability, we find that there are variations in projected changes in both indicators across GCMs and RCPs. Reduction in the frequency of low values of RFWR under RCP8.5 tends to be much greater than those in RCP2.6 for Cachar and Sonepat districts (Table 4.2). However, for Dhar and Hassan districts, there is greater variability in these projections as we move from RCP2.6 to RCP8.5 (Table 4.2) Similarly, the frequency of high values of RFWR shows an increasing trend for Cachar district when moving from RCP2.6 to RCP8.5. However, for the remaining districts, there is more variability in the relative changes of the indicator. For example, the projected relative change in the frequency of high values of RFWR ranges between -49.0% and 25.2% for Sonepat district under RCP2.6. The range expands to -72.3% and 38.5% under RCP8.5. For Dhar, the frequency of high values of RFWR is expected to increase across all GCMs under RCP2.6 but may reduce or increase under RCP8.5.

4.5. Conclusions

Our estimates of likely changes in water availability over India indicate that water availability may increase over most parts of India under impending climate changes. This result is in agreement with different analysis carried out globally as well as at the scale of India (Mishra and Lilhare, 2016; Narsimlu et al. 2013; Schewe et al. 2014; Whitehead et al. 2015). However, when analysing the changes at finer spatial resolution, we notice considerable disagreements between various GCMs regarding the direction of change. Noticeably, three out of five GCMs project an increase in water availability over the majority of India, while the remaining two indicate that reductions will be faced by a considerable number of districts under RCP2.6. There is more agreement on GCMs that water availability will increase under RCP8.5. Finally, we note that the uncertainties in the projections stem mainly from the choice of GCMs as there is more agreement between projections across RCPs for individual GCMs.

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Chapter 5

Climate Change and Reservoir Storage in India

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Abstract

Reservoirs play a major role in irrigation and hydropower along with protecting downstream regions from flooding. Despite the large implications of reservoir storage for flood protection, irrigation, and hydropower, a real-time monitoring system has been lacking in India. To study the storage variability in the six major reservoirs, we develop a satellite-based near real-time monitoring systems for six large reservoirs in India using observations for the period of 2002-2017. We combined Moderate Resolution Imaging Spectroradiometer (MODIS) 8-day 250 m enhanced vegetation product (EVI) and ICESat/GLAS elevation data to provide remotely sensed reservoir storage. Satellite-based estimates of reservoir storage after bias correction provide satisfactory performance against the observations where R^2 is calculated after removing seasonality from observed and satellite reservoir storage data. To study the impacts of climate change on reservoir storage, we used bias-corrected data from five General Circulation Models (GCMs) and two Representative Concentration Pathway (RCPs) for the period 1951-2099. We simulated streamflow upstream of seven reservoirs using the Variable Infiltration Capacity (VIC) model and a standalone routing model. Results indicate an increase in streamflow at the end of the 21st century under the projected climate at upstream of the major reservoirs and a majority of which will occur during the monsoon season. Therefore, the current reservoir storage may need expansion to accommodate increased flow under the warming climate.

5.1. Introduction

Indian summer monsoon precipitation accounts for about 80% of the mean annual precipitation and has 10% (of long-term mean) year-to-year variability (Rahman et al., 2009; Rajeevan et al., 2006, 2005). Reservoirs address this variability by capturing excess flow during the monsoon season and releasing the storage during the dry season, hence, augmenting the demand-supply mismatch. Apart from attenuating floods, reservoirs are used for generating hydropower and meeting domestic, agricultural and industrial demands.

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The current monitoring of reservoir storage by the Central Water Commission (CWC) has a latency period of about 25 days (http://www.cwc.nic.in/newsite/ReservoirMonitoring.html). CWC provides weekly information on reservoir storage that can be used for decision making in water management for irrigation and hydropower production. Near-real-time monitoring of the reservoir storage with a reduced latency period is helpful in optimizing reservoir operation during climatic extremes. With climate change found to exacerbate the frequency and intensity of climatic extremes, near-real-time monitoring of storage gains relevance. Satellite-based reservoir storage monitoring based on radar altimetry (Berry et al., 2005) has shown potential to provide accurate storage estimates. In recent years, remotely sensed data have been widely used to monitor surface water extent and storage (Avisse et al., 2017; Gao, 2015; Kaptué et al., 2013; Khandelwal et al., 2017; Zhang et al., 2014). Since reservoir storage capacity of the major reservoirs in India has a considerable variability, monitoring reservoir storage at a higher temporal resolution (~ 8-day) is necessary. Monitoring reservoir storage at a high temporal resolution (~ 8-day) is particularly important during the dry-season (October to May) when reservoir storage can rapidly change due to irrigation and atmospheric water demands. Most of the previous studies estimated 16-day reservoir storage and were only limited to large reservoirs (Gao et al., 2012; Zhang et al., 2014). We use the 8-day Enhanced Vegetation Index (EVI) from MODIS and ICESat/GLAS dataset to provide near-real-time monitoring of six major reservoirs in India.

Other than the real-time monitoring aspects, reservoirs have witnessed long-term changes in streamflow and sediment due to the warming climate. Most of the climate change studies project substantial changes in precipitation and air temperature that affect streamflow and hence the water availability (Haddeland et al., 2014). Immerzeel et al. (2010) and Mishra and Lilhare (2016) reported that climate change could substantially affect water availability in the Indian subcontinental basins. Climate change can cause a reduction in meltwater availability from glaciers (Immerzeel et al., 2010), which will mainly affect the Brahmaputra and Indus basins resulting in a reduction in streamflow. General Circulation Models (GCMs) project climate variables at the end of the 21st century as per the changes in greenhouse gases in the atmosphere. According to Hsu et al. (2013), 17 out of 19 GCMs show an increase in global monsoon precipitation under Representative Concentration Pathway (RCP) 4.5 scenario, which can result in an increase in the monsoon (June to September) precipitation and streamflow to the reservoirs. Shah and Mishra (2016) reported that the past few decades were significantly warmer than the previous decades in the Indian region. Summer monsoon rainfall is the primary factor for the streamflow to the reservoirs, which are located mainly in the central and southern parts of the country. In this chapter, we focus on satellite-based monitoring and climate change impacts on reservoir storage.

5.2. Data and Methods

We obtained 0.25° daily observed precipitation, temperature (minimum and maximum) data for Indian region from India Meteorological Department (IMD) from 1951 to 2010 (Mishra et al., 2014; Pai et al., 2015; Rajeevan et al., 2006). We obtained daily wind speed data from the NCEP-NCAR reanalysis dataset, which was regridded to 0.25° to make it consistent with precipitation and temperature. We selected seven large reservoirs, Nathpa Jhakri, Bhakra Nangal (Gobindsagar), Srisailam, Nagarjuna Sagar, Hirakud, Sardar Sarovar and Indira Sagar which are located in the north, south, east and west part of India (Table 5.1, Fig. 5.1, Ali et al., 2018). We simulated daily streamflow to these reservoirs from 1951-2099 using the Variable Infiltration Capacity (VIC) model and a standalone routing model (Lohmann et al., 1996). As some part of Bhakra Nangal and Nathpa Jhakri reservoir basins fall outside India, we used data from APHRODITE Yatagai et al. 2012 and Princeton University Sheffield et al. 2006.

Table 5.1: Details of the 7 selected large Indian reservoirs (Source – Derived from India WRIS)

S. No.	Reservoir	Latitude	Longitude	Height (m)	Gross Storage Capacity (BCM)	Area (km^2)	Area-Elevation Relationship	Basin
1	Bhakra Nangal	31.4108	76.4333	167.64	9.86	168.35	E=0.3266*A+ 430.03	Indus
2	Nathpa Jhakri	31.5639	77.9803	62.5	3.43	234.5	-	Indus
3	Srisailam	16.0869	78.8972	145	8.72	615	E=0.0414*A+ 248.14	Krishna
4	Nagarjuna Sagar	16.5756	79.3117	124.66	11.55	285	E=0.5174*A+ 65.611	Krishna
5	Hirakud	21.57	83.87	60.96	8.1	743	E=0.025*A+ 176.31	Mahanadi
6	Sardar Sarovar	21.8303	73.7472	163	1.54	375.33	E=0.9477*A+ 38.191	Narmada
7	Indira Sagar	22.2839	76.4714	91.4	12.2	913.48	E=0.0315*A+ 234.47	Narmada

We used five General Circulation Models (GCMs: GFDL-CM3, GFDL-ESM2M, MIROC-ESM, MIROC-ESM-CHEM, and NorESM1-M) and two Representative Concentration Pathways (RCP) scenarios (RCP 2.6 and RCP 8.5) corresponding to each Global Climate Model (GCM). Details about all these five models can be found on Su et al. (2013) and Table 5.2. Here RCP2.6 and RCP 8.5 represent the low and high emission scenario, respectively (Meinshausen et al., 2009; Taylor et al., 2007). We used Hempel et al. (2013) method to bias-correct the GCM data from 1951-2099 against the observed IMD data (1951-2010) for the

Indian region and APHRODITE and Princeton data for the region outside of India for the two reservoirs (Bhakra Nangal and Nathpa Jhakri).

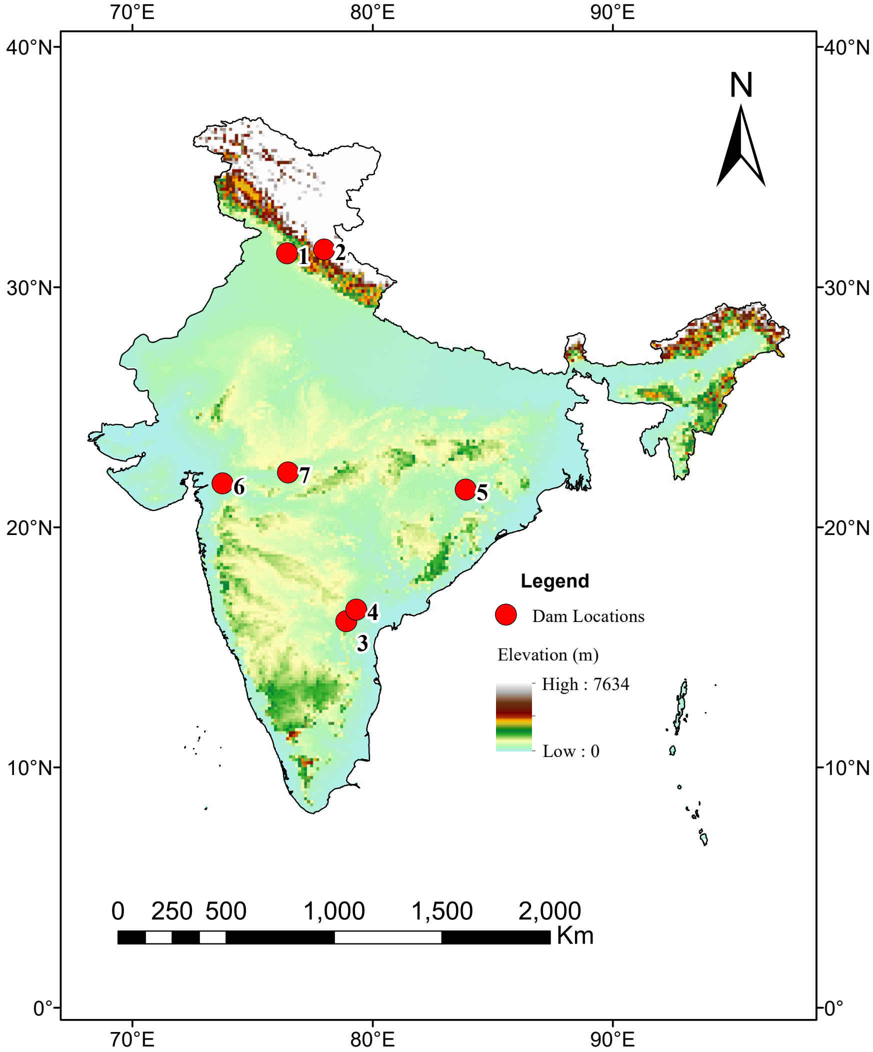


Figure 5.1. Locations of the seven large dams in India.

We obtained observed reservoir storage data for six reservoirs (Bhakra Nangal, Srisailam, Nagarjuna Sagar, Hirakud, Sardar Sarovar and Indira Sagar) from India-WRIS for the 2004-2017 period. The Central Water Commission (CWC) monitors reservoir storage on a weekly basis (http://www.cwc.nic.in/newsite/ReservoirMonitoring.html). Observed reservoir storage data of Nathpa Jhakri reservoir is not available, so we removed that reservoir from the storage monitoring from satellite data.

Table 5.2: Details of the General Circulation Models (GCMs) data used

Model	Name	Developed by	Native resolution	
			Latitude	Longitude
GFDL-CM3	Geophysical Fluid Dynamics Laboratory-Coupled Model version 3	Geophysical Fluid Dynamics Laboratory	2	2.5
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory-Earth System Model		2.0225	2.5
MIROC-ESM	Model for Interdisciplinary Research on Climate – Earth Surface Model	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	2.7906	2.8125
MIROC-ESM-CHEM	Model for Interdisciplinary Research on Climate – Earth Surface Model – Chemistry coupled		2.7906	2.8125
NorESM1-M	Norwegian Earth System Model 1 - medium resolution	Norwegian Climate Centre (NCC)	1.8947	2.5

5.2.1. The Variable Infiltration Capacity (VIC) and Routing model

We used Variable Infiltration Capacity model (VIC: (Cherkauer et al., 2003; Cherkauer and Lettenmaier, 1999; Liang et al., 1996, 1994) http://www.hydro.washington.edu/Lettenmaier/Models/VIC/) to simulate the streamflow for all seven reservoirs. The VIC is a macroscale hydrology model, which simulates daily/sub-daily water and energy fluxes at each grid cell and represents the sub-grid variability of elevation, soil, and vegetation (Gao et al., 2010). Shah and Mishra (2016) calibrated and validated the VIC model against observed data from Central Water Commission (CWC) and Global river discharge database-SAGE at different gauge stations. We have used a calibrated VIC model to simulate the streamflow to these reservoirs as presented in Ali et al. (2018).

5.2.2. Satellite-based Reservoir storage

We used the 8-day Enhanced Vegetation Index (EVI) estimated using 8-day surface reflectance at 250 and 500m resolutions (MOD09Q1) from Land Processes Distributed Active Archive Center (http://lpdaac.usgs.gov/). Since 250m surface reflectance data are only available for red and near infra-red (NIR) bands, the surface reflectance for the blue band was obtained at 500 m and was used to generate 250m information as described in (Huete and Justice, 1999). We used 11 scenes of the 8-day composite from MOD09Q1 in sinusoidal projection (Solano et al., 2010).

We estimated EVI using the following equation (1) (Huete and Justice, 1999)-

$$EVI = 2\,\frac{(\rho_{NIR} - \rho_{Red})}{(L + \rho_{NIR} + C_1\rho_{Red} + C_2\rho_{Blue})} \tag{1}$$

Where ρ is 'apparent' (top of the atmosphere) or 'surface' directional reflectance, L is a canopy background adjustment term, and C_1 and C_2 are coefficients that describe the use of the blue band in the correction of the red band for atmospheric aerosols scattering. The EVI values estimated at 250m spatial resolution ranged between -10000 to 10000, and a multiplication factor (0.0001) was used to the actual values. The quality and pixel reliability of the EVI data was checked using the appropriate flags and pixels with high cloud contamination were omitted from the analysis. EVI, in comparison to NDVI, has an improved sensitivity for high biomass. For the evaluation of the water surface area, we used the enhanced classification method used by Zhang et al. (2014).

We extracted the reservoir surface elevation from ICESat/GLAS data that were obtained from National Snow and Ice Data Center (NSIDC: http://nsidc.org/data/icesat/), which are available from January 2003 to February 2010 (Shuman et al., 2006; Wang et al., 2013; Zhang et al., 2011). The ICESat/GLAS data have 8-day repeat cycle for 20 February 2003 to 21 March 2003 and 25 September 2003 to 04 October 2003 and a 91-day repeat cycle for the rest of the period. The vertical precision of the ICESat/GLAS data is higher than 10 cm (Zwally et al., 2008) with a horizontal spacing of 172 m (Kwok et al., 2004). ICESat/GLAS observed the entire globe 2-3 times a year from 2003 to 2009, which resulted in a maximum of 24 samples (Wang et al., 2011). ICESat/GLA14 Release-34 elevation data were obtained from the National Snow and Ice Data Center (NSIDC). Considering medium spatial resolution (250 m x 250 m) and narrow tracks of the ICESat/GLAS data, we selected at least five along track surface elevation measurements for each reservoir. ICESat/GLAS elevation was estimated after corrections for geoid and offset as described in (Zhang et al., 2011) and (Bhang et al., 2007).

$$ICESat\_elevation = ICESat\_elevation\_measured - ICESat\_geoid - 0.7 \quad (2)$$

With the help of reservoir surface water area from MODIS and reservoir surface water elevation from ICESat/GLAS, we estimated a linear surface area-elevation relationship:

$$E = a \times A + b \quad (3)$$

Where E is the water surface elevation from mean sea level, A is the reservoir surface area, and a and b are constants (Table 5.1).

Due to the limited availability of ICESat/GLAS elevation, reservoir storage from the ICESat/GLAS and MODIS data cannot be obtained directly. Using elevation data from the area-elevation relationship, we estimated reservoir storage using equation (4) as mentioned in Gao et al. (2012) and Zhang et al. (2014).

$$V_{RS} = V_C - (h_C - h_{RS})(A_C + A_{RS})/2 \quad (4)$$

Where V_c, $h_{c,}$ and A_c represent storage, water elevation and area at capacity (maximum storage), and V_{RS}, H_{RS} and A_{RS} are the estimated storage, water elevation and area using remote sensing. The observed storage, area, and water elevation at full capacity for each reservoir are obtained from India-WRIS (http://india-wris.nrsc.gov.in/wrpinfo/index.php).

5.2.3. Change in Reservoir Inflow under Projected Climate

We used the VIC model calibrated using streamflow at observed gauge locations over Indian river basins as described in Ali et al. (2018). We run the VIC model for projected bias-corrected forcing for all five GCMs (GFDL-CM3, GFDL-ESM2M, MIROC-ESM, MIROC-ESM-CHEM, and NorESM1-M) under two scenarios (RCP2.6 and RCP8.5). We used stand-alone routing model (Lohmann et al., 1996) to simulate daily streamflow to the reservoir using daily surface runoff and baseflow generated for each grid cell by the VIC model. More details on routing model used in this study can be found in Lohmann et al. (1996). Further, we calculated the mean of streamflow values generated using the 5 GCMs. We evaluated the percentage change in streamflow for the near (2010-2039), mid (2040-2069) and end (2070-2099) period with respect to historic reference period (1971-2000) for both scenarios.

We used the simulated streamflow data and the monthly release (Rm) of the reservoir to evaluate the reservoir storage using generic regulation rules as described in Hanasaki et al. (2006), which was implemented in Ali et al. (2018). Where monthly release Rm (m^3/s) from a reservoir considering zero irrigation demand is calculated using the method of Hanasaki et al. (2006).

$$R_m = \begin{cases} k_y i_a & c \geq 0.5 \\ \left(\frac{c}{0.5}\right)^2 k_y i_a + \left\{1 - \left(\frac{c}{0.5}\right)^2\right\} i_m & 0 < c < 0.5 \end{cases} \tag{5}$$

Where-

i_m = monthly inflow (m3/s),

i_a = mean annual inflow (m^3/s),

$k_y = S_{beg}/\alpha C$

$c = C/I_a$.

S_{beg} = reservoir storage at the beginning of a year (m^3),

C = maximum storage capacity of the reservoir (m^3),

I_a = mean total annual inflow (m^3/yr),

α = empirical coefficient (Here 0.85)

5.3. Results and discussion

Near-real-time monitoring of the reservoir storage is warranted considering the implications of long-term droughts on water storage and irrigation water requirements. We developed an 8-day near-real-time monitoring system of the reservoir storage for six reservoirs in India while most of the previous efforts were limited to a 16-day repeat cycle (Gao et al., 2012; Zhang et al., 2014). Moreover, the previous studies (Gao et al., 2012; Zhang et al., 2014) were limited to only a few large reservoirs. Since our objective is to provide near-real-time reservoir storage monitoring, we further bias-corrected the satellite-based reservoir storage assuming that there is only a systematic bias. Bias-correction was performed using the simple ratio of mean observed and satellite storages for each observation day of a year during the training period (2002-2009). Then the same correction factor (s) was applied for the testing period (2010-2017). We find that our satellite storage compares well with the observed storage (Fig. 5.2) with a correlation coefficient value (R^2) greater than 0.5 except for Sardar Sarovar reservoir. Low correlation in case of this reservoir can be attributed to its small spatial extent and, the possibility of developing mixed pixel effect.

We notice a higher temporal variability in satellite-based storage due to higher variation in surface area estimates and other uncertainties (surface area, elevation, depth-area relationship) associated with MODIS EVI and ICESat/GLAS data (Gao et al., 2012; Zhang et al., 2014). Reservoirs with smaller surface area may experience a considerable variation due to relatively coarser spatial resolution (250m), which may create a mixed pixel effect for the boundary pixels (Kaptué et al., 2013). Zhang et al. (2014) reported that the uncertainty in MODIS surface area estimates is higher than the uncertainty in ICESat/GLAS elevation. Zhang et al. (2014) reported that uncertainty was less than 10% in the MODIS surface area. Uncertainty and relatively poor storage estimation of small reservoirs may be attributed to errors in surface-area estimation due to coarse resolution. Overall, we find that our satellite-based storage monitoring successfully captures the temporal variability of the observed storage. This real-time monitoring system can be valuable to manage the reservoir storage during the drought and flood periods, which often hampers reservoir operation in India.

One of the major questions that attract the scientific community is—if the reservoir storage has been changing in India. To answer this, we have estimated trend in the reservoir storage using the non-parametric Mann-Kendall trend test and Sen's slope method (Hamed, 2008; Hamed and Ramachandra Rao, 1998) (Fig. 5.2). We examined the observed monthly storage variation of six reservoirs from 2004 to 2017 based on data availability. We find that Bhakra Nangal, Indirasagar, and Sardar Sarovar reservoirs are showing a positive trend in mean annual storage with 5% of significance level while Nagarjuna Sagar and Srisailam are showing a significant negative trend with 5% of significance level. There is no significant change in the annual storage of Hirakud reservoir (Fig. 5.2). Therefore, based on the limited data we find that there is a mix trend in the storage of the selected reservoirs.

Next, we simulated streamflow upstream of the selected reservoirs using the bias-corrected climate data from the five GCMs and two RCPs. We took the ensemble mean of streamflow values generated for each GCM for both warming scenarios. We analyzed the change in mean annual streamflow across our study period from 2010-2099. Figure 5.3 shows mean annual streamflow simulated at the upstream of reservoirs for RCP 2.6 (Fig 5.3a-i) and RCP 8.5 (Fig 5.3h-n). We find that all the seven reservoirs are projected to receive increased streamflow under the warming climate (Fig. 5.3), which is consistent with the findings of Ali et al. (2018). On the other hand, we find only a moderate change in projected streamflow for Bhakra Nangal and Nathpa Jhakri reservoirs under the RCP2.6 scenario (Fig. 5.3a, 5.3c). However, under the high warming scenario (RCP 8.5) streamflow is projected to increase substantially for Bhakra Nangal and Nathpa Jhakri reservoirs (Fig. 5.3h, i).

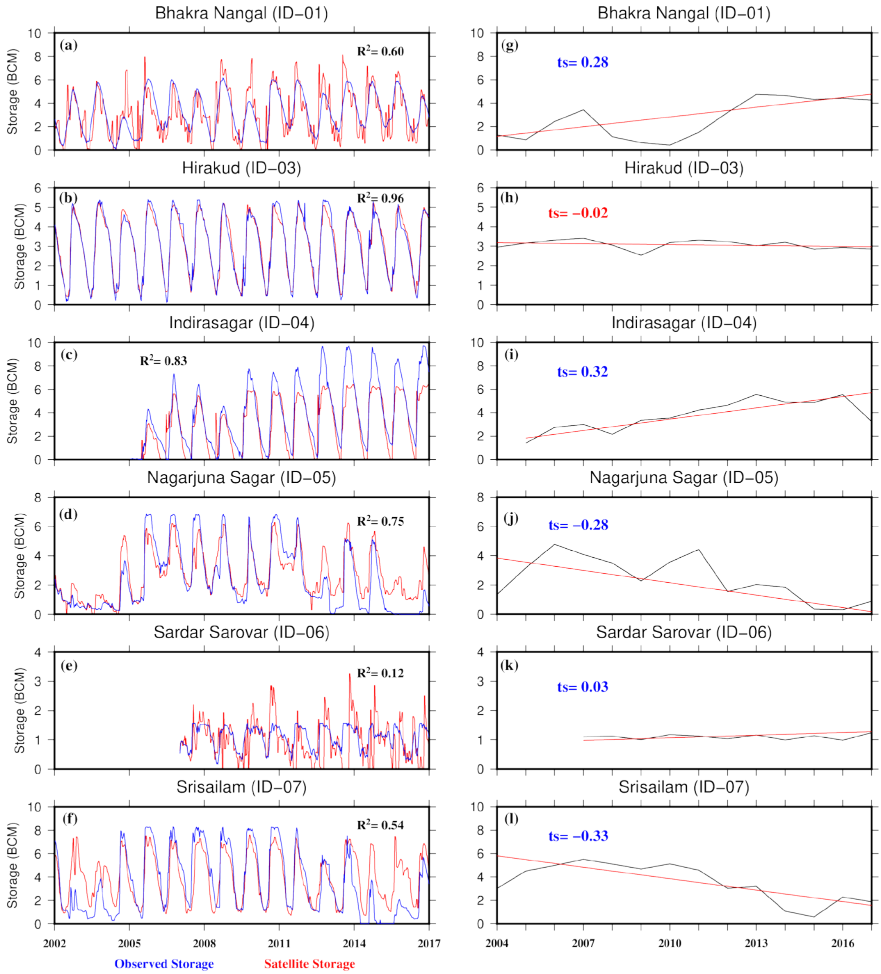


Figure 5.2. **(a-f) Comparison between observed and satellite storage for 6 reservoirs, (g-l) Mean annual reservor storage time series from 2004-2017. Here 'ts' is trend slope.**

The study conducted by Palazzi et al. (2013) on the trend in streamflow generated at the upstream of reservoirs in the period from 1951-2007 reports a significant reduction in streamflow for Nathpa Jhakri reservoir while moderate decline was observed in the rest five reservoirs. They observed a significant increase in precipitation and a moderate increase in temperature in the catchment area of Nathpa Jhakri reservoirs during this period. While substantial warming is projected for all the catchments in the future climate, relatively high warming (6.25 +1.5° C) is predicted in the catchment of Nathpa Jhakri and Bhakra Nangal (Lutz et al., 2016; Rajbhandari et al., 2014). Also, Nathpa Jhakri and Bhakra Nangal reservoirs have high contribution from snowmelt. Ali et al. (2018) found a decrease in snow cover & snow depth in the catchment areas of these reservoirs which is consistent with the pattern observed from 1922-2004 (Bhutiyani et al., 2008). Hence, the absence of a positive trend in streamflow in these reservoirs may be attributed to relatively higher warming and reduction in snowmelt contribution in the future climate (Immerzeel and Bierkens, 2012; Lutz et al., 2016; Mishra and Lilhare, 2016).

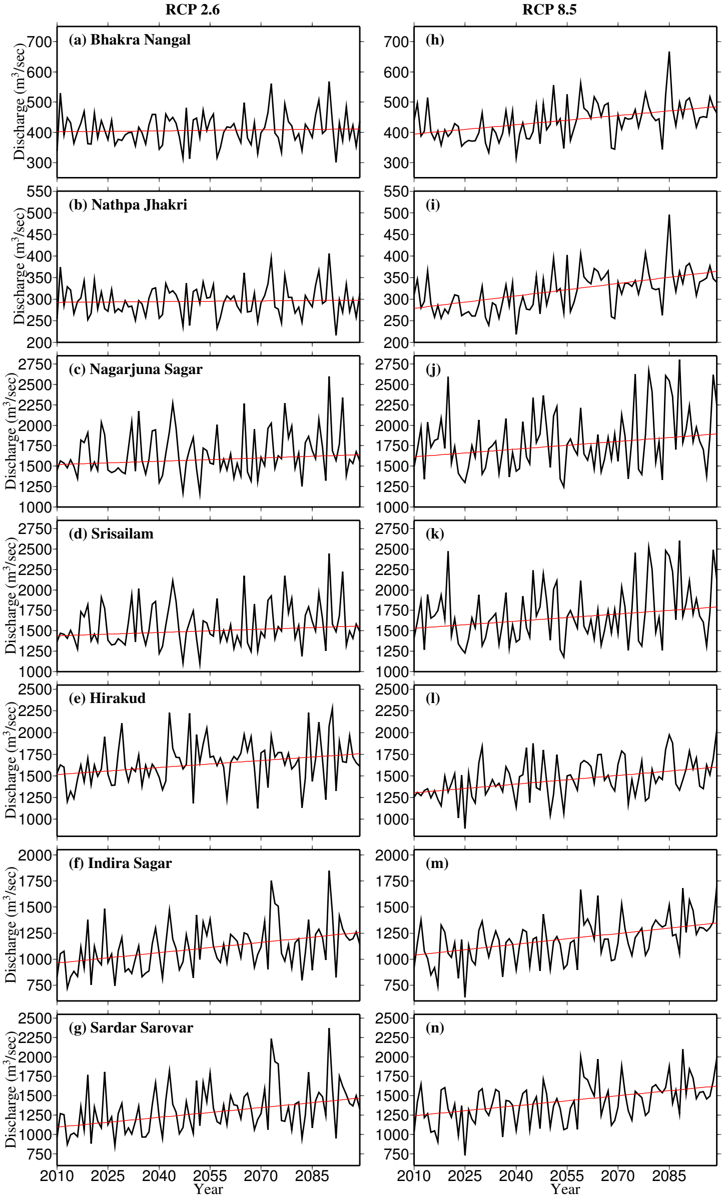


Figure 5.3. Projected annual mean streamflow simulated upstream of reservoirs from the year 2010 to the year 2099 for (a-g) RCP2.6 and (h-n) RCP 8.5 scenarios.

For the better understanding of change in streamflow with respect to the reference period (1971-2000), we evaluated percentage change in 30-year moving mean streamflow from 2010 to 2099. We find that all the reservoirs in both scenarios except Bhakra Nangal and Nathpa Jhakri under low warming scenarios show a significant increase in streamflow with respect to the reference period (Fig. 5.4) which is consistent with the findings of Ali et al. (2018).

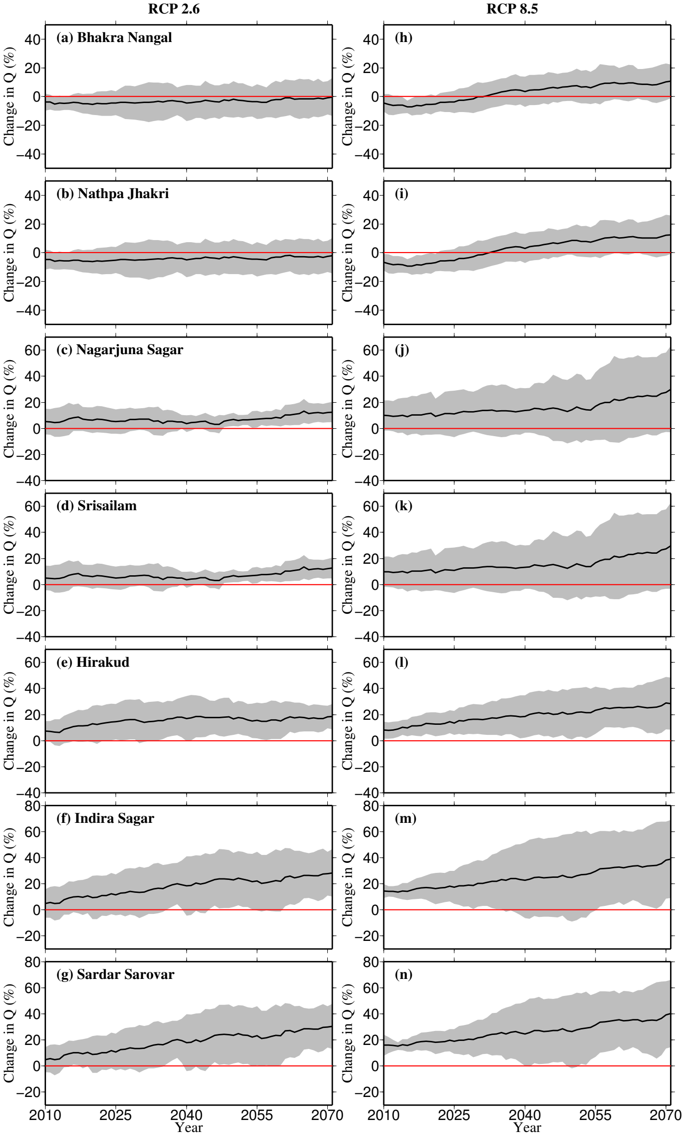
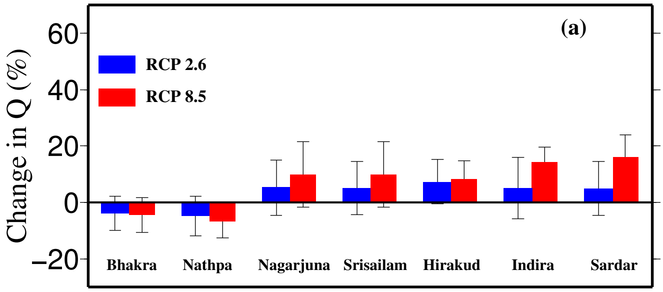


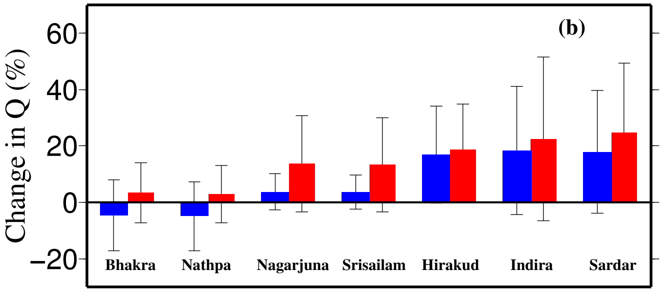
Figure 5.4. Percentage change in 30 year moving mean streamflow with respect to the base period of 1971 to 2000 for (a-g) RCP2.6 and (h-n) RCP 8.5. Here grey part shows standard deviation.

Again we compared the percentage changes in streamflow for the near, mid, and end terms of the 21st century with respect to the historical reference period. We find that Bhakra Nangal and Nathpa Jhakri reservoirs show a decrease in streamflow for near, mid and end period under low warming scenarios, and for near period under high warming scenario (Fig. 5.5). In all other conditions, streamflow is projected to increase substantially (Fig. 5.5). Also, we found that the intermodal variability in streamflow increases towards the end of the 21st century resulting in an increase in uncertainty in the streamflow predictions (Fig. 5.5).

Near Period (2010–2039)



Mid Period (2040–2069)



End Period (2070–2099)

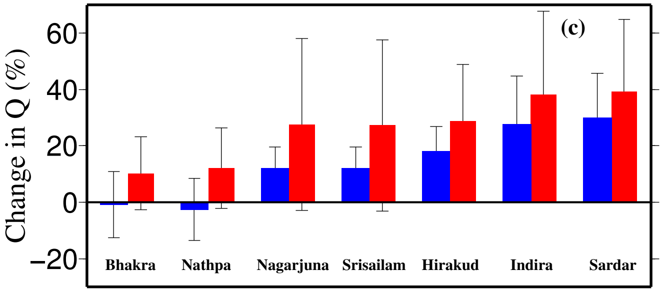


Figure 5.5. **Percentage change in streamflow for (a) near period (2010-2039), (b) mid- period (2040-2069), and (c) end period (2070-2099) with respect to base period (1971-2000) for RCP2.6 and RCP 8.5. Uncertainity is shown in terms of statand deviation.**

We found that by the end of the 21st century mean annual streamflow for all the reservoirs is projected to increase with respect to the reference period (Fig. 5.4 and Fig. 5.5). The influx to reservoirs in the central and southern part of India is predominantly contributed by monsoon season precipitation, which is found to increase in the future projections. (Kumar et al., 2006; Menon et al., 2013). Monsoon season precipitation plays the major role that decides the streamflow and water availability in the country (Mishra et al., 2017, 2016).

Sedimentation is one of the main problems for the life of the reservoirs. Sedimentation in the reservoir is also the main challenge to measure reservoir storage accurately. Srisailam is showing more than 0.8 percent annual loss of storage capacity (*Compendium on silting of reservoirs in India*, 2015) (Table 5.3). Today, the worldwide yearly mean loss of storage capacity due to sedimentation is higher than the increase of capacity by the construction of new reservoirs for various purposes (Schleiss A. J., 2013). In this chapter, we do not discuss the preventive measures for the sedimentation.

Table 5.3: Details of sedimentation of 7 selected large Indian reservoirs

S. No.	Res. Name	Year of first impoudment	Designed Rate of Siltation (Th. Cu.m/ Sq.km./ Yr)	Total Number Of surveys (year of last survey)	Observed Rate of siltation (Th. Cu.m./ Sq.km./ yr)	Total loss of capacity up to the last survey	Percentage loss of capacity up to the last survey	Percentage annual loss of capacity	Total Loss (%)
1	Bhakra Nangal	1958	0.429	32(2012)	0.682	2098.34	21.26	0.39	23.01
2	Nathpa Jhakri	-	-	-	-	-	-	-	-
3	Srisailam	1976	0.079	3(2011)	0.36	2613.97	29.96	1.2	49.2
4	Nagarjuna Sagar	1967	0.215	2(2009)	0.301	2716.96	23.52	0.56	28
5	Hirakud	1957	0.25	5(2000)	0.616	2210.21	27.27	0.63	37.8
6	Sardar Sarovar	-	-	-	-	-	-	-	-
7	Indirasagar	-	-	-	-	-	-	-	-

5.4. Conclusions

Satellite data from MODIS and ICESat at 250m and 8-day temporal resolution successfully captured the temporal variability of observed storage. Bias-correction of satellite-based reservoir storage further improved the performance. Here R^2 is calculated after removing seasonality from observed and satellite storage data. Satellite-based reservoir storage estimates after the bias-correction provide promising results that can be used for near-real-time monitoring. Our findings demonstrate the potential of satellite-based monitoring in India that can be valuable for water management. The performance of satellite-based monitoring can be further enhanced based on the availability of higher (spatial and temporal) resolution data.

Nathpa Jhakri and Bhakra Nangal reservoirs are only reservoirs out of 7 reservoirs which get streamflow from snow as well. Under the projected future climate snowfall is projected to decline while rainfall is projected to increase (Ali et al., 2018). In the past, in Satluj river basin the contribution of snowmelt to the streamflow is declined during 1922-2004 (Bhutiyani et al., 2008). As streamflow of these basins is more dominated by rainfall in future climate, the overall streamflow is projected to increase. Central and southern Indian reservoir's streamflow is monsoon precipitation dominated. These reservoirs are projected to increase in streamflow, which is mainly because of an increase in the monsoon season precipitation (Chaturvedi et al., 2012; Kumar et al., 2006; Menon et al., 2013).

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Chapter 6

River Response to Climate Change: Geomorphic Approach to Understand Past Responses and River's Future

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Abstract

Impact of climate change on natural systems is a major challenge in near future. It can also cause significant changes in river processes and appearance (morphology) by modulating water and sediment flux, which can finally affect river health. However, river response to climate change is not a linear phenomenon. It is characterised by nonlinear and complex response. Fundamental understanding of river processes and application of basic concepts related to cause-effect relationship is needed to understand river response to climate change in past or future. River responses to palaeoclimatic changes in geological past suggest that rivers in different geographical settings responded differently to similar climate change events. Currently, climate models and hydrological models are available to project future changes in river fluxes. There is still a need of geomorphological model(s) to project future of river systems through hydrology-morphological relations at cross-over of scales. Integration of all these model will help to define future trajectory of a river system in response to future climate change.

6.1. Introduction

Rivers are natural conduits of freshwater, sediments and nutrients, which support complex biodiversity within its riverscape. Rivers are also lifelines for civilisations and govern societal well-being. Assessment of river condition to support biodiversity in its riverscape and its ability to sustain societal well-being is defined as 'river health' (Karr, 1999; Norris and Thoms, 1999). A river with good health should have sufficient flow to carry out its physical, chemical and biological functions. Fluvial flow regime indicates the behaviour of its generalised flow pattern from seasonal to annual timescale. Changes in flow regime may affect river health by further causing changes in physical (morphological) and biological (ecological) characteristics of a river.

Climate change disturbs the flow regime and transfers it from one stable state

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to another (Krasovskaia and Gottschalk, 2002). Flow regime and modified hillslope processes further cause change in the sediment flux of a river system. Flux variability leads to change in channel morphology, which is defined as the form and behaviour a river system (Brierley and Fryirs, 2005; Jain and Sinha, 2004; Sinha et al., 2005). These hydro-morphological changes in a river system in-turn governs physical habitat for biodiversity in a river system, which finally defines the ecological state of a river (Maddock, 1999). These physical habitats constitute the fundamental units to analyse and manage good river health (Harper et al., 1995). Hence, changing patterns of climate not only affects the flow regime but also governs the river ecosystem and river health, which will have a significant impact on societal well-being (Fig. 6.1).

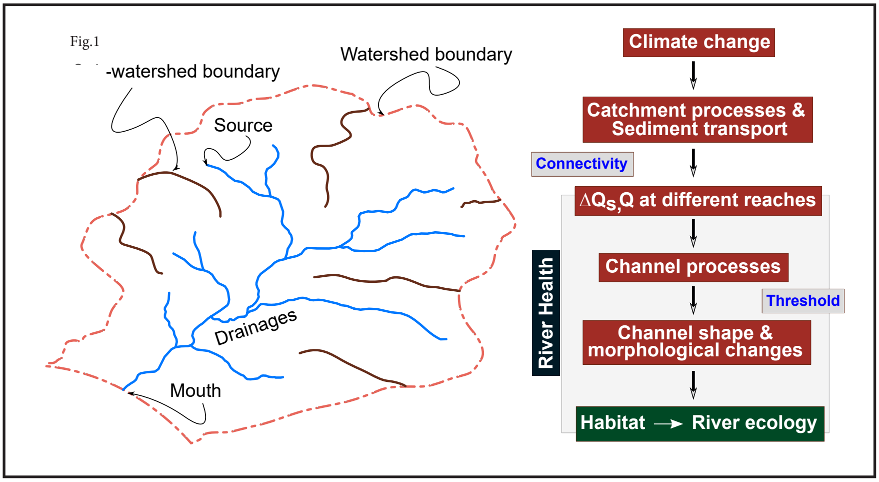

Figure 6.1: A conceptual figure showing impact of climate change from basin scale to reach scale and significance of geomorphic concepts in understanding the cross-scalar linkages. Climate change affects the whole river basin, which leads to variability in water and sediment fluxes at different reaches. Flux variability leads to physical and ecological changes, which finally affects the river health at different reaches.

River systems are now viewed as an ecosystem entity (Brierley and Fryirs, 2005). This highlights the significance of understanding hydrology-morphology process interaction, as hydro-physical characteristics finally define the ecological state of a river system. Hence, an in-depth knowledge of river response to climate change requires an understanding of process based interaction between flow regime and the physical state of a river. A flow-sediment balance diagram (after Lane, 1955) provides a simplified explanation for process variability and the role of major governing factors.

River processes in a channel reach are governed by driving forces characterised by water discharge flowing on a given slope and resisting forces governed by calibre and volume of available sediment with a given channel roughness condition (Fig. 6.2). Variability in these processes may affect channel processes and physical structure of a river system. Climate change affects a river system by altering water and sediment fluxes in channel reaches. Further, sediment in a channel reach are entrained in the river system from different sources and transported in accordance with available power. The source regions of the fluvial systems are strongly controlled by hillslope erosion and these eroded materials contribute to the erosion of lower order drainage systems. The channel morphology is strongly controlled by influx of the sediments from the basin area. Therefore, river response to climate change is governed by sensitivity of these processes to climatic parameters, which may vary from one river basin to another basin. Indian river system in different climatic settings can be characterised by spatio-temporal variability of discharge, sediment load and channel characteristics in response to climate change.

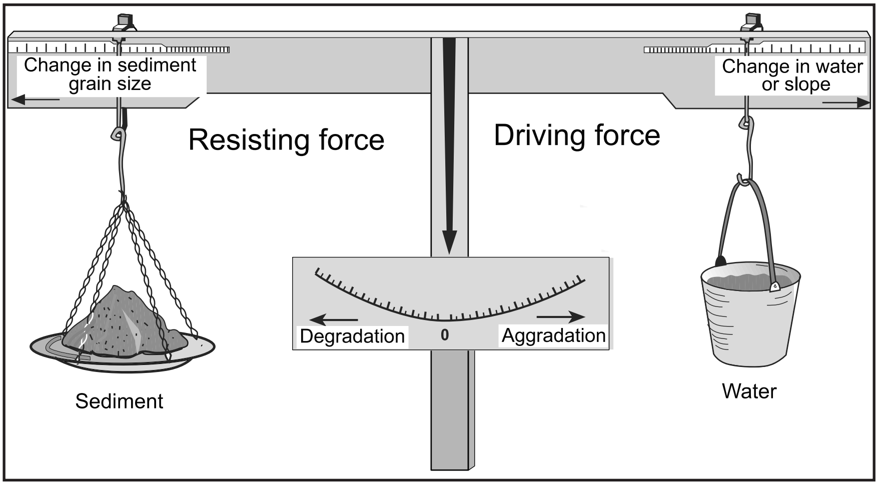

Figure 6.2: Lane's balance diagram (Lane, 1955) showing the river processes as function of water discharge, channel slope (as representative of driving force) and sediment load and calibre (as representative of resisting force). Climate change events affect both driving force (through change in water discharge) and resisting force (through change in sediment load and calibre). Hence, river response to climate change will always be complex and will depend on the relative increase of sediment load with respect to discharge in different physiographic settings (channel slopes) (Modified from Brierley and Fryirs, 2005).

Distinctive climatic forcing of water discharge and sediment load is a major challenge due to the high socio-economic and ecological dependencies on water and sediment. This manuscript will aim to understand river responses to climate change by considering past examples and future projections. It describes major concepts of fluvial system with reference to climatic forcing of river systems. River responses to climate change were analysed by considering the present day climatic setting in different river basins. Past data and present understanding of river processes were used to (a) project the future of Indian rivers and (b) to highlight the major gaps in our understanding of river response to climate change for the near future.

6.2. Indian River systems and different climatic zones

River response to climate change may vary from one climatic setting to another. The Indian climate system is primarily divided into 7 major sub categories according to the Köppen classification (Peel et al., 2007). However, the major river basins in India does not essentially follow the distinct climatic zones and rather share different climatic regimes (Fig. 6.3). Different sections of the drainage basins are affected by differing forcing which produce local dissimilarities of hydrological processes. There are about ~120 major and medium size river basins in India (Mirza et al., 2003). The major drainage basins in India are divided into 4 major systems namely (a) Himalayan river systems (b) East flowing Peninsular river systems (c) West flowing Peninsular river systems (d) Rivers in the drier north-western India (Fig. 6.3a). The details of the major river basins in these different zones are provided in Table 6.1.

The river basins are also characterised by significant variability in topographical and rainfall variability (Fig 6.3a, b). The Himalayan rivers are characterised by high relief terrain and higher rainfall in comparison to other river systems. Hence, Himalayan rivers are characterised by higher energy and will be more sensitive to climate change in comparison to other river systems. In general, rainfall is minimal in west flowing Peninsular rivers and in the drier north-western India. These rivers may show higher resilience in response to climate change.

River basins in India are characterised by different climatic conditions (Fig. 6.3c). The Himalayan river systems are generally occupied by the Cwa and Csc climate system where the majority of discharge and sediment load is transported during the monsoon. However, a substantial amount of the discharge is driven by glacial melt during the ablation period. On the contrary, the majority of the east-flowing peninsular river systems displays Aw type climate where the hydrology is strongly controlled by the rainfall distribution and duration. The west-flowing river basins that flank the Western Ghat are dominated by high monsoon rainfall and discharge and characterised by Am climate. Rivers in the drier northwestern India flow through the Bsh to Bwh of climate where rainfall amount and intensity is very less especially in the downstream part of the river basins.

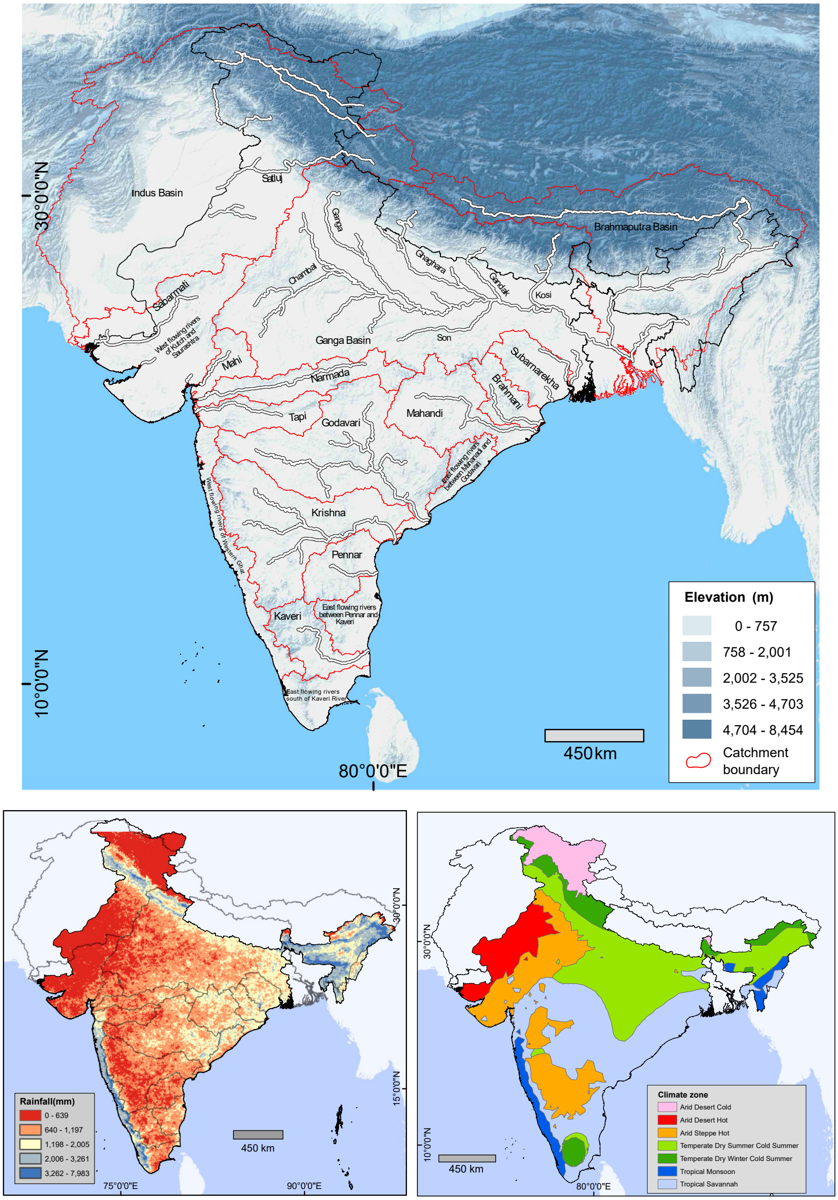

Figure 6.3: **(a) Major rivers basins superimposed over the relief map of India. Different physiographic settings of river basin govern river processes, morphology and sensitivity to change in response to climate change. (b) Indian river basins are characterised by significant spatial variability in rainfall pattern, which also reflects in the river processes and morphology. (c) Distribution of Indian river basin in different climatic zones (after Peel et al., 2007). Position of river basins in different climatic zones indicates that river response to any climate change event may be different.**

Table 6.1: Indian river basins and distribution of different climatic zones

River system	Drainage basins	Major climate type	Climate code
Himalayan river system	Ganga	Temperate dry and cold summer	Csc
	Brahmaputra (within India)	Temperate dry and cold summer	Csc
	Indus (within India)	Arid cold desert, temperate dry and cold summer, Arid desert hot	BWk, Csc, BWh
East flowing Peninsular river system	Subarnarekha	Tropical Savannah	Aw
	Brahmani	Tropical Savannah	Aw
	Mahandi	Temperate dry and cold summer, Tropical Savannah	Csc, Aw
	Godavari	Tropical Savannah	Aw
	Krishna	Arid Steppe hot	BSh
	Pennar	Arid Steppe hot	BSh
	Kaveri	Tropical Savannah, Temperate dry winter, hot summer	Aw, Cwa
	East flowing rivers between Mahanadi and Godavari	Tropical Savannah	Aw
	East flowing rivers between Pennar and Kaveri	Tropical Savannah	Aw
	East flowing rivers south of Kaveri River	Tropical Savannah	Aw
West flowing Peninsular river systems	Narmada	Tropical Savannah	Aw
	Tapi	Arid Steppe hot	BSh
	West flowing rivers of Western Ghat	Tropical monsoon	Am
Rivers in the drier north-western India	Mahi	Tropical Savannah	Aw
	West flowing rivers of Kutch and Saurashtra	Arid Steppe hot, Arid desert hot	BSh,BWh

6.3. Geomorphic concepts to study cause-effect relationship in a river system

A river system may undergo different kinds of changes in response to climate changes, however response of different rivers to the same climate change may vary. Understanding of such cause-effect relationship is based on some fundamental concepts (Jain et al., 2012). These are as follows.

6.3.1. Equilibrium

Channel processes and morphology are governed by equilibrium between driving and resisting forces in a river system. Driving force is mainly represented by discharge and channel slope, while resisting forces are governed by sediment flux and its calibre. Driving force is governed by either stream power (Ω) at reach scale or specific stream power (ω) at cross-section scale or shear stress (τ) at site scale (Appendix - 1). All these parameters are related and are represented as–

$$\Omega = \gamma.Q.s$$
$$\omega = \gamma.Q.s/w$$
$$\tau = \gamma.d.s$$

where, Q – discharge, s – energy slope which is generally considered equivalent to channel slope, w – channel width, d – average channel depth.

Climate change disturbs the river system by disturbing its equilibrium. Climate change may change driving forces by changing discharge, energy slope, channel width and channel depth. Variability in sediment erosion and transportation processes in response to climate change causes changes in resisting forces. Equilibrium in river system is finally governed by the relative variability in these parameters, which may be different from river to river or even from one reach to another reach in a same river system. Hence, understanding the equilibrium is the key to understanding river response to climate change.

6.3.2. Geomorphic Threshold

Geomorphic threshold is defined as the condition of significant landform change (Schumm, 1979). A change in a river system may either be governed by external controls like climate change or by internal adjustments of its various parameters. These are defined as external and internal thresholds respectively. Climate change is one of the important sources of external control that shifts any system from one regime to other. Any change in the boundary conditions is primarily a product of the change in water and/or sediment flux. A change in climate primarily leads to change in the amount of water within the drainage system. An increase or decrease in the discharge will lead to difference in the grain size distribution of the deposits. In high energy condition, during enhanced monsoon, the threshold for entrainment of sediment transportation changes from smaller to larger grain sizes. Larger grain size associated with higher slope tends to metamorphose a channel from meandering to braided river. Although the effect of climate change on sediment characteristics is prevalent across the channel types, the metamorphosis from one form to another mostly occurs in the alluvial channels (Schumm, 1985). Therefore, flow regime, sediment delivery ratio and topographic setting that governs channel slope defines the threshold of any river system. Substantial changes in these elements result in the change in morphological characteristics of the channels that are defined by different threshold conditions.

Threshold conditions cause nonlinearity in the physical state of river system, as river response to flux variation will not be linear across the threshold (Phillips, 2003). In general, geomorphic equilibrium will be different across a threshold value. Hence, variability in parameters across a threshold may also cause change in equilibrium condition. Geomorphic changes in any river system are not gradational changes. However, the physical appearance of river system changes significantly only after the breaching of a threshold condition. Hence, flux change within threshold condition will not make significant geomorphic changes, but similar flux change across the threshold value will cause significant change in morphological state (Jain et al., 2012) (Fig. 6.4).

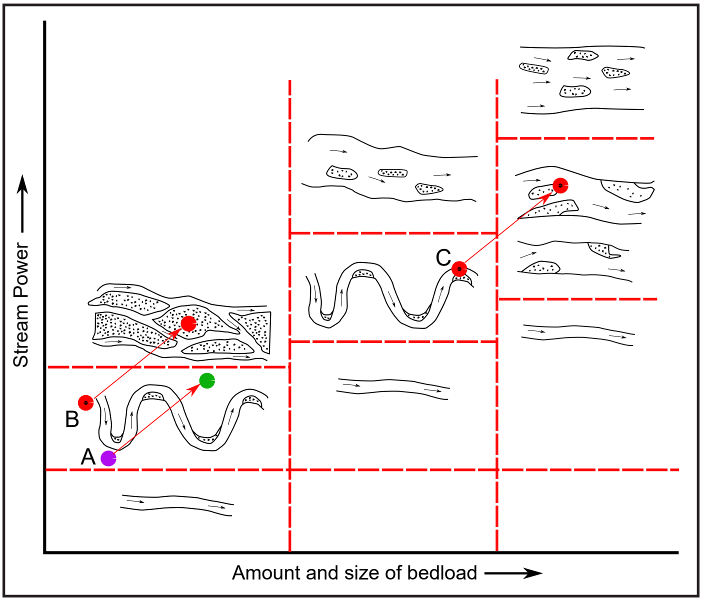

Figure 6.4: **Figure showing significance of threshold condition in defining the physical (morphological) changes in a river system. Morphological change occurs, only when fluxes will cross the threshold condition. Hence, river response to climate change will vary from reach to reach. In the figure, the rivers A, B and C have experienced similar impact of climate change (similar change in fluxes). However, river B and C will be changed from meandering river to braided river, while river A will be the least affected and will remain a meandering river. (Variability in channel patterns were mapped from Ferguson, 1987)**

6.3.3. Geomorphic Connectivity

River processes are governed by basin scale processes and hence a river basin is the fundamental unit for river studies (Chorley, 1969). Geomorphic connectivity is defined by the nature of connectedness between different landforms of river basin (Brierley et al., 2006; Jain and Tandon, 2010). It may be defined as functional connectivity or structural connectivity on the basis of the connection between processes or physical connectedness (Jain and Tandon, 2010; Wainwright et al., 2011). For example, the role of hillslope erosion processes on channel silting and flood hazard at downstream reaches is a connectivity problem. The presence of a number of depositional landforms, namely floodplain, river terraces, alluvial fans, reduce connectivity between hillslope and channel. In a disconnected system, eroded sediments from hillslopes will not quickly reach the channel, hence hillslope processes will have limited or no contribution on flood hazards at downstream regions.

Understanding of connectivity is vital to analyse river responses to climate change. Increase in precipitation and enhanced hillslope erosion can occur through increase in landslides, debris flows and soil-erosion processes. However, the impact of these upstream processes is governed by connectivity. The river channels will be affected only when the drainage basin is geomorphologically connected (Fig. 6.5).

6.3.4. Geomorphic Sensitivity

Geomorphic sensitivity defines the stability and resilience of the physical state of a river system in response to external forcing like climate change (Brunsden, 2001). River responses to climate change vary from river to river and may even vary from reach to reach in the same river. River sensitivity is a function of threshold conditions and geomorphic connectivity. A river will be sensitive to climate change if its geomorphic system is close to threshold condition. In such a scenario, minor change in water or sediment fluxes will cause significant change in channel morphology (Fig. 6.4). Further, flux variability in a given reach will be governed by hillslope-channel connectivity. Rivers will be sensitive in a connected system, as most of the sediment eroded from hillslopes will reach to the channel reaches, however a disconnected system will be least affected by climate change (Fig. 6.5). Further, sensitivity of river system may vary across the tributaries and reaches, hence different parts of a river system will respond differently to the same climate change. This scenario is a complex response to external changes, which is defined by inconsistency in output (new physical state) at different spatio-temporal scales in response to the same input (climate change forcing) (Jain et al., 2012; Phillips, 2003). Therefore, quantitative estimation of geomorphic sensitivity to flux variability is a major research question in defining the impact of climate change on river systems (Jain et al., 2012).

6.4. River response to climate change

Climate change is a dominant factor that causes changes in river regimes by modulating the discharge and sediment load in any river system. These changes are generally gauged from sedimentary archives which record past changes in the climate system as any system tends to adjust to its present boundary conditions. The majority of changes in the fluvial systems are generally linked to change in the Indian Summer Monsoon which affects the hydrological sensitivity of the drainage system.

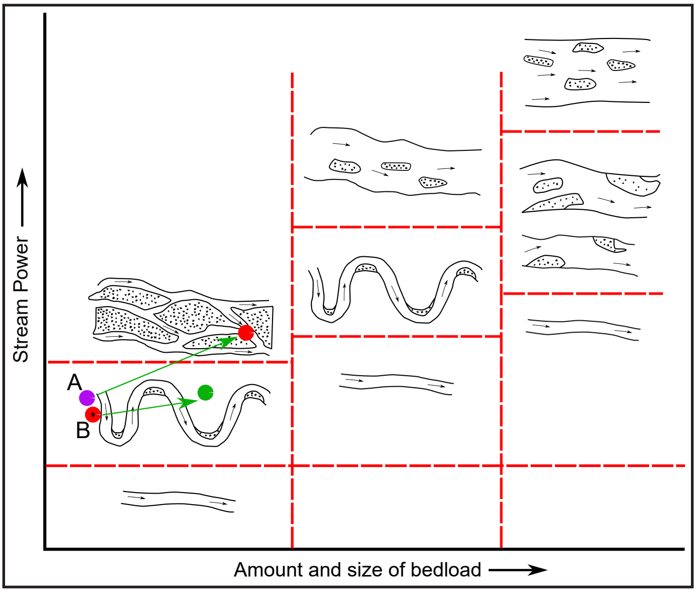

Figure 6.5: Figure showing impact of geomorphic connectivity on different river response to the same climate change event. Both, rivers A and B are characterised by similar channel pattern and similar distance from threshold condition, though geomorphic connectivity in river A is better than river B. In this case, flux variability at a given reach in River A will be less in comparison to reach in river B. Hence, river A will be more sensitive and will change to new morphological condition, where river B will remain more resilient to the same climate change. (Variability in channel patterns were mapped from Ferguson, 1987)

6.4.1 Past climate change and river response

Indian sub-continent has experienced late Quaternary fluctuations in climate due to strong oscillation of monsoon. Most of the palaeoclimatic records are based on marine cores. However, recent data from glacier cores and land surface (lake sediment and carbonate deposits in caves) provided more information about major events in the land surface. ~72 ka there was a phase of enhanced monsoon, which was observed in the sedimentary archives in the intermontane basins in Himalaya. However, in the arid region ~74 ka has been characterised as weakening of monsoon phase. A general strengthening of the monsoon activity by enhanced moisture condition is ubiquitous both in the Himalayan highlands and in the western arid region. Post ~30 ka can be characterized by strong decline in the monsoon activity due to initiation of Last Glacial Maxima (LGM). Post LGM, monsoon intensification around 12-10 ka was a major event of climate change towards wetter phase. Although there is coherence in monsoon activity in the Indian Peninsula, strong anomalies can also be noted from the table 6.2.

Table 6.2: Major events of climate change in different parts of India in last 100 ka

Himalayan River		Peninsular River		Western Arid Rivers	
Time (ka)	Pattern of Climate Change	Time (ka)	Pattern of Climate Change	Time (ka)	Pattern of Climate Change
~72	Enhanced summer monsoon[1]	85-72	Low monsoon activity[4]	~74	Weakening of monsoon[7]
58–30	Enhanced Summer monsoon[2]	31-21	Reduced monsoon activity[4]	50 –30	Strengthening of monsoon[7]
30 – 23	Decline in monsoon activity[3]	10 -4.5	Strong monsoon[5,6]	30 – 15	Weak monsoon[7]
20–16	Weak summer monsoon[1]			~12	Strong aridity[7]
15-5	High monsoon activity[3]				

1. Suresh et al. (2007), 2. Benn and Owen (1998), 3. Gibling et al. (2005), 4. Gibling et al. (2008), 5.Kale and Rajaguru (1987), 6. Kale et al. (2010), 7. Jain and Tandon, (2003)

River responses to palaeoclimatic changes were recorded from different parts of India. The nature of response varies from one river basin to another river basin. The following sections discuss a few case studies to highlight the differences and complex nature of river response to climate change in the past.

Himalayan river systems

Rivers in the Himalayan region responded differently to the same climate change events. For example, Marsyandi river in the Nepal Himalaya aggraded in response to monsoon intensification around 10 ka (Pratt et al., 2002), while the Yamuna river in the Sub-Himalaya was characterised by degradation in response to the same climate change (Dutta et al., 2012). The variability was due to higher erosion and sediment supply in the Marsyandi river basin in response to the same climate change (Jain et al., 2012). Increase in channel deposition in response to monsoon intensification was also recorded from other river systems in the Himalaya. This intensified monsoon phase was also the causal factor for fivefold increase of sediment transport and deposition in the lakes in NW Himalaya (Bookhagen et al., 2005). Similar, response of channel aggradation was recorded in the foothill region, where rivers in Himachal Pradesh are characterised by high sediment supply during enhanced monsoon and lower sediment supply in periods of weakened monsoon intensity (Dey et al., 2016). Suresh et al. (2007) suggested that the two major aggradation phases of fan deposit in Pinjor Dun in Siwaliks (~83 and 72 ka) was discontinued by a high monsoon time at ~72 ka. However, in the eastern part of Dehradun, the incision of terraces was strongly linked to aggravated erosion due to the enhanced monsoon period at ~11 and 6 ka (Sinha et al., 2010). Wasson et al. (2013) reconstructed 1000 year palaeoflood history for the Upper Ganga river basin on the basis of written reports, lithostratigraphy and sedimentology. They suggested variable frequency and clustering of flood events, which were caused by variation of monsoon rainfall.

River response to climate change is recorded in the alluvial part of any river basin, as the thick sedimentary archives can be used to decipher the complex history of river processes. Srivastava et al. (2003) suggested a strong linkage between the climatic fluctuations and the sedimentation in the northern Ganga plain. Sedimentary deposits along the Yamuna river representing succession from 90 ka provide information about incision and aggradation of channel bed in response to different events of climate changes (Gibling et al., 2005). Major channel incision and widespread badland formation occured during ~15-5 ka in response to enhanced monsoon intensification after the LGM. Further, similar thick sediments along the Ganga River deposited at ~100 ka suggested five major aggradational events in the Ganga valley in response to climate change. These main aggradation events in the Ganga valley correlate well with declining monsoon strength, which resulted decline in river carrying capacity. Major channel incision events were initiated during monsoon intensification highlighting the impact of enhanced stream power on river process (Roy et al., 2012).

East flowing Peninsular river systems

Kale and Rajaguru (1987) observed that major aggradation in Peninsular rivers occurred between ~30-10 ka with incision in the interglacial between 10-4 ka. They suggested that the change from the coarse grain bedload regime (~30-17 ka) to suspended load dominated deposits was a marker of the low monsoon activity during the end of Pleistocene. Additionally, the early Holocene fluvial rejuvenation and incision indicate a strong monsoon phase with increased discharge and stream power. Using stratigraphic and chronological methods in the southern margin of the Ganga plain, Gibling et al. (2008) identified a strong and sustained monsoon (between ~85-72 ka) indicated by mixed load meandering rivers. This area witnessed fewer vigorous river processes and floodplain gully erosion at ~31-21 ka in response to reduced monsoon activity around the (LGM). In the same region, other studies also showed that a widespread phase of aggradation took place between 39±9 to 16±3 ka which is directly linked to the weak summer monsoon and indicates the start of warmer and wetter conditions (Williams et al., 2006).

High magnitude floods have been generally associated with atmospheric depressions created by monsoon. Therefore, the clustering of paleoflood events also shows a direct relation with the intensification of the monsoon (Kale, 2007). In Peninsular India, Kale et al., (2010) first reported discrete Holocene floods at ~8-2 ka in the Kaveri river basin. Such events were not present anywhere in the rivers originating in the Western Ghat escarpment. They argued that the initiation of the flash floods was concurrent with the south-ward migration of the ITCZ and a steady decrease of monsoon precipitation starting at ~7.8 ka.

West flowing Peninsular river systems

The west flowing rivers, such as Narmada and Tapi rivers, responded to climate change through distinct phases of deposition and erosion. Sedimentary archives in the upstream reaches of the Narmada River suggest that it was a sand bed meandering river in the Late Pleistocene (Gupta et al., 1999). The present day valley and deep gorges in upstream reaches of the Narmada River were formed during the Holocene, which may have resulted from large palaeofloods in response to monsoon intensification in early Holocene (Kale et al., 1993). Sediment archives at downstream reaches of the Narmada valley provide ≈ 125 ka history of fluvial processes and its response to climate change and other external forcings (Chamyal et al., 2003). Alluvial plain sediments in the Lower Narmada valley indicate a large sand bed dynamic channel in this region with low channel sinuosity and high discharge level, which was hydrological depleted during LGM time in response to a decline in monsoon activity (Bhandari et al., 2005). Presently, the Narmada River in its downstream river valley is a misfit river in a wide valley (Chamyal et al., 2002; Gupta et al., 1999). Laskar et al. (2013) have related the availability of moisture and the deposition of the Holocene sediments in the lower Narmada river valley. They suggested a humid condition during the late Holocene (~3 ka) which was responsible for the deposition of the ~2 m thick Holocene sediments.

Impact of climate change on flood hazards in the Central Ganga Basin and Peninsular India was analysed by Kale (2007) through palaeoflood analysis. Kale (2007) observed a distinct pattern of flood events with clustering in some particular time zones. The flood frequency variation at the century and millennium scale was linked to temporal variability in monsoon strength.

Rivers in the north-western arid area

In the western part of India which is dominated by strong arid condition, rivers were subjected to change in fluvial regime due to high amplitude climatic fluctuations. River sediments and occurrence of scroll bars in the Sabarmati River basin near Ahmedabad suggest a meandering channel around 54 to 30 ka, which was considered as wetter phase (Srivastava et al., 2001). However, river activities were reduced significantly and river sediments were overlain by aeolian dune sediments during the LGM. Monsoon intensification ~ 10 ka caused significant channel incision and development of badland topography along the river due to increase in steam power and river carrying capacity (Srivastava et al., 2001).

River sediments and stratigraphy in Rajasthan and Gujarat suggest significant changes in river processes and morphology in response to climate change (Jain and Tandon, 2003). Data from this area show that these rivers in the dryland area are more sensitive to climate change. Rivers in this area changed from meandering to gravelly braided rivers to ephemeral sand bed rivers in response to climate change. The rivers also became defunct during drier phases of climate and aeolian activity dominated. The humid phase was strongly dominated by the incising gravel bed channels. The changes in the river style were attributed to the change in discharge and sediment supply in response to the change in rainfall pattern and interaction with well-developed vegetation cover (Jain and Tandon, 2003). Jain and Tandon (2003) also observed different sensitivity of rivers to climate change, which was governed by the origin of rivers in different climatic zones. The rivers in the arid western region, such as Luni, Mahi and Sabarmati responded to an increase in humidity by an enhancement in erosion processes and increased depth. However, other rivers in Upland Maharashtra, which originated from the humid area but flow through a semi-arid region, responded to the same climate change event by increasing depositional processes. The difference in response was interpreted as a consequence of vegetation difference in these different river basins (Jain and Tandon, 2003).

River deposits on the southern margin of the Thar desert provide a history of river response to climate change since 130 ka (Juyal et al., 2006). Sedimentary architecture reveals that ~130-120 ka was a major phase of enhanced monsoon and resulted in a well-developed meandering river system on the southern margin of the Thar desert (Juyal et al., 2006). These meandering rivers changed into braided rivers in response to decrease in precipitation at ~120-100 ka, which caused reduction in the transport capacity of the rivers. Enhanced monsoon during ~100-70 ka resulted in enhanced river activities and deposition of fine grain floodplains. The LGM time was dominated by aeolian activities and river activities declined. Further monsoon intensification after LGM was responsible for channel incision and creation of present day river channels (Juyal et al., 2006).

6.4.2. Future climate change and river response

Recently, numbers of studies have been carried out in different river basins to project the fluxes in river systems in response to climate change. These studies were based on the integration of climate and hydrological models to analyse water and sediment flux variability in response to precipitation and temperature change.

Increase in runoff and flooding hazards in the Ganga and Brahmaputra Rivers in response to climate change was suggested by earlier studies (Mirza et al., 2003). Gosain et al. (2006) analysed and projected hydrological scenarios for 2041-2016 for 12 major rivers by integrating HadRM2 daily weather data with the Soil and Water Assessment Tool (SWAT), a distributed hydrological model. Some of the rivers, namely Mahanadi, Brahmani, Ganga, Godavari, Cauvery, will receive higher runoff while other rivers, namely Narmada, Tapi, Krishna, Pennar, Mahi, Luni, Sabarmati will be characterised by decrease in runoff.

Mishra and Lilhare (2016) also analysed hydrological changes in 18 major rivers of India through the SWAT model by using downscaled data from General Circulation Model (GCM) that was bias corrected for future climate projections for two representative emission concentration pathways (RCP) 4.5 and 8.5. The runoff was projected for three different periods; i.e. in the Near-(2010-2039), Mid-(2040-2069) and End- (2070-2099). Streamflow projections under RCP 4.5 show that most river basins will be characterised by increase in runoff, though it will be variable in different periods and in different rivers. Near-term projection shows that all rivers except Mahi and Tapi rivers will experience increase in streamflow during the monsoon season. Mid-term projections suggest that all rivers except the Indus River will be characterized by increase in discharge. End-term projections indicate that all major rivers will experience increase in streamflow. Projections under RCP 8.5 suggests that all rivers will be characterised by increase in streamflow with variability ranging from 20% to 40% increase in streamflow. Flow in the major rivers basins, namely Mahanadi, Brahmani, Ganga, Godavari, and Cauvery increased in both models. However, western rivers in the arid area (Narmada, Tapi, Krishna, Pennar, Mahi, Luni, Sabarmati rivers) are characterisd by variability in streamflow in different models.

Further study at the global scale shows that streamflow increase in the Ganga River basin will be significant compared to other large rivers basins (Mishra et al., 2017). Though, uncertainty in streamflow variability will be higher. Mishra et al. (2017) further suggest that most of the uncertainty comes from the climate models while uncertainty due to hydrological model is less. The SWAT hydrological model was also used with A1B scenario of output from two Regional Climate Models for the Koshi River basin, Nepal Himalaya, to assess future changes in hydrological regime under climate change (Devkota and Gyawali, 2015). In the Himalayan terrain, the average water availability will not change significantly, however temporal distribution will change. Enhanced runoff during monsoon period will increase flood events and magnitude. Projected hydrological variability within this part of the Himalayan terrain suggests significant increase in return periods of flood events.

Hydrological projections were also made using another process-based, semi-distributed model (i.e. the Integrated Catchment Model INCA-N) (Whitehead *et al.*, 2015; Khan et al., 2018). Both studies suggest an increase in runoff and flood frequency in response to climate change. Whitehead et al. (2015) investigated the hydrological system of the Ganga River basin in future climate scenario for 2050s and 2090s with INCA model. The INCA-N was integrated with a higher resolution 25 km Regional Climate Model (RCM). They projected an increase in water availability due to an increase in monsoon flow, which will also enhance flood hazards in downstream reaches. Whitehead et al. (2015) further suggested variability in the nutrient supply in the rivers in response to hydrological changes. The concentration of nitrate and ammonia will decrease in downstream reaches due to increase in water flow in the river channels. Therefore, the advent of high energy discrete events and low concentration of nutrients in response to climate change will cause significant impact on river ecology and river health.

Variability in hydrological fluxes was also used to estimate increase in sediment load in the near future. Darby et al. (2015) used an empirical lumped sediment transport model (HydroTrend) and suggested an increase in sediment load for the Ganga River by 34–37% at the end of the century. Khan et al. (2018) projected higher (35-79%) increase in sediment load by the end of the century. Higher increase in sediment load was projected by analysing the Integrated Catchment Model for Sediments (INCA-Sed) and standard HadCM3 coupled GCM (global climate model) to project discharge and sediment load variation in the Ganga River basin.

6.4.3 Glacier and snowmelt contribution to the Himalayan rivers in response to climate change

River response to climate change may become more complex for the Himalayan rivers because of the increased influx from glacial melt. Most of the climate models currently don't include glacial dynamics and variability in glacial and snowmelt contribution. Hence, there is a need to further understand the nature of glacial and snowmelt contribution to the Himalayan rivers. Glacial and snowmelt contribution lends a perennial character to the Himalayan rivers as opposed to peninsular rivers. It sustains river flow during drier pre and post-monsoon months in the Himalayas (Immerzeel et al., 2010). Thus, glacier retreat and wastage will alter hydrological regimes, sediment transport and biogeochemical and contaminant fluxes to systems downstream (Milner et al., 2017). Majority of the world population that stands to be impacted by changed river discharge arising from changed glacial dynamics are in the High Asia region (Schaner et al., 2012).

Glacial melt contribution in river discharge has been estimated by various researchers using different methods. The most direct way of estimating glacier melt contribution to river discharge is through discharge gauge stationed at the snout of a glacier. Indirect methods include hydrological modeling using snow and glacier cover data and various flow routing algorithms, hydrological balance equations, hydro-chemical tracer method that includes stable isotopic analysis of water samples, hydrograph separation and glaciological mass balance approach (Frenierre and Mark, 2014). The last decade has witnessed many studies on this phenomenon and now the data are available from different river basins. Melt contribution varies spatially, seasonally and longitudinally along the rivers across the Himalayas (Fig. 6.6). The hydrological modeling approach has shown that annual snowmelt contributions varied from up to 66 % in the Indus basin in the western Himalayas to 25% in the eastern Brahmaputra basin to ~20% elsewhere (Bookhagen and Burbank, 2010) (Fig. 6.6a). The same study also showed that the snowmelt contribution during pre and early monsoon season is significant. In the Sutlej River basin, an attempt to differentiate glacier and snowmelt using a distributed hydrological model that is based on daily, ground-calibrated remote-sensing observations estimated the snowmelt contribution at 35% and glacier melt at 10% (Wulf et al., 2016). The same work showed that glacier melt increased by up to 30 % in the higher elevation interior of the basin.

Seasonal variation in melt contribution had been observed in the Din Gad basin, where summer discharge reduction led to doubling of the glacier melt contribution during summer (Thayyen et al., 2007). The cited work showed that if catchment hydrology is dominantly controlled by winter snow and monsoon precipitation, glacier melt might not increase river run-off to a great extent. The seasonal contribution of melt variation has also been observed in the Bhagirathi River near Gaumukh (Rai et al., 2009).

The mean annual glacier melt contribution in the Chenab River basin at Akhnoor was estimated using the water balance approach at 49.1 % between 1982-1992 (Singh et al., 1997). For Beas River basin, the contribution is 37.4 % at Pandoh Dam between 1998-2004 (Kumar et al., 2007). In the Sutlej River basin, the contribution is 59 % between 1986-1996 at Bhakra Dam (Singh and Jain, 2002). In the Ganga River basin, the mean annual glacier contribution has been estimated to be 28.7 % at Devprayag (Jain, 2002). In the Bhagirathi sub basin, a model based study has found that the average snowmelt contribution to the Bhagirathi was 70.54% during 1999-2002 at Loharinag Pala H.E. Project site whereas in the DhauliGanga the average contribution of snowmelt was 77.35% during the study period of 1983, 1984 and 1987 at Tapovan Vishnugad Project site (Arora et al., 2010). Using a water budget model, the contribution of snowmelt to annual runoff is 60% while that of glacier ice is only 2% in the Liddar watershed (Jeelani et al., 2012). A summary is provided in Fig 6.6b

The significance of melt water contribution varies from basin to basin and also within an individual basin. Melt water plays an extremely important role in the Indus river basin, less so in the Brahmaputra basin and even lesser in other Himalayan river basins (Immerzeel et al., 2010). Within a basin, there is a variation of melt contribution from upstream to downstream. For example, a water budget based estimation by Jain (2008) suggests that contribution of Gangotri glacier to melt water at Allahabad is only around 4 %.

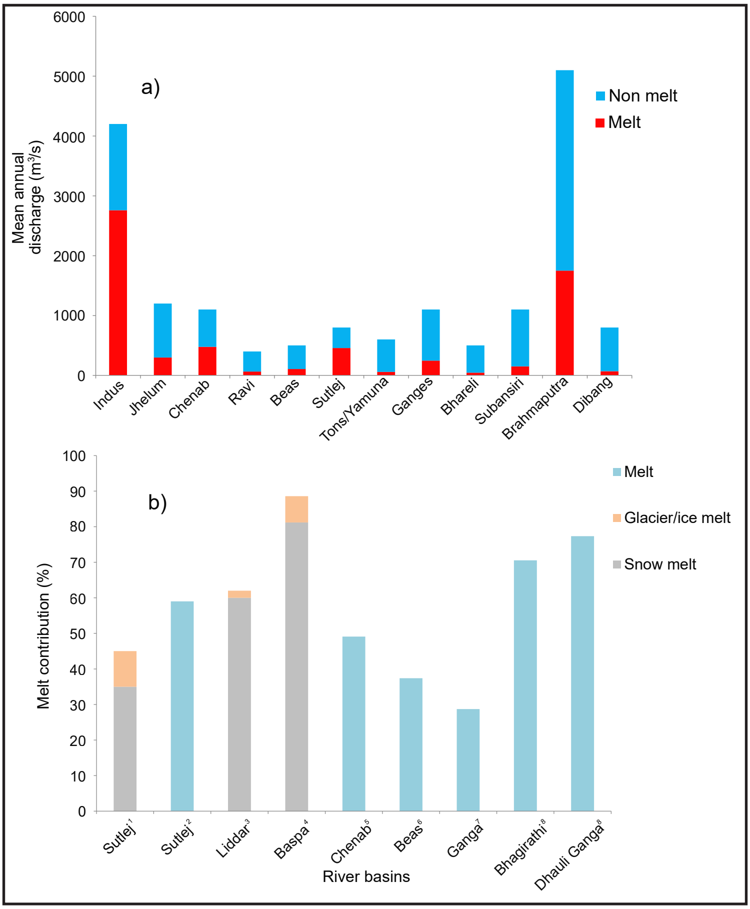

Figure 6.6: **(a) Spatial variability in contribution from snowmelt and glacial melt to river discharge (after Bookhagen and Burbank, 2010). Melt water contribution from snow and glacier to river discharge vary from 10- 50% in major Himalayan river systems. Hence, any enhancement in glacial melting in response to climate change will have different hydrological and morphological impacts across the river systems (b) Meltwater contribution to river discharge in different Himalayan river basins, as compiled from different sources ([1]Wulf et al., 2016, [2]Singh and Jain, 2002, [3]Jeelani et al., 2012, [4]Gaddam et al., 2018, [5]Singh et al., 1997, [6]Kumar et al., 2007, [7]Jain, 2002, [8]Arora et al., 2010).**

Using stable isotopic analysis, glacier and snowmelt contribution to the Spiti-Sutlej and Tons Rivers (the glaciated tributary of the Yamuna River) has been estimated to be between 41.1% to 66.8% and 6.6% to 10.6% respectively (Varay et al., 2017a). These values are in broad agreement with the values derived using snowmelt models.

According to a mass balance model study, Chhota Shigri Glacier in the Western Himalaya has seen an increase in mean run-off from 2.0 m^3/s in 1955-99 to 2.4 m^3/s in 2000-2014 (Engelhardt et al., 2017). In the Baspa basin, a tributary of the Sutlej River, based on runoff models, snowmelt contributes 81.2% of the total runoff and ice melt contributes 7.4% to the total runoff (Gaddam et al., 2018).

Glacial melt models have been further used to project future melt contribution scenarios. Under warming climate scenarios, solid winter precipitation reduces and the snowmelt season starts earlier. This will shift the runoff from the season when it is needed the most (Barnett et al., 2005). However, warming will impact melt contributions to varying degrees in different basins. The Indus and Brahmaputra basins will be more susceptible to altered flow regimes (Immerzeel et al., 2010). Large scale, high resolution, cryospheric–hydrological modeling in the Himalaya has projected an increase in discharge at least till 2050 due to increase in melting in the upper Indus and increase in precipitation in other parts (Lutz et al., 2014). Others have shown that glacier melt will increase by 1-2% in the next few decades but will dwindle thereafter (Xu et al., 2007). Within a basin, melt contributions from the lower part of the basin can decrease whereas contributions from the higher elevation part of the basin will increase (Singh and Bengtsson, 2004).

It has been observed that the impact of glacial melting on geomorphic condition will vary (Varay et al., 2017a). A study in the Yamuna and Sutlej river basins shows for that similar change in the glacial and snowmelt runoff, the high-energy reaches will be more affected in comparison to the low energy reaches. Therefore, quantification of stream power profiles is one of the important method to quantify channel sensitivity and threshold condition.

The sensitivity of the permafrost region is one of the least studied, which may have a significant impact on river processes in the mountainous reaches or further downstream. A remote sensing based preliminary study of permafrost in the western Himalaya suggests that permafrost degradation in response to an increased temperature may release huge amounts of sediments in the river system, which will significantly change the appearance and behaviour of these river systems (Varay et al. 2017b). Further, the impact of permafrost degradation will vary from one river basin to another, as Varay et al. (2017b) have shown the Sutlej river will be more affected in comparison to the Yamuna river system.

6.5. Discussion and Conclusions: Climate change and river's future

River response to climate change is governed by many processes specific to different components/models and also feedback between these components (Fig. 6.7). Currently, there are many climate models at global and regional scale (GCM and RCM) to project the future changes in temperature and precipitation for different emission scenarios. Though these global and regional climate models are at coarse resolution, they can be downscaled at basin scale through different modelling and statistical approaches. Recently, output from these analyses have been used in hydrological models to project future changes in water, sediment and nutrient fluxes. Integration of climate and hydrological models provides an important tool for projecting the future state of rivers.

Flux variability is important but not sufficient to understand the future of a river system and flood hazards, because of dynamic behavior of rivers and important role of morphological processes (Jain et al., 2018; Sinha et al., 2014). For example, an increase in streamflow in response to climate change will not always cause enhanced flooding, but it may lead to intense channel bed and bank erosion to increase the bankfull capacity. Hence, analysis on climate change impacts on water and sediment flux needs to be merged with morphological studies for sustainable management of flood hazard and risk management (Wasson et al., 2018).

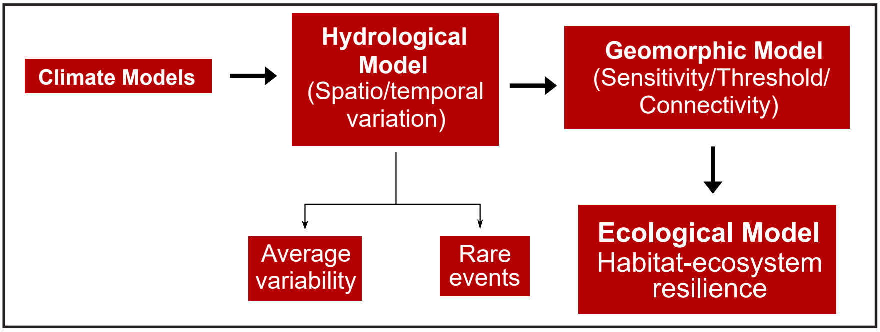

Figure 6.7 **Role of different models and its feedbacks in understanding the river response to climate change. Climate and hydrological models have already been integrated to project future change in water, sediment and nutrient fluxes in river systems. However, complete understanding of climate change impact on river health needs integration of geomorphic and ecological models. Quantitative understanding of geomorphic concepts namely threshold, connectivity and sensitivity are needed to build process based geomorphic model(s) for river systems.**

Hydrology-geomorphology relationship is a nonlinear relationship, which is governed by thresholds and connectivity. Further, the variable sensitivity of different tributaries or different reaches of the same rivers will make it a complex system to define responses of a river basin to climate change. The nature of nonlinear and complex relationships between climate and channel morphology suggests that different rivers or different reaches in the same river can react differently to a similar variation of climate. Quantitative estimation of these aspects namely geomorphic threshold, connectivity and sensitivity are needed to understand the future projection fully. Therefore, the geomorphic model(s) need to be developed and to be integrated with climate and hydrological models for understanding the effect of climate change on river system (Fig. 6.7).

The future of rivers will not only be governed by future projection of climatic parameters, but will also be governed by anthropogenic impacts. The effect if anthropogenic interventions in terms of barriers across rivers like dams and barrages, have not been analysed in such modelling studies. Presence of such dams disconnects a river system in such a way that the impact of climate change may be limited, i.e. impact of climate change driven flux variability will be limited to reaches at upstream of dam. Rivers that have already been disturbed by anthropogenic impacts thereby reducing their sensitivity to climate change (Jain et al., 2016). For example, The Yamuna river is highly disconnected due to anthropogenic impact (Bawa et al., 2014), hence the impact of climate change will not be significant in the midstream and downstream reaches. Similarly, the rivers in the Bihar plains are significantly disconnected due to a rail-road network (Kumar et al., 2014). Hence, flux variability in the rivers of north Bihar in response to climate change will be limited to reaches upstream of major rail-road embankments. Major dams on the Indian rivers have already reduced sediment load by 70% (Panda et al., 2011). Current studies on future projection of sediment load suggest increase in sediment flux of around 35 % for Himalayan rivers (Darby et al., 2015; Khan et al., 2018). A similar increase in sediment flux in the relatively low energy peninsular rivers most likely will not cause any significant change in morphology.

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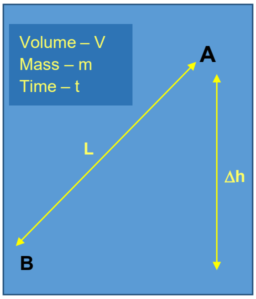
Appendix: 6.1. Quantitative expression of driving forces at different scales which define forcing of climate change in river systems

Stream power is defined as the rate of potential energy conversion when water moves downstream in a river channel (Bagnold, 1966). Total stream power represents available power for a unit length while specific stream power is defined as stream power per unit bed area.

Hence, expression of stream power for a water of volume 'V', mass 'm' flowing from point A to B on channel slope 's' will be given as -

$$\text{Stream Power} = (m.g.\Delta h)*(1/t) \qquad W$$

$$= (V.\,\varrho.g.\,\Delta h\,))*(1/t) \qquad W$$



Hence, Total stream power (Ω) will be given as-

$$\Omega = (V.\varrho.g.\Delta\, h)*(1/t)*(1/L) \qquad W/m$$

$$= (V/t)*(\varrho.g)*(\Delta\, h/L) \qquad W/m$$

$$= \gamma.Q.s \qquad W/m \qquad (1)$$

Specific stream power (ω) will be given as -

$$\omega = \gamma.Q.s \quad / \, w \qquad W/m^2 \qquad (2)$$

Another measure of driving force at site scale is given by shear stress (τ), which is defined as and shear stress acting on the channel bed by the water body and is given as Robert, (2014) -

$$\tau = \gamma.d.s \qquad N/m^2 \qquad (3)$$

Shear stress and stream power are related with each other. It can be shown by merging Equation 2 and 3. It will result as –

$$\omega = \gamma.d.v.s \text{ (as for rectangular channel, } Q = w.d.v\text{)}$$

$$\text{Or} \quad \omega = \tau.v \qquad (4)$$

Notations –
Q – discharge,
γ - unit weight of water
w – channel width
d – water depth
v- average channel velocity

Chapter 7

Impact of Climate Change on Drought Frequency over India

Saran Aadhar[1] and Vimal Mishra[1*]

Abstract

Historical observations suggest that severe drought frequency has been increasing in the recent decades over India. In the future climate, significant variability and change in monsoon rainfall and temperature would further affect the future drought conditions. Here, we analysed data from five Global Climate Models (GCMs) that participated in the coupled model intercomparison project-5 (CMIP5) to estimate the changes in drought conditions under the warming climate in India. Our analysis show more frequent droughts in the warming climate in near (2011-2040), mid (2041-2070), and end (2071-2100) period using standardized precipitation evapotranspiration index (SPEI) whereas the drought projections based on just precipitation (Standardized Precipitation Index: SPI) show a decrease in the drought frequency in the 21st century. The change in drought frequency is projected to increase by more than two-three severe droughts per decade over the majority of India using SPEI in the end period. The increased warming resulted in an increased atmospheric water demand (potential evapotranspiration: PET) in the region, which is reflected in the increased drought frequency. The change in area under severe drought is projected to increase by 150% at the end of the 21st century using SPEI against the reference period 1971-2000. Overall, we conclude that the drought frequency of severe drought is projected to increase in warmer and wetter future climate in India and the increased frequency of droughts can be largely attributed to increased PET due to anthropogenic warming. This chapter highlights that despite the projected increase in the monsoon season precipitation, the risk of frequent droughts in India is higher under the warming climate, which will have implications to water management in the future.

7.1. Introduction

India is the world's second most populated country where the majority of the population depends on agriculture for livelihood. In the last few decades, increasing drought frequency (Mishra et al., 2016) and weak summer monsoon (Roxy et al., 2015) have adversely affected agriculture production, water availability, and socio-economic conditions. Moreover, the growing population and declining water availability pose further challenges to food and water security in the future in India.

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Drought hampers surface and groundwater availability and can create a disaster situation in any place. For instance, in India, more than 300 million people were affected due to the extreme drought in 2002 (Bhat, 2006). In 2014 and 2015, the Gangetic region and Maharashtra experienced more than 500 year return period drought that resulted in severe water scarcity and affected millions of people living in these regions (Mishra et al., 2016) Increased CO_2 emissions due to anthropogenic activities has triggered changes in the global climate in the past decades (Reichstein et al., 2013; Wang et al., 2015). In the changing climate, weak Indian Summer Monsoon (ISMR) has been reported in India (Roxy et al., 2015; Sinha et al., 2015). India has faced frequent and severe drought (once in every three years) in the last few decades (Aadhar and Mishra, 2017; Mishra et al., 2016; Shah and Mishra, 2015). However, drought severity and frequency in the future warming climate remains largely unexplored over India.

Here, using the observed and future simulations, we report the changes in the drought frequency in the past and future projected climate over India. Future simulations using the global climate models (GCMs) from Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al., 2012, 2007) have been widely used in hydro-climatic (Mishra et al., 2017; Mukherjee et al., 2018; Trenberth et al., 2014) studies for future projection. We use Standard Precipitation Index (SPI) (Mckee et al., 1993) to measure the meteorological drought over the study region. SPI calculates the precipitation deficit for multiple time scale at the end of a particular period. However, SPI does not consider the role of temperature in drought. Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010), which considers the role of temperature by estimating PET, is also used. Based on the SPI and SPEI drought indices, we assess the frequency and areal extent of severe drought (drought index < -1.2) events in observed and future climate across India. The information of drought in future warming climate can be helpful to develop the mitigation and adaptation policies in this region.

7.2. Observed and Model Data.

We obtained monthly gridded observed precipitation data from India Meteorological Department (IMD) at 0.25° spatial resolution for the period 1951-2016. The gridded dataset was developed using 6995 stations across India (Pai et al., 2015). Station data were interpolated using Inverse Distance Weighting (IDW) interpolation method as described in Shepard (1968). The gridded dataset effectively captured the features of precipitation variability and climatology over India and showed a better representation of orographic precipitation in the Western Ghats and north-eastern India (Shah and Mishra, 2015). Moreover, the dataset captured the extreme rainfall variability very well in the foothill of Himalaya region and Western Ghats (Kumar et al., 2013; Pai et al., 2014). The IMD-rainfall dataset has been widely used in drought studies over India (Mishra et al., 2016; Shah and Mishra, 2015). Detailed information about data development can be obtained from Pai et al. (2015).

Also, we used temperature data in this study to analyse the combined effect of precipitation and temperature on droughts. We obtained monthly observed minimum and maximum temperature datasets from IMD at 1° resolution from 1951-2016. Temperature data were developed using 395 quality controlled observing stations across India (Srivastava et al., 2009), and gridded using a modified angular distance weighting interpolation method (Shepard, 1968; Srivastava et al., 2009). Further, we regridded the minimum and maximum temperature data from 1° to 0.25° resolution (for consistency with precipitation data) using the lapse rate method described by Maurer et al. (2002).

For future drought projection, we obtained daily Precipitation, minimum and maximum temperature data from Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al., 2012, 2007) global climate models (GCMs) from the r1i1p1 experiment for RCP 4.5 and RCP 8.5 (https://esgf-node.llnl.gov/search/cmip5/) for the period 2006-2100. We selected five GCMs (GFDL-CM3, GFDL-ESM2M, NorESM1-M, MIROC-ESM, and MIROC-ESM-CHEM) out of about 40 CMIP5-GCMs based on their skill to simulate the monsoon rainfall over India. Our selection of the best five models was consistent with other studies (Jayasankar et al., 2015; Saha et al., 2014). Further, we downscaled (Maurer et al., 2002) the CMIP5-GCMs data at 0.25° resolution and corrected the bias in GCMs data against the observed IMD data for the historic (1951-2005) and future (2006-2100) periods. Bias correction in GCMs was performed using the trend-preserving statistical method developed within the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) as described in Hempel et al. (2013).

7.3. Drought Analysis.

We analysed the observed data from IMD from 1951-2016 for historical drought information and CMIP5 GCMs data for future projection of drought over India. Standardized Precipitation Index (SPI) (Mckee et al., 1993) and Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) drought indices are used to estimate the severe drought frequency (SPI or SPEI < -1.2). R SPEI (Čadro and Uzunovi, 2013) package was used to evaluate the 4-month or 12-month SPI and SPEI drought indices in observed and future simulation using Gamma and log-logistic distribution, respectively. In SPEI, we used the Hargreaves-Samani method (Hargreaves and Samani, 1985) method to estimate the potential evapotranspiration (PET). PET estimated using the Hargreaves-Samani method showed similarity with the Penman – Montieth method (Kingston et al., 2009). We estimated the projection of drought severity for near (2011-2040), mid (2041-2070), and end (2071-2100) period in RCP 4.5 and RCP 8.5 scenarios.

7.4. Drought Frequency during the Observed Period.

Figure 7.1 illustrates the drought frequency during the observed period 1957-2016 in India. We used 4-month and 12-month SPI and SPEI drought indices to evaluate the severe drought (<-1.2) frequency and areal extent in the last few decades. The analysis shows that the large frequency (>10 events in last 60 years) of severe drought occurred in highly populated and agriculturally intense Indo-Gangetic Plain, North, South, and Eastern parts of India (Fig. 7.1). Recently, Mishra et al. (2016) reported an increase in the occurrence of drought in post-1960 compared with the pre-1960 period. We estimated the drought indices for 4-month and 12-month time-scale, which show the deficit in the monsoon season and annual cycle at the end of September and December, respectively. We also estimated area (%) under severe drought during the period 1957-2016 using SPI and SPEI for 4-month and 12-month time scales (Fig. 7.1e-f). We find that 1965, 1972, and 2002 were the most severe droughts in the last 60 years with more than 35% area under severe drought for the 12-month time-scale. Droughts estimated using SPEI show a higher drought frequency and area under drought compared to SPI, which considers only precipitation (Fig. 7.1).

7.5. Drought Frequency in the Changing Climate.

To evaluate the characteristics of drought in future climate, we estimated change in the severe drought (drought index <-1.2) frequency using SPEI and SPI (Fig. 7.2-4) in near (2011-2040), mid (2041-2070), and end (2071-2100) period against the reference period of 1971-2000 using multi-model ensemble mean of the five CMIP5-GCMs. Future drought severity was estimated for 12-month time-scale at the end of December using SPI and SPEI for the period 1971-2100 using the reference period 1971-2000. Figure 7.2 shows the change in the frequency of severe drought using 12-month SPI and SPEI drought indices for the near period. Frequency of severe drought changes from -1 to 3 severe drought events per decade in the near period (2011-2040) for RCP 4.5 and RCP 8.5 (Fig. 7.2). The ensemble mean of GCMs shows -0.5 to 1.5 drought events per decade under the RCP 4.5 scenario and decrease in severe drought events per decade under the RCP 8.5 across most of the regions in India using SPI. Change in drought frequency based on SPEI is projected to increase compared to estimates based on SPI indicating an elevated atmospheric water demand in the warming climate (RCP 4.5 and RCP 8.5). Under the RCP 4.5, the occurrence of severe drought is projected to increase by 1-1.5 events per decade in Gangetic plains, Northern, and part of southern India using SPEI. The projected increase is lower in SPI compared with SPEI. In the near period, increase in drought is more in the RCP 4.5 compared to the RCP 8.5 which shows more water scarcity under the RCP 4.5.

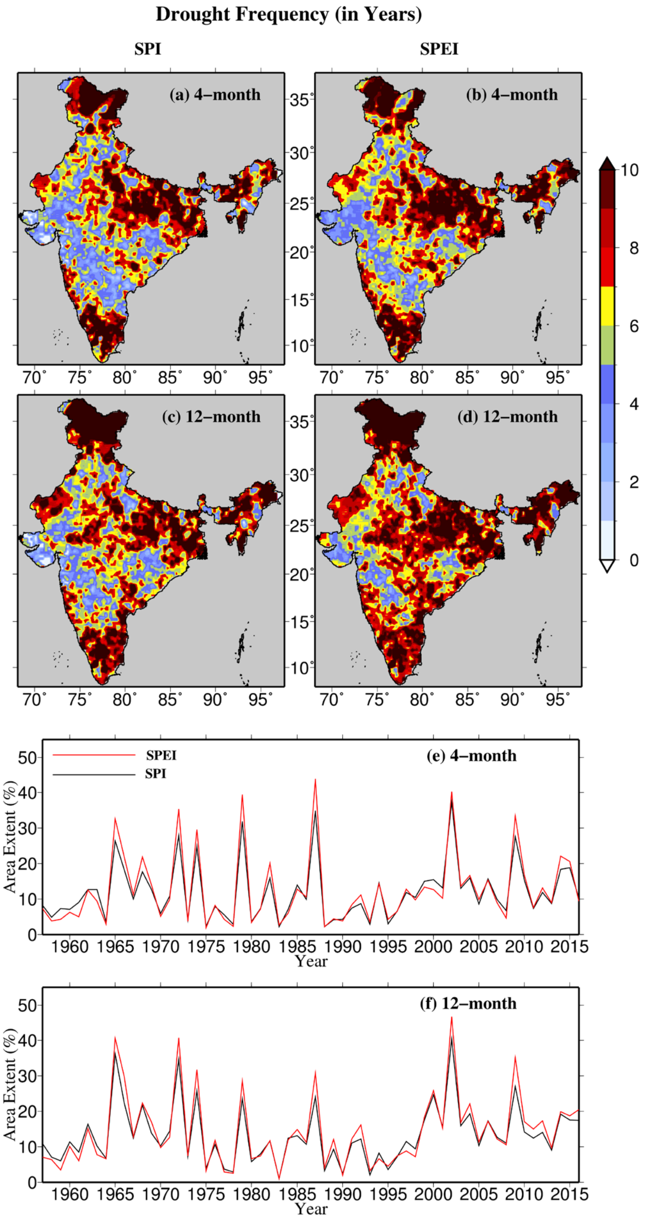

Figure 7.1 **Observed drought frequency and areal extent over India for the period 1957-2016. (a, b, c, d) Frequency of severe droughts (SPI or SPEI <-1.2) based on 4-month and 12- month SPI (Left) and SPEI (Right) at the end of September and December, respectively for the reference period 1971-2000. (e) percentage area under the severe drought using 4-month SPI and SPEI at the end of September and (f) percentage area under the severe drought using 12-month SPI and SPEI at the end of December.**

During the mid-period (2041-2070), change in severe drought frequency based on SPI is projected to decrease over the majority of India under the RCP 4.5 and RCP 8.5 while the occurrence of drought based on SPEI is projected to increase by more than 1.5 events per decade (Figure 7.3). Gangetic plain, Northern, and Southern regions show a high increase (more than two events per decade) in droughts based on SPEI under both RCP 4.5 and RCP 8.5 (Figure 7.3c-d). On the other hand, drought projection based on SPI show a decline in the frequency in the majority of India (Figure 7.3a-b). The decline in the drought frequency using SPI shows that precipitation is projected to increase in the mid-period. However, high drought frequency using SPEI shows an increase in atmospheric water demand in the mid-period compared to the reference (1971-2000) and near period (2011-2040).

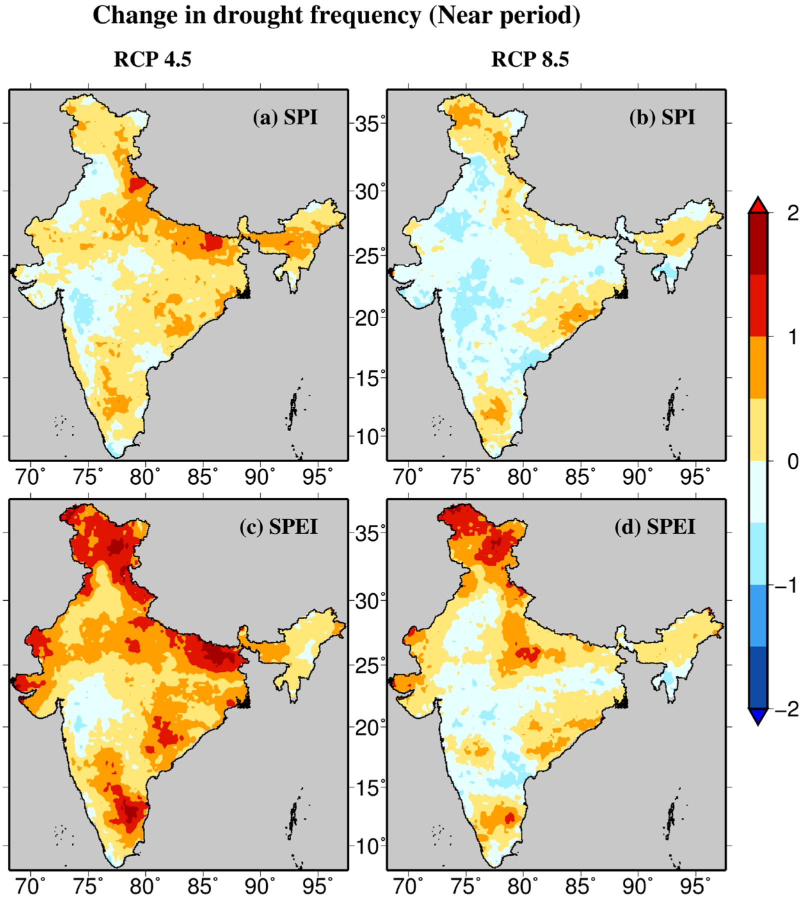

Figure 7.2 **Change in drought frequency (per decade) in near period (2011-2040). Change in the frequency of severe droughts (per decade) using five CMIP5-GCMs based on 12- month SPI (a, b) and SPEI (c, d) in the near period (2011-2040) against the reference period 1971-2000 in RCP 4.5 (left) and RCP 8.5 (right).**

Moreover, drought frequency is projected to increase more under RCP 8.5 in comparison to RCP 4.5 using SPI and SPEI. These results indicate towards more water scarcity under the RCP 8.5 in the mid-period (Fig. 7.3). In the end period, the projection of drought is significantly different using SPI and SPEI drought index (Figure 7.4). The severe drought frequency based on SPI is projected to decline during the end period. However, drought frequency based on SPEI is projected to increase by more than two events per decade in Northern and Southern India (Fig. 7.4c-d). Under RCP 8.5, drought frequency based on SPEI is projected to increase by 2-3 events per decade using SPEI showing a high risk of water availability at the end of the 21st century. Increase in the drought frequency based on SPI and SPEI is higher in the RCP 8.5 compared to the RCP 4.5. Since SPI does not consider the effect of temperature on drought estimation, it shows lesser drought frequency under the future warming climate (Figure 7.4). Therefore, drought projection using SPEI is more robust under the warming climate.

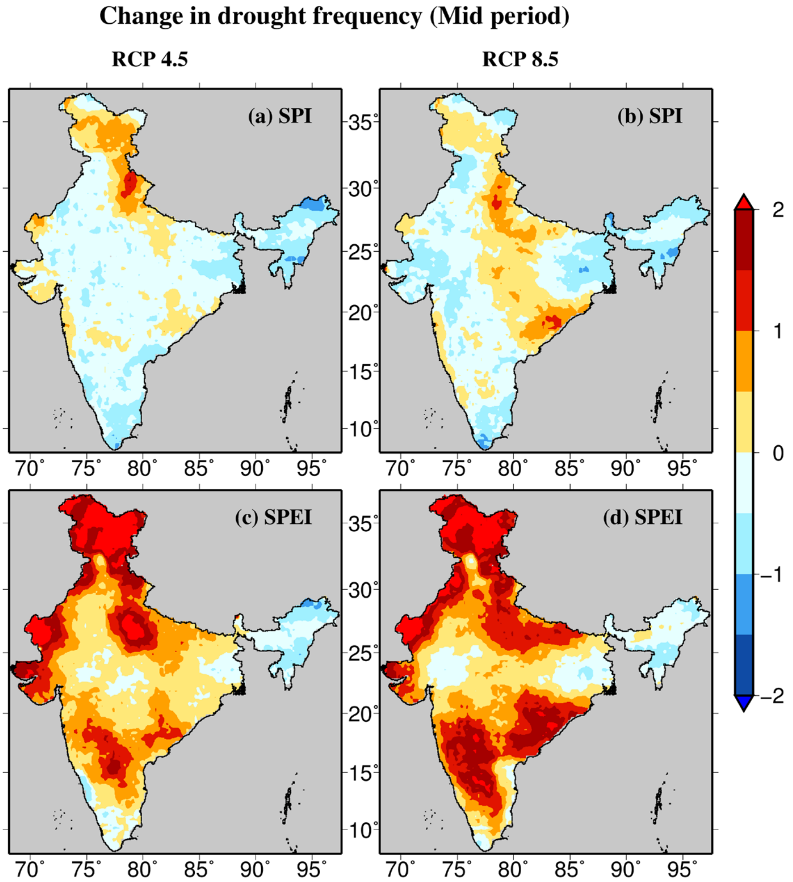

Figure 7.3 **Change in drought frequency (per decade) in mid period (2041-2070). Change in the frequency of severe droughts (per decade) using five CMIP5-GCMs based on 12- month SPI (a, b) and SPEI (c, d) in the mid period (2041-2070) against the reference period 1971-2000 in RCP 4.5 (left) and RCP 8.5 (right).**

We also estimated the changes in the area under severe droughts in India using 12-month SPEI and SPI for the period 2011-2100 against the reference period 1971-2000 under RCP 4.5 and RCP 8.5 (Figure 7.5). The change in drought area is estimated using 30-year moving mean starting from the year 2011 (2011-2040, 2012-2041, and so on) against the reference period 1971-2000. The area under severe droughts is projected to increase using SPEI in the RCP 8.5. Moreover, the change in the area is increased by 150% at the end of the 21st century against the reference period 1971-2000 using SPEI under the RCP 8.5. In the future climate, the area under severe drought based on SPI is projected to decrease under the RCP 4.5 while the area is projected to decrease constantly (about -10 %) under the RCP 8.5 (Fig 7.5). Similarly, based on SPEI, the area under the severe drought is projected to increase steadily (about 50-60%) under the RCP 8.5. Overall, the change in drought area and its frequency are projected to increase by the end of the 21st century using SPEI.

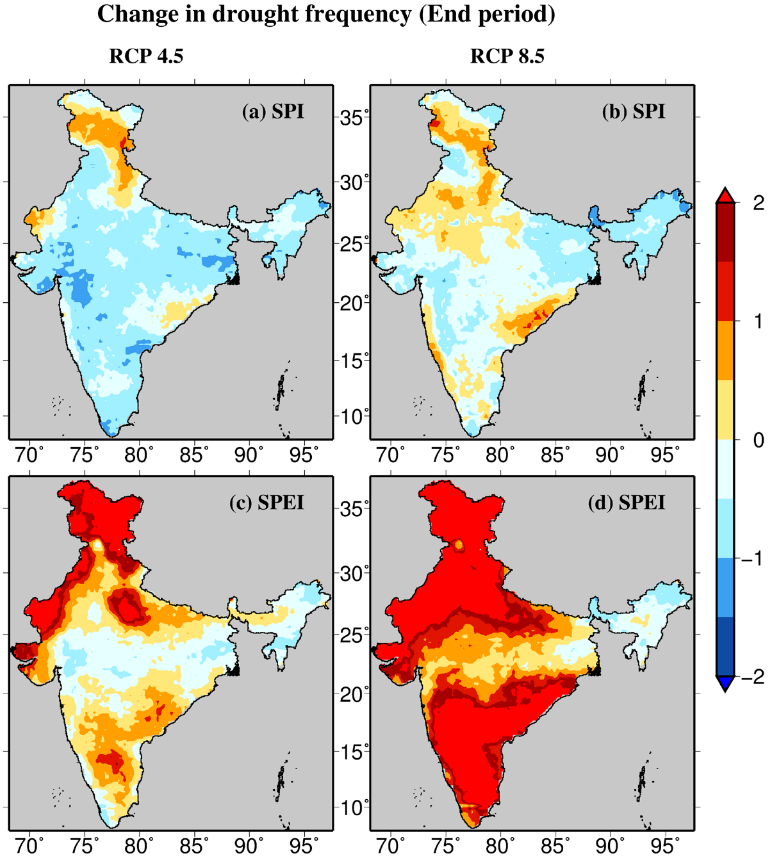

Figure 7.4 **Change in drought frequency (per decade) in end period (2071-2100). Change in the frequency of severe droughts (per decade) using five CMIP5-GCMs based on 12- month SPI (a, b) and SPEI (c, d) in the end period (2071-2100) against the reference period 1971-2000 in RCP 4.5 (left) and RCP 8.5 (right).**

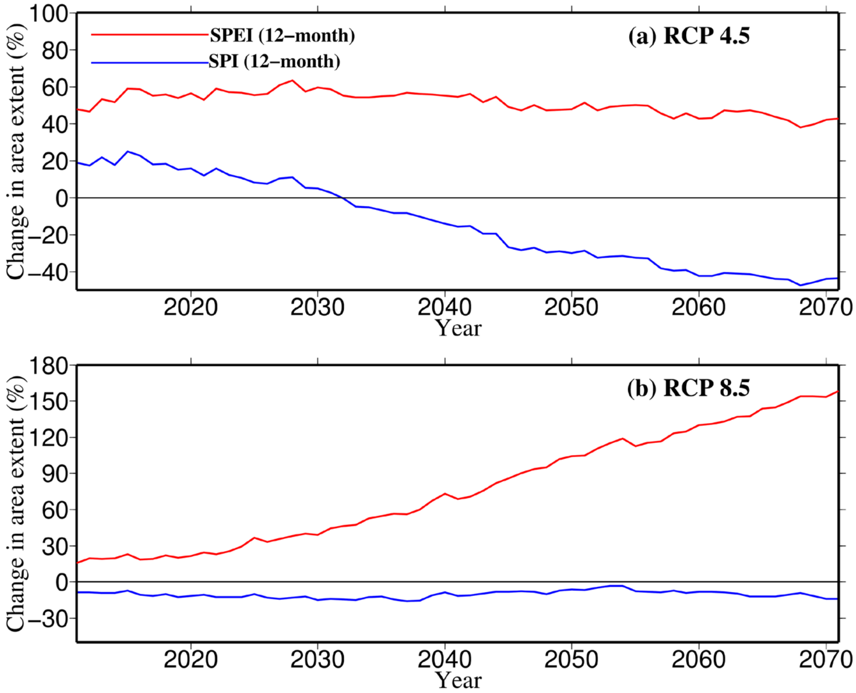

Figure 7.5 **Multimodel ensemble mean changes (%) in the area under severe drought. Change (%) in area under the severe drought from 2011 using 30-year moving mean (2011-2040, 2012-2041, and so on) against the reference period 1971-2000 using 12-month SPI (blue) and SPEI (red) at the end of December in (a) RCP 4.5 and (b) RCP 8.5 scenarios.**

7.6. Discussion and Conclusions

In Recent decades, drought severity has been reported to increase in the Indian region (Aadhar and Mishra, 2017; Dey et al., 2011; Mishra et al., 2016). Highly populated Indo-Gangetic plain is severely affected in recent decades with the occurrence of more than 9 severe drought events in the last 60 years (Mishra et al., 2016). Sinha et al. (2015) reported that Indian summer monsoon rain (ISMR) is currently in the decreasing phase of multi-decadal oscillation using two millennia proxy data. Assessing the drought severity information for changing climate is helpful for this region to develop adaptation and mitigation policies related to climate change. Recent studies reported strong ISMR under the future climate (Jayasankar et al., 2015; Lee and Wang, 2014). However, strong monsoon does not confirm the less drought severity in the region. Since, atmospheric water demand is projected to increase with warming in the future climate (Roderick et al., 2015; Scheff and Frierson, 2015).

Here, we studied the spatial extent and frequency of severe drought events under warming climate using the five CMIP5-GCMs. The projections of droughts using the SPI and SPEI are significantly different under the future warming climate. Dissimilarities in the projection of drought using SPI and SPEI are mainly due to the lack of consideration of the role of temperature in the SPI under the warming climate (Vicente-Serrano et al., 2010).

More frequent severe drought events based on SPEI are projected by the end of the 21st century under both the RCP 4.5 and RCP 8.5. Due to projected increase in monsoon rainfall (Jayasankar et al., 2015; Turner and Annamalai, 2012), SPI shows less frequent droughts in the end period as it neglects the effect of atmospheric water demand. Under the warming climate, the temperature is projected to increase, which affects the atmospheric water demand (PET) and drought conditions (Greve et al., 2014; Scheff and Frierson, 2014). Under the RCP 8.5, the majority of the country shows high-frequency of severe drought events (more than three severe events per decades) in the end period. The area affected by severe drought is projected to increase by 150% with warming under the RCP 8.5 by the end of the 21st century. However, the area under severe drought based on SPI is projected to decrease in the end period under the RCP 4.5. The risk of severe drought is more (~60% change in area) in the RCP 4.5 compared to the RCP 8.5 scenario (~30% change in area) in the near period and high risk of severe drought is projected (more than 100% change in area) in the RCP 8.5 during the mid and end period. Under the warming climate, there is an increase in the precipitation, and more than 2-degree rise in temperature leads to more atmospheric water demand and an increase in drought severity by the end of the 21st century. Overall, this study suggests that the severity of drought in India is projected to increase under wetter and warmer future climate.

Acknowledgments

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Chapter 8

Climate Change Impacts on Irrigation Water Requirement

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Abstract

The direct and indirect effects of climate change have started showing adverse impacts on water resources, agricultural production system, and food security. Though the uncertainty in the projected climate change is higher, it is still necessary to assess its impacts on crop productivity for formulating response strategies. Keeping these general observations in view; the impact of climate change on water resources, irrigation water requirement, and crop yield in India have been discussed with scientific findings in this chapter. It was found that annual average discharge will increase, in the future, as precipitation is projected to increase over the majority of Indian river basins. The rice evapotranspirational demand, analysed from the lowest emission scenario (Representative Concentration Pathway (RCP) 2.6) to the highest emission scenario (RCP 8.5) of projected climatic conditions in the future, is also projected to increase. However, the average rice yield is projected to decline from 2.13 t/ha to 1.67 t/ha and 1.62 t/ha under the future climatic conditions (RCP 4.5 and RCP 8.5, respectively). Therefore, the major finding of our work highlights that the irrigation requirement is projected to rise under the climate warming and this additional water may not help in increasing the crop production. The finding of the study may be useful to develop appropriate adaptation strategies for reducing the negative impact of climate change on water resources, crop evapotranspiration, and crop yield under the warming climate, which are vital for sustainable production and food security of the country.

8.1. Introduction

India houses and serves about 17% of the world population from 4% of the world's total freshwater resources. Among the anthropogenic uses of renewable water resources, agriculture is the largest consumer, withdrawing 90% of the total available freshwater resources (FAO-Aquastat, 2015). However, only around 50% of agricultural water withdrawals reach the fields; the remaining amount is lost in irrigation conveyance system (seepage and evaporation losses from irrigation canals and pipes). Nevertheless, only 44% of the total cultivated area of India falls under irrigated agriculture (Suresh et al., 2014), accounting to net irrigated area of approximately 68.1 Mha (MoA & FW, 2017) leading to

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low production and low resource use efficiency. Consequently, to supply the future demands of ever-increasing population under new challenges posed by climate change, it is inevitable to increase the land and water productivity of our agrarian sector. Collectively, agriculture and allied sectors like forestry and fisheries contributed 17.3% to the country's Gross Domestic Production (GDP) in 2016-17.

Crop production and food security are the two major concerns to researchers as climate change and rising food demand are expected to affect the global community adversely (Bodirsky et al., 2015). Though crop production in India has substantially increased after the Green Revolution, still about 14.5% of the Indian population is undernourished (The World Bank: https://data.worldbank.org/indicator/SN.ITK.DEFC.ZS?locations=IN). It is estimated that total 325-350 million tonnes of food grain production will be required by 2025 to meet the food, feed, fodder and fibre requirements of India (FAO-Aquastat, 2015). In response to this requirement, Borlaug (2000) pointed out the continuous decrease in availability of cultivable land as a challenge to increase the food grain production, and hence it is high time to embark on a second green revolution to increase yield through the optimal use of farm inputs.

Irrigation is one of the most precious farm inputs, which plays a vital role in crop yield. Good quality seeds and fertilizers fail to achieve their full potential yield if crops are not optimally irrigated. The quantity of irrigation water used in India in the last century was of the order of 300 km^3 of surface water and 128 km^3 of groundwater, leading to a total of 428 km^3 (Bhadra et al., 2012). These estimates indicate that by the year 2025, the irrigation water requirement would be 561 km^3 for low demand scenario and 611 km^3 for high demand scenario. However, the agricultural water withdrawal is expected to fall to 70% of total withdrawal by 2025, against 90% at present (Bhadra et al., 2012). The increasing irrigation water requirement highlights the necessity of optimal use of irrigation water. Efficient irrigation will help in meeting the growing crop water requirement, and hence maintains sustainable crop productivity and ensures food security. Past investigations indicate that most studies of future irrigation scarcity focused on the compounding effects of efficiency improvements and water quantity restrictions whereas much less attention had been given to understanding the individual role of each of them (Hanjra and Qureshi, 2010, Schmitz et al., 2013).

Around the world, climate change has been recognised as the major cause behind the diminishing water resources availability vis-à-vis changed hydrological regime (Arnell, 1999) encompassing increased annual rainfall variability, solar radiation, temperature and atmospheric CO_2 concentration which affects the crop yield adversely (Ceglar and Kajfez-Bogataj 2012; Chun et al. 2016; Rao et al. 2016). Extensive review of previous studies (Arunrat et al., 2018; Parry et al., 2004; Nagarajan et al., 2010; Rosenzweig and Parry, 1994; Singh et al., 2017) indicates that climate change, i.e. changes in seasonal temperature and rainfall, is likely to cause a significant decrease in world food production (Liu et al., 2016) in developing countries in the future. A regional study performed by Bhattacharya and Panda (2013) shows the effect of climate change on rice yield using AquaCrop model in West Bengal, India, and reported that the yield would decrease with per °C increase in average monthly temperature due to heat stress, and increase with per mm increase in average monthly rainfall in subtropical region. Mishra et al. (2013) studied the spatial variability of climate change impacts on rice yield using Regional Climate Models (RCMs) and reported a significant reduction in rice yield from potential value because of cyclic stress and changes in the management inputs.

In addition to the direct impacts of climate change on crop production (Dubey and Sharma, 2018; Fischer et al., 2005; Lobell et al., 2011; Tubiello and Fischer, 2007), there is concern regarding future irrigation water demand and water availability under the combined effects of climate change, growing population demands, and competition from other economic sectors under future socioeconomic development. In the recently released Sustainable Development Goals (United Nations 2015), one target set forth by the United Nations for 2030 is to ensure sustainable withdrawal and supply of freshwater in the coming decades. Ensuring food and irrigation water security under increasing population and climate change along with rapid economic growth in recent years, sustainable use of natural resources remains a significant challenge in modern India. Keeping the above points in view, the focus of the present document is to elaborate the impact of climate change on water resources, irrigation water requirement and crop yield through reviewing the finding of researches in India and around the globe, and to discuss the regional case studies on these aspects.

8.2. Climate Change Impact on Water Resources

Climate change impacts on water resources have received scientific attention over the last few decades due to the detrimental effects on hydrologic variables such as precipitation, streamflow, evapotranspiration and its significance on the surrounding ecosystems at global as well as regional scale (Frederick and Major, 1997; Juen et al., 2007; Xu and Singh, 2004; Xu et al., 2011). Global scale looks for a general view of the larger context and patterns, whereas regional scale focuses on the details of the studies. Gosain et al. (2011) examined the effect of future climate change on the water resources of Indian River system by using a distributed hydrological model SWAT (Soil and Water Assessment Tool) fed with PRECIS (Providing Regional Climates for Impact Studies) climate model outputs for two future periods 2020-2050 and 2070-2098. Climate model output showed that, in future, precipitation is expected to increase over the majority of river basins in India except for Brahmaputra, Cauvery and Pennar river basins where a marginal decrease in precipitation and consequent decrease in water yield is expected. The model analysed evapotranspiration

(ET) showed an expected increase of ET in the future (up to 10% by 2021-2050 and up to 40% during 2071-2098) in most of the river basins.

Jeuland et al. (2013) investigated the climate change impact on the hydrologic response of Ganges and correlated it with the economics of water use, and reported that evaporation rate and theoretical crop water requirement would increase due to increased temperature. They concluded that harvesting of available precipitation is required to secure regional water security. However, this will lower the runoff/water yield in rivers. Mittal et al. (2014) investigated the hydrologic alteration caused by dam construction in historical and future time period in a monsoon-dominated Kangsabati river basin in India at meso-scale. They used high resolution (25 km) SRES A1B scenario of four Regional Climate Models' (REMO-ECHAM5, HadRM3-ECHAM5, HadRM3-HadCM3 and REMO-HadCM3) output and their ensemble mean to simulate the streamflow in the Kangsabati river basin in historical (1970-1991) and future (2021-2050) period by using SWAT hydrological framework. To quantify the hydrological alterations by different flow characteristics, the Indicators of Hydrologic Alteration (IHA) method was used. The study revealed that flow variability in the Kangsabati river had been significantly reduced due to dam construction with a reduction in high flows during monsoon and a considerable increase in low flows during non-monsoon months. However, simulated stream flow under projected climate scenario is found to have reduced monsoonal flows with marginal changes in non-monsoon stream flow.

Kumar et al. (2017) assessed the impact of climate change on water balance components for the Upper Kharun Catchment in Chhattisgarh, India using PRECIS and SWAT models. The future climate projection, generated from PRECIS showed an increasing trend of rainfall and temperature over the catchment. The hydrological simulation of SWAT model showed over-proportional runoff-precipitation whereas under-proportional percolation-rainfall relationships. The results of the simulation revealed that annual average discharge would decrease by 2.9% in the 2020s and increase by 12.4% and 39.5% during the 2050s and 2080s, respectively. The percolation estimates showed an expected decrease of 0.8% in the 2020s whereas the same is expected to get increased by 2.5% and 7.5%, respectively in the 2050s and 2080s.

Goyal and Surampalli (2018) used SWAT and MIKE 11 NAM hydrological models coupled with global climate models (GFDL CM3 and GFDL ESM2M) for analysing the climate change impact on hydroclimatology of two different river basins Teesta and upper Narmada basin. Annual mean precipitation, maximum and minimum temperature and streamflow were found to have an increasing trend during 2016-2100 for both the basins. For the upper Narmada basin, it was found that both annual mean maximum and minimum temperature are expected to increase by 0.5 and 0.75°C in the 21st century. There is a significant increasing trend in streamflow varying from about 150 to 250

m^3/s in the 21st century. In case of Teesta river basin, annual mean maximum and minimum temperature showed a significant warming of 0.02 and 0.13°C, respectively, whereas mean annual stream flow is expected to increase by 28 m^3/s by the end of 21st century.

8.3. Climate Change Impact on Evapotranspiration/Crop Water Requirement

Chatterjee et al. (2012) determined ET for potato crop in lower Ganga river basin, West Bengal by applying field water balance method to validate CROPWAT model for assessing the impact of climate change on irrigation water requirement. They reported an increased irrigation requirement, respectively, 7-8% and 14-15% during the 2020s and 2050s in Ganga basin. Parekh and Prajapati (2013) investigated the impact of climate change on water requirement of kharif crops (millet, groundnut, maize, small vegetables and tomato) and rabi crops (wheat, sorghum, maize, tomato, gram and cowpeas) in Sukhi command area in Gujarat. The result showed that the crop water requirement of both kharif and rabi crops would increase considerably in future periods 2012-30, 2046-65 and 2080-99. Rehana and Majumdar (2013) studied the monthly irrigation water requirement using statistically downscaled GCM data at Bhadra reservoir command area. The result showed that monthly rainfall and reference ET (estimated using the FAO Penman-Monteith method) is expected to increase in future climate scenarios. They further reported that irrigation water requirements are expected to increase under a warming scenario. Therefore, the effect of a projected increase in rainfall on irrigation water requirement would offset by the effect of changes in other meteorological variables such as maximum and minimum temperatures, solar radiation, relative humidity and so on.

Wada et al. (2013) analysed the impact of future climate change on irrigation water demand of global irrigated area using a set of seven global hydrological models. They reported that reduction in irrigation water demand over south Asia including the Indus and Ganges basins are expected to occur in the 2080s under the RCP 2.6 scenario. However, irrigation water demand is expected to increase (up to 10%) over other parts of the world and decrease up to 20% for South Asia under the RCP 8.5 scenario. Dhage et al. (2017) studied the impact of projected temperature on paddy crop ET under future climate change scenarios on the Kansabati reservoir command area of West Bengal. Results showed that kharif (monsoon) crop ET demand of Kangsabati reservoir command area will increase by approximately 10, 9, and 18% over historical demand under RCP 2.6, 4.5, and 8.5 scenarios, respectively.

8.4. Impact of Climate Change on Crop Yield

Agricultural production depends on the climate of that area; mainly precipitation, temperature, atmospheric carbon dioxide (CO_2) concentration and humidity. Various researchers analysed the impact of these factors on crop production in different parts of the world as well as in India. Some of the studies are summarised here as below.

Attri and Rathore (2003) investigated the impact of modified climate on wheat yield by changing the maximum and minimum temperatures with the rise in CO_2 concentrations in northwest India, and the increase of 29-37% and 16-28% in wheat production under rainfed and irrigated condition, respectively, were observed under modified climate condition. The study suggested that an increase in temperature by 3°C or more could nullify the positive effects of CO_2. Subash and Mohan (2012) analysed the trends of climatic variables over five selected locations in Indo-Gangetic Plains (IGP) during the last 25-30 years and simulated yields of rice-wheat cropping system by using Decision Support System for Agro-technology Transfer (DSSAT). They found that the trend of rice yield ranged from -0.023 t/ha per year, a significant negative trend, at Samastipur to 0.055 t/ha per year in Faizabad. Rice yield decreased from the west to east IGP whereas an increasing trend in wheat yield, varying from 0.01 t/ha per year at Samastipur to 0.096 t/ha per year in Hisar, was found. All the sites had a positive trend of wheat yield. However, significant positive trends were found at three stations (Hisar, Faizabad and Kanpur). Wheat yields appeared to be increasing throughout the IGP.

Mishra et al. (2013) studied the spatial variability of climate change impact on rice and wheat yield at three different locations (upper, middle and lower) within Indo-Gangetic Basin (IGB). They used the DSSAT crop model and two RCMs (REMO and HadRM3) for analysing the response of both the crops under future climate change scenarios for the period of 2011-2040. The results indicated that the largest potential yield reductions (43.20% and 20.90% by REMO and 24.80% and 17.20% by HadRM3 for rice and wheat, respectively) were obtained for the upper IGB. However, conflicting results were obtained for the lower IGB. The climate projections of REMO model showed reduced potential yields whereas HadRM3 model exhibited increased potential yields.

Soora et al. (2013) analysed the regional vulnerability of rice yield under climate change in India using one GCM (MIROC3.2.HI) and one RCM (PRECIS). The results of these climate models based yield simulations indicated that irrigated rice yield tend to reduce approximately 4%, 7% and 10% during the 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099) climate scenarios, respectively. On the other hand, rainfed rice yield may reduce approximately 6% in the 2020s but marginally (< 2.5%) in 2050 and 2080.

Sathpathy et al. (2014) evaluated climate change impact on four rice cultivars (IR 36, Swarna, Swarn sub1, and Badshabhog) in the subtropical Indian conditions. DSSAT model was used to simulate yield of these varieties for both ambient CO_2 (≈390 ppm) and elevated CO_2 environment (25% higher than the ambient) during the wet season (June-November) at Kharagpur, West Bengal. The simulated yield results showed that rice yield is expected to reduce by 13%, 17% and 4% for IR 36, Swarna and Swarna sub 1, respectively; whereas the Badshabhog rice variety yield is expected to increase by 7% with increasing CO_2 level of 100 ppm and rising temperature of 1°C as compared to the ambient conditions. Future climate projection for all four rice cultivars revealed that the yield of IR 36 and Swarna are expected to decrease under plausible A2 and B2 scenarios occurring in the 2020s, 2050s and 2080s with increasing temperature of 0.8 °C. However, Swarna sub1 and Badshabhog were found to be least affected under elevated CO_2 with rising temperature up to 2 °C in the sub-tropical climate of India.

Saadi et al. (2015) analysed climate change impact on ET, irrigation requirement and yield of tomato and wheat in northern Mediterranean countries, and showed that ET will reduce by 5 to 6% resulting in reduced irrigation requirements; up to 11% for wheat and 5% for tomato with a slight increase in relative yield loss of wheat in future.

8.5. Case Studies

8.5.1. Impact of Temperature on Paddy crop Evapotranspiration

The impact of plausible daily temperature scenarios on reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c) of paddy were analyzed for the reference period (1976-2005) and future projections (2011-2040, 2041-2070, 2071-2100) in the Kangsabati river basin of West Bengal state of India by using climate scenarios (RCPs 2.6, 4.5, and 8.5) of CanESM2 General Circulation Model. ET_o was estimated using the Hargreaves method as it depends on minimum and maximum temperature. ET_c was calculated by multiplying ET_o with crop coefficients (K_c). Bankura, Jhargram, and Kharagpur stations were selected under Kangsabati reservoir command, and seasonal ET_o and ET_c over the study area were calculated by averaging spatial ET_o and ET_c concerning these three stations for historical and future scenarios.

Climate Change Impact on Reference Evapotranspiration (ET_o)

Computed ET_o for the kharif season for four chosen stations under the historical and RCP scenarios (RCP 2.6, 4.5, and 8.5) are given in Table 8.1. During kharif season of the historical period (1976–2005), the highest and lowest ET_o of 534.78 mm and 523.90 mm were found at Bankura and Purulia stations, respectively. ET_o at all locations under RCP scenarios shows an increase with respect to historical period which is in tune with the changes in the maximum and minimum temperatures under different scenarios. The kharif season ET_o over the study area showed an increase by about 6–10 %, 7–9 %, and 6–17 % during three future time periods under RCP 2.6, 4.5, and 8.5 scenarios, respectively.

Table 8.1 Reference evapotranspiration (mm/kharif season) under the RCP scenarios for four stations of West Bengal

Station	OBS	RCP 2.6			RCP 4.5			RCP 8.5		
	1976–2005	2011-2040	2041-2070	2071-2100	2011–2040	2041–2070	2071–2100	2011–2040	2041–2070	2071–2100
Bankura	534.78	583.53	607.99	604.28	602.15	596.99	587.97	588.33	616.94	643.30
Purulia	523.90	559.57	578.39	576.52	575.56	570.58	563.30	568.32	589.39	610.34
Jhargram	526.91	547.85	578.46	570.53	566.91	560.11	563.30	535.41	582.50	624.34
Kharagpur	532.25	552.18	568.08	566.47	568.39	562.87	555.63	561.07	579.61	595.22

Table 8.2 Changes in seasonal crop evapotranspiration (mm) under the RCP scenarios with respect to the historical period (1976–2005) for four stations of West Bengal

Station	RCP 2.6			RCP 4.5			RCP 8.5		
	2011-2040	2041-2070	2071-2100	2011–2040	2041–2070	2071–2100	2011–2040	2041–2070	2071–2100
Bankura	55.63	79.77	75.32	72.76	68.78	60.12	60.01	89.95	117.92
Purulia	41.49	59.98	57.53	56.43	52.07	44.99	50.50	72.16	93.99
Jhargram	23.09	54.89	46.12	36.71	42.80	36.45	38.43	59.11	105.04
Kharagpur	23.04	38.68	36.49	38.13	33.51	26.53	31.46	50.88	67.67

Climate Change Impact on Crop Evapotranspiration (ET_c)

Kharif paddy ET_c was calculated at all stations under three RCP scenarios. For all locations and RCP scenarios, ET_c increased over the historical period. The change in seasonal ET_c showed different trends for different stations and RCP scenarios (Table 8.2). The highest and lowest ET_c were calculated for all three periods at Bankura and Kharagpur stations, respectively. The estimated paddy ET_c demand over the study area showed a variation from 580 to 604 mm under RCP 2.6, 587–595 mm under RCP 4.5 and 579–643 mm under RCP 8.5 scenarios with predefined three-time slices. The kharif paddy ET_c over the command area increased by about 6–11 %, 8–9 %, and 6–18 % during future three time periods under RCP 2.6, 4.5, and 8.5 scenarios, respectively.

8.5.2. Effect of Climate Change on Crop Yield

Rice yield was simulated under rainfed condition by using a well calibrated DSSAT model for seventeen major rice-growing states of India for historical (1981-2005), transition (2006-2015) and a future period (2016-2040). Observed weather data (i.e. maximum temperature (T_{max}), minimum temperature (T_{min}) and rainfall) from India metrological department and regional climate model (RegCM4) outputs (i.e. T_{max}, T_{min}, solar radiation and rainfall) were used in the model simulation. Fig. 8.1 shows the spatial distribution of mean and trend in rice yield during the study periods. The spatial yield results indicated that the average rice yield (Ya) ranges from 0.60 to 4.99 t/ha with an average value of 2.13 t/ha over the study region during the historical period whereas, during the transition period, Ya was found to be 2.17 t/ha. The model simulation outcomes for the future period indicated that Ya of the study area is expected to reduce from 2.13 t/ha (historical period) to 1.64 t/ha and 1.67 t/ha under RCP 4.5 and 8.5 scenarios, respectively. The trend analysis of simulated yield showed that rice yield would remain stagnated or decreased in considerably large portion of the study area (78-82%) under expected future climatic conditions.

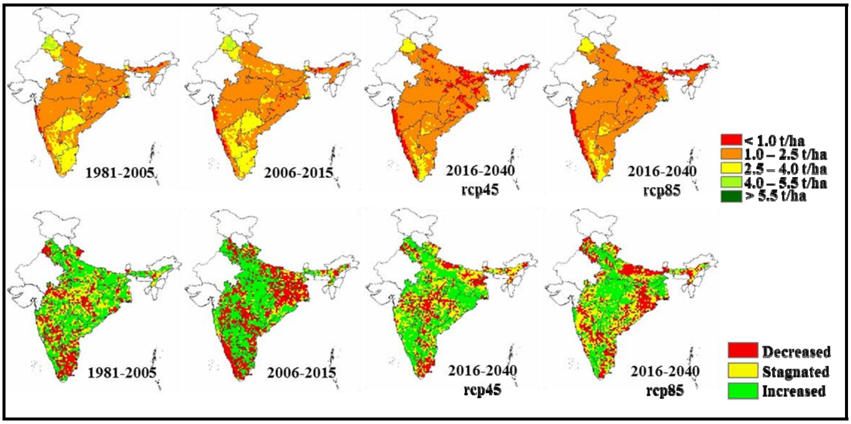

Figure 8.1. **Spatial patterns of mean and trend in rice yield during historical (1981-2005), transition (2006-2015) and future period (2016-2040)**

8.5.3. Effect of Climate Change on Evapotranspiration of Rice Crop in West Bengal, India

Climate change impact on evapotranspiration (ET) of rice crop was analysed for West Bengal, India by using well calibrated DSSAT model enforced with an ensemble of multiple GCMs outputs. Fig. 8.2 shows the spatial variation of averaged ET during the historical period (1976-2005) over the study area. Results showed that rice ET varies from 599 mm to 853 mm with an average of 738 mm in the historical period. Fig. 8.3 represents the average ET of rice crop for three future time periods (the 2020s, 2050s and 2080s) under four RCP scenarios (RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5). The results indicate that average rice ET may vary from 654 to 673 mm, 676 to 692 mm, 669 to 697 mm and 578 to 653 mm during the 2020s to 2080s under RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 scenarios, respectively. However, maximum ET over West Bengal was found to be 721 mm in the future period. The results suggested that rice ET is expected to decrease for all time periods under all four scenarios with respect to historical ET.

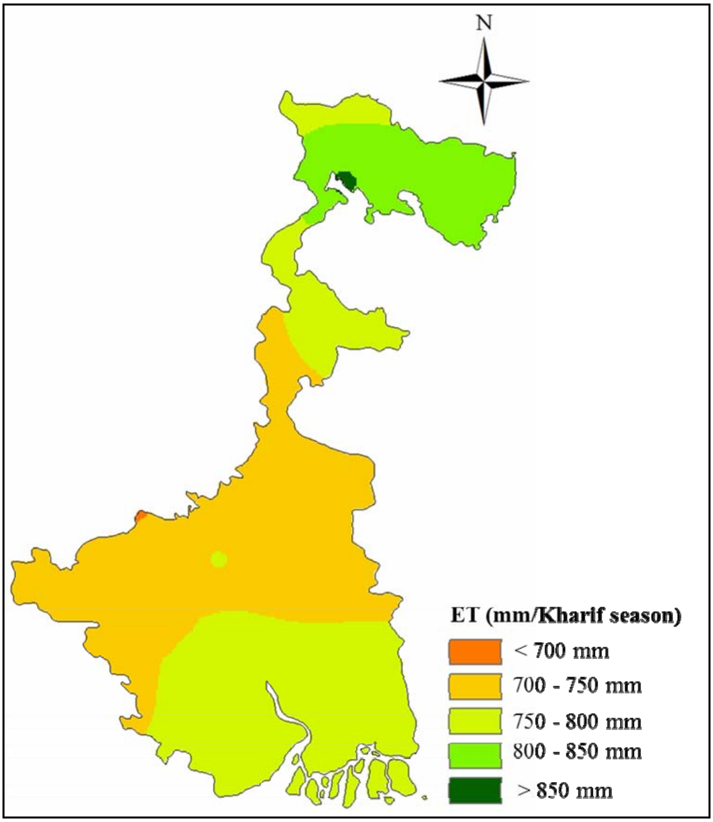

Figure 8.2. Spatial variation of average evapotranspiration of kharif season rice crop during historical period (1976-2005)

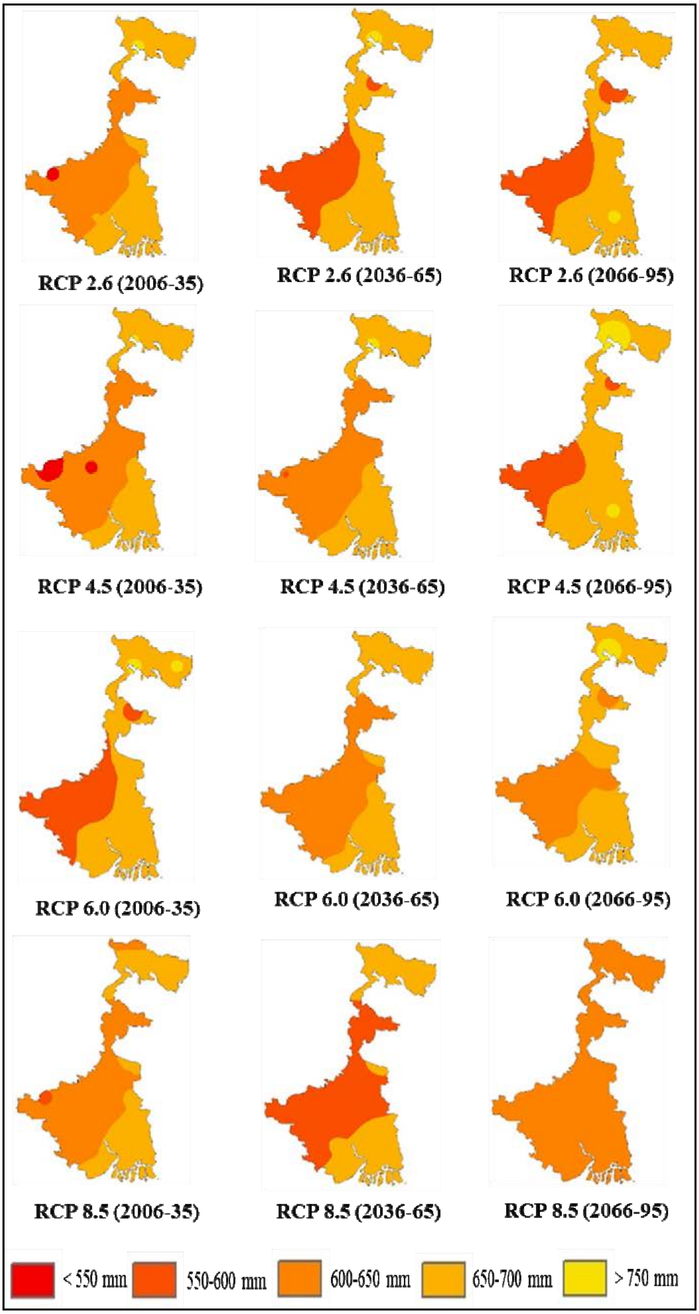

Figure 8.3. **Average rice evapotranspiration (mm/kharif season) for three future time periods: 2006-35, 2036-65 and 2066-95 under RCP 2.6, 4.5, 6.0 and 8.5 scenarios**

8.6. Conclusion

Climate change has severe impacts on the water resources, evapotranspiration and ultimately on crop yield. To assess these impacts, many studies integrated different climatic scenarios in hydrological modelling to project the status of future water resources, draw a conclusion and plan adequately to manage land and water resources. It has been observed from studies that precipitation is expected to increase in most of the Indian river basins in the future; accordingly, the annual average discharge will increase in future. The model simulated evapotranspiration results projects an increase in the same in future in the majority of river basins. The analysed trend of simulated crop yield; however, showed that the yield would remain stagnated or decrease in considerably large portions of the country under expected future climatic conditions

To understand the impact of climate change on crop evapotranspiration and yield of rice under present and expected future climatic conditions in India, we discussed a few case studies briefly. The results of these studies showed an increase in rice evapotranspirational demand from the lowest emission scenario (RCP 2.6) to the highest emission scenario (RCP 8.5) of projected climatic conditions. The spatial yield results showed that average rice yield is also expected to be reduced from 2.13 t/ha to 1.67 t/ha and 1.62 t/ha during future climatic conditions. These results are indicative of future changes in crop evapotranspiration and yield of rice and may be helpful for decision makers in better management of irrigation water demand. Further studies are necessary to explain the gap between projected irrigation water supply and irrigation water demand at expected future climatic conditions to ensure the optimum irrigation water supply and food security.

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Chapter 9

Water Use Projections in Industry Sector Under Different Climate Change Regimes

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Abstract

Industry (manufacturing) contributes to about 26% of the gross domestic product (GDP) and employs about 22% of the workforce. Some of the main industries such as textiles, chemicals, food processing, steel, and cement have been observing water stresses as an emerging risk and recognize its influence both directly and indirectly (through supply chains). Moreover, changing climate will impact both the quantity and quality of India's water resources. In this study, we have used a bottom-up model to estimate the future water demand in industry sector under business as usual (BAU), Intended Nationally Determined Contributions (INDC), and low carbon futures (2°C and 1.5°C) scenarios till 2050. We also simulate the impact of water constraint on all the scenarios. Our results show that India's industrial water demand will exceed its supply after 2020 in all the scenarios. Textile, paper, and the pulp industries will be the worst hits in water-constrained, low-carbon future resulting in shutdown and increased production costs. Some of the major policy recommendations include improving the current water use efficiency standards to 30-35%, implementing recycling and zero liquid discharge measures.

9.1. Introduction

Industry sector is the third largest consumer of water after agriculture and power sector[3]. More than 54% of India is already under high to extremely high water stress[4] conditions. This will disrupt surface-water supply connections, which will impact over 600 million people (WRI, 2015, AQUASTAT 2015). The

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[3] Industry sector can be classified based on macroeconomic activity (economics), and resource systems (such as energy, water). In certain literature (especially water resource planning), power sector is categorized as a sub-sector of industry sector for simplicity. Technically, power sector is different from the other industries as it generates and supplies electricity and hence it is termed as 'energy supply sector'. Agriculture, industries (such as cement, steel, paper and pulp, textiles etc.), residential and commercial sectors are termed as 'energy demand sectors'. Therefore, from a techno-economic-resource perspective, industry sector is considered different from power sector in this study.

[4] Water stress is the ratio of total water withdrawals to the total water supplied

share of water demand in the industrial sector for India in 2000 and 2010 is observed to be the same as presented in Table 9.1 in spite of the overall increase in total water demand. The quantity of water withdrawn by industry sector in industrialised nations like China and developed nations like the USA is comparatively huge. Therefore, with growing industrialisation, the industrial water use in India has been estimated to grow significantly in the coming decades.

Table 9.1: Water Use in the Industry sector

Country	2000	2010
India	10 (2)	17 (2)
China	114 (21)	142 (24)
USA	299 (53)	248 (51)

Source: AQUASTAT (2015), In brackets (industry water withdrawal as a share of total water withdrawal), Unit: km3/year

Changing climate due to warming temperatures causes shifts in hydrological cycles which adversely influence the quantity as well as the quality of water sources. Increase/decrease in the frequency of precipitation across India, precipitation intensity, future potential climate extremes (flood, especially drought), and sea-level[5] affects the water quantity in the industry sector. Discharge from industries in general and chemical, textiles, paper and pulp industries, in particular, contaminate water, deteriorating quality of available water resources. Rising water temperature due to climate change affects the water chemistry which in turn makes certain chemicals such as ammonia, pentachlorophenol more toxic to aquatic life (Bates et al. 2008). Garg et al. (2015) have projected an increase in the frequency of temperature (hot days and hot nights) and precipitation extremes across India that may result in devastating floods which may cause substantial damage and economic loss to human life and infrastructure. The frequency of droughts has been estimated to increase during 2016-2045 under the representative concentration pathway (RCP) 4.5 scenario.

The industry has faced and will continue to face the consequence of extreme climates. Large-scale industry has been affected by cyclones and flood extremes, while medium and small-scale industry estates and clusters have been one of the worst hits during droughts in the past decade after agriculture and power. Reducing water levels in reservoirs and dams directly impacts the industrial growth as it hits major water-intensive industries which include textiles, paper mill, food products and beverages[6], and cold storage facilities. In 2016, Sinnar, Satpur and Ambad industrial estates of Maharashtra Industrial

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[5] Rise for industries located near coastal areas

[6] Textiles, paper and paper products, food and beverages weight about 14% in index of industrial production – Manufacturing.

Development Corporation (MIDC) in Nashik suffered production loss of up to $53 million in just three to four months. Due to frequent droughts since 2012, Maharashtra reduced its water supply to 15,500 industrial units by 20-50 percent based on geographic location of the cluster, which has impacted the overall industrial production and growth of the state. During dry months and non-monsoon months of rainfall deficit years, industrial clusters in numerous districts of Maharashtra, Karnataka and Telangana are forced to shut down or reduce production. Industries (mainly large-scale and sometimes medium scaled) that continued operations in water-scarce regions incurred an increase in production costs as they had to buy water from private tankers during the period (Ghosh, 2017, Das, 2016, Ghoge, 2016, Sinha, 2016, TOI, 2016, Phadke, 2015).

Along with the National Environment Policy in 2006, the revised National Water Policy in 2012, National Water (NWM) Mission under the National Action Plan on Climate Change and Intended Nationally Determined Contributions (NAPCC 2008, INDC 2015) provide measures to address major issues concerning water. With the objective of "conservation of water, minimizing wastage and ensuring its more equitable distribution both across and within States through integrated water resources development and management", National Water Mission (NWM) under NAPCC incorporate five goals: a) comprehensive water database in public domain and assessment of the impact of climate change on water resource, b) promotion of citizen and state actions for water conservation, augmentation and preservation, c) focused attention to vulnerable areas including over-exploited areas, d) increasing water use efficiency by 20%, and e) promotion of basin level integrated water resources management (NWM, 2011, NAPCC, 2008).

Sustainable Development Goals (SDGs) were proposed in 2012 to build on the momentum gained by Millennium Development Goals (MDGs) to guide international action to end poverty, fight inequality and injustice, and tackle climate change from 2016 to 2030. Being a complex concept, the achievement of sustainable development requires inter-linking of the set goals, as the success or failure of one goal will directly or indirectly impact the associated goals (UNGA, 2014, Copenhagen Consensus, 2015). SDG 6 (water) under target 6.4[7], SDG 9 (industry, innovation and infrastructure) under target 9.4[8] along with SDG 13 (climate action) under target 13.2[9] call for "water- efficient actions in industry sector by integrating with climate measure under national policies

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[7] SDG 6, Target 6.4: "To substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity."

[8] SDG 9, Target 9.4: "To upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities."

[9] SDG 13, Target 13.4: "To integrate climate change measures into national policies, strategies and planning."

through upgrading current infrastructure and adopting resource-efficient, environmentally sound innovations" (UNSDG, 2018).

The Paris Climate Change Conference in December 2015 emphasised the implementation of climate action to achieve mitigation and adaptation goals. Mitigation pertaining to the energy sector consists of reducing emissions and moving towards 'decarbonised' and 'carbon neutral society' in line with the (intended) nationally determined contributions ((I)NDC[10]). Adaptation, on the other hand, consists of 'enhancing the adaptive capacity by strengthening resilience and reducing the vulnerability of the ecosystem to climate change' (C2ES. 2015). Water has been given particular focus under climate adaptation strategies, as it is one of the most important development challenges to attain. The Paris Pact on 'Water and Adaptation' has been designed to motivate countries to mobilize organizations at all levels (national, state, local) to commit and take actions to build capacity and knowledge to govern and manage the water resources at basin level. It also calls for establishing sustainable investment and financial programs to implement the actions (UNFCCC LPAA, 2015).

Very few studies have been carried out on water usage and water use efficiency especially in industry sector at a national level for India. No independent legislation addresses the water use and water use efficiency from not only 'holistic' perspective but also from an 'integrated resource system' approach. Additionally, studies have not yet looked into the impact of climate change and low-carbon futures on overall industrial water demand for India. A bottom-up optimization modeling framework (AIM/Enduse) is used in this study. The subsequent sections give detail about the methodology, results from the model followed by key insights on future water demand and water-use efficiency in the industry sector.

9.2. Methodology

Integrated water-energy systems captured through top-down models such as GCAM have been used to project global irrigation water demand (Chaturvedi, 2013), bottom-up models such as MARKAL have been used to capture water-energy nexus at national level (Bazaz, 2011) and MESSAGE model was used to project the water demand for national electricity generation (Mitra et al., 2014). IAMs have also been used to assess the risk exposure of Delhi to extreme events such as floods by integration of regional climate models, river computer-aided design (CAD), a glacial model with AIM/Energy Snapshot (ESS) in a GIS framework (Khan, 2009). Pre-1990s global water demand projections include

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[10] The Intended Nationally Determined Contribution (INDC) for India became its Nationally Determined Contribution (NDC) on 2nd October 2016, a year after it was ratified during the Paris Agreement in 2015.

population as the sole driver of change (WRI 1990, L'vovich, 1974). Post 1990s, the projections considered region wise structural changes in economic growth, demography, lifestyles and consumption patterns, and technological advances in improving water-use efficiencies in addition to variation of climatic factors and their impact on water use (Alcamo et al., 2003; Cosgrove and Rijsberman, 2000; Lundqvist and Gleick, 1997; Rosegrant et al., 2002; Seckler et al., 1998; Shiklomanov, 1997, 2000; Shiklomanov and Balonishnikova, 2003). Shiklomanov (1997) contributed to comprehensive assessments of the freshwater use of the world to the United Nations Commission on Sustainable Development (UN 1997) and the World Water Council at its Second World Water Forum. It also provided estimates of water withdrawals and consumption patterns for the base year for many other studies. International Water Management Institute (IWMI) studies (1998 to 2014) have estimated water demand for 193 countries (Amarasinghe and Smakhtin, 2014).

9.2.1. Addition of Water Module in AIM/Enduse

The current study aims to model the energy and environment systems of major sectors in India to capture the impact of multiple objectives of the exiting and implementable policies on water and energy systems. Vishwanathan et al. 2018 explain why AIM/Enduse is well-suited to model the techno-economic perspective with sectoral granularity for India. Vishwanathan et al. 2017 describe in detail the development of model set-up and drivers for the energy sector to report primary and final energy mix, emission from the energy system, electricity generation capacity additions and related mitigation costs for various sectors. In this chapter, we focus on the water module that been added and developed[11] to capture the water-energy nexus of industry sector to simulate future water demand, water type and technology mix for reference and alternate climate change regimes.

Figure 9.1 demonstrates the general water and energy flow into the major sectors. Figure 9.2 illustrates the addition of water as an input into the major sectors of the AIM/Enduse energy model. It aims to capture the water system from the source (rainwater, surface water, groundwater) to processing (treatment), transmission (conveyance systems) and through the end-use.

The advantage of the integration is multi-fold. The model works as a decision support tool for planners and policymakers as it projects total water withdrawal and consumption for major sectors and wastewater generation from the major sectors. It also estimates the energy needs in both the water and wastewater sectors. The technologies for both water and energy (W-E) are optimized simultaneously to configure the least cost water and energy system, subject to the policy, resources (energy, water) and emission constraints. Data

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[11] Parts of this section have been mentioned in MILES and COAL TRANSITIONS reports

from secondary literature has been used in the water-energy model to estimate the water supply until 2050. This is used as a resource constraint in the techno-economic AIM/Enduse W-E model to understand how it impacts both energy supply and sectoral demand of water, thereby improving the dynamics of the water resource supply curve. This study focuses on the aspect of future water demand (quantity) and touches on the quality aspect from availability perspective (recycled water). Limitation of the current study is that it does not include the source (rainwater, surface water, groundwater) of water supplied.

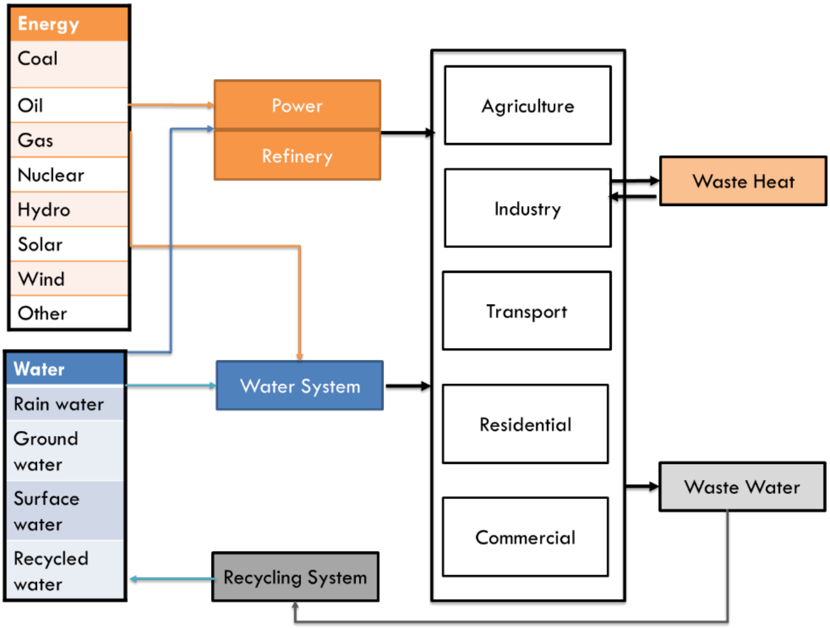

Figure 9.1: General Energy and Water Flow in any economy

9.2.2. Key drivers, boundary and enabling conditions

Boundary conditions, in this case, include carbon budget (Vishwanathan et al. 2018, Tavoni et al., 2014) and water supply limit (NAPCC, 2008). The model is set up for five major sectors and their respective services, technologies, reference years and discount rates. These sectors include agriculture, power, industry, and buildings. The maximum shares for the base year are taken from various government and research publications. We estimate the shares for the projected years based on population, economic growth, and sectoral transformation and using current policies (Vishwanathan et al. 2018). Various driving forces influence water supply and demand for a service, which include sectoral demand (population and economic growth), water parameters (input

– rainwater, groundwater, recycled water, output – wastewater) as material flow and set of technologies (new, improved, replacement).

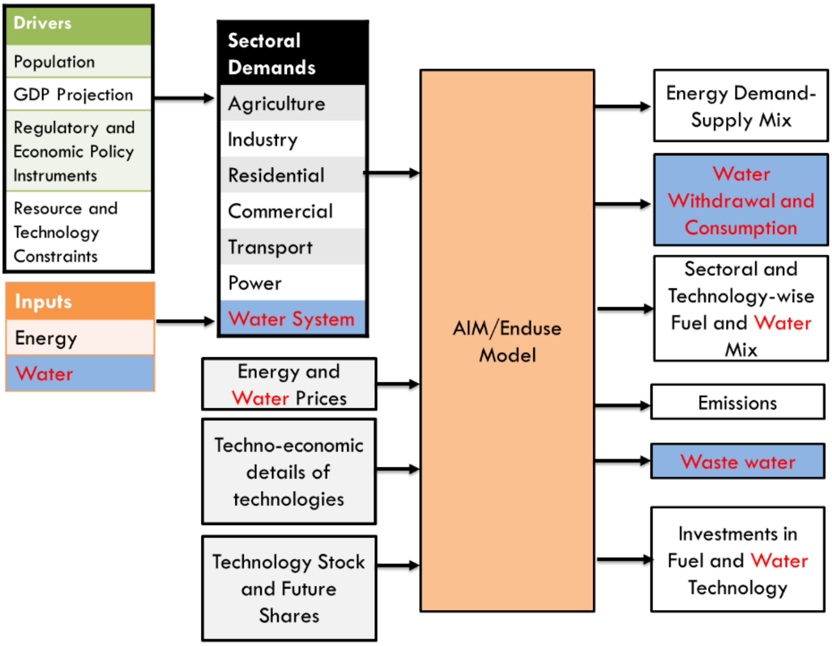

Figure 9.2: Modified AIM/Enduse Water-Energy (W-E) Modelling Framework

Note: Model developments pertaining to water are highlighted in red Energy modelling framework adapted from Vishwanathan et al. 2018, Shukla, et al., 2004, Kainuma, et al., 2003

9.2.2.1. Sectoral Demand

Vishwanathan et al. (2017) describe the trend from 2000-2015 and growth of major industries till 2050 in detail. The water requirements per unit for industries differ according to the sources. For instance, the share of water demand for industry differs from 6-15% depending on the reporting agency[12]. The water demand will rise rapidly, however, at the same time, there is an increase in pollution. In spite of regulation, more than 40% of the wastewater generated is discharged without being treated (IIR 2015). Table 9.2 presents the water productivity of industries used in the model for the base case scenario. We have also modelled for reuse of recycled industrial wastewater.

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[12] Ministry of Water Resources (MoWR), Central Pollution Control Board (CPCB), World Bank (WB), National Commission on Integrated Water Resources Development (NCIWRD). The estimation differ based on the methodology used by each of the agency.

Table 9.2: Water productivity of industries

Industry	Unit	CSE, 2004	GoI, 2014	Global average
Steel	m^3/tonne	4	22	5.0-10
Oil refineries	m^3/tonne	1.5	NA	NA
Smelters	m^3/tonne	NA	82.5	NA
Paper and Pulp	m^3/tonne	85	200	50-75
Textile and Jute	m^3/tonne	200	200	<100
Fertilizers	m^3/tonne	5.5-6.5	NA	NA
Leather products	m^3/tonne	NA	30	NA
Distillery	m^3/tonne	NA	22	NA
Inorganic Chemicals	m^3/tonne	NA	200	NA
Pharmaceuticals	m^3/tonne	NA	25	NA
Cement	m^3/tonne	0.5-1	NA	NA

9.2.2.2. Policy Assumptions

The Water (Prevention and Control of Pollution) Act, 1974 provides 'prevention and control of water pollution, and for the maintaining or restoring of wholesomeness of water' in the country. The Water (Prevention and Control of Pollution) Cess, 1977, provides 'levy and collection of a cess on water consumed by persons operating and carrying on certain types of industrial activities'. The Water (Prevention and Control of Pollution) Cess Rules, 1978, provide 'the maximum limit of water allowed to be consumed by industries (Table 9.3).

Table 9.3: Maximum water consumption limit

Industry	Sub-industry	Category	Water Consumption per unit (m^3/tonne of product category)
Steel	Steel	finished product	20
Metal	Copper	Copper	100
	Zinc smelters	zinc smelters	50
Textile	Manmade fibre	manmade fibre	NA
	Nylon	Fibre	170
	Viscose	Fibre	200
Paper and Pulp	Agro residue	Paper	200
	Waste paper	Paper	75
	Pulp and paper	Paper	250
	Rayon	Paper	200

Source: Water (Prevention and Control of Pollution) Cess Rules, 1978

9.2.3. Scenario Development

The water scenarios in the model follow India's commitment to its adaptation goal through National Water Mission (NWM) which are supported by programmes such as Integrated Watershed Management Programmes (IWMP), scaling up of micro-irrigation (sprinkler, drip) technologies under National Mission for Sustainable Agriculture (NMSA) and so on. Table 9.4 summarizes the main assumptions under BAU, INDC, 2 °C and 1.5 °C scenarios.

Table 9.4: Scenario Assumptions in current and alternate futures for the industry sector

Scenarios	Policies	Comments
Business as usual (BAU)	Existing policies	20-25% during 2005-2020
(Intended) National determined contributions (INDC) (3- 3.5 °C)	Existing policies + Implementation of INDC polices (National water mission) + National Water Policy (NWP)	WUE: 20%, decrease in water consumption in thermal power plants, 40% non-fossil-fuels
2 °C scenario	Aggressive implementation existing and INDC polices (NWM) + Demand reduction + Carbon capture and Storage (CCS)+ (NWP)	WUE: 20- 30%, decrease in water consumption in thermal power plants, Carbon budget : 115-130 Bt CO_2 during 2011-2050
1.5 °C scenario	Aggressive implementation existing and INDC polices (NWM) + Demand reduction + CCS+ (NWP)	WUE: 30-35%, decrease in water consumption in thermal power plants, Carbon budget : 90-115 Bt CO_2 during 2011-2050

9.3. Results

9.3.1. Water Demand under BAU until 2050

Figure 9.4 shows that impact of WUE policy on water demand. It is observed to increase in both reference (BAU) and INDC scenarios, exceeding the country's water supply limit of 1122-1197 bcm per year in and after 2020. However, there is a reduction in the demand for water in INDC scenario when compared to the reference. The demand exceeds the supply limit by 34% in 2030 and by 79 % in 2050 under the BAU scenario as illustrated in Figure 9.3.

Agriculture water demand share decreases from 80% of total demand in 2000 to 72% in 2050 in the BAU scenario. Power and industry share increase from 7% and 5% in 2000 to 13% and 7% in 2050 respectively. Figure 9.4 presents the segregation of the demand among major water-intensive industries. Share for cement, steel, fertilizer, textile and paper account for more than 60% of the total industrial water demand.

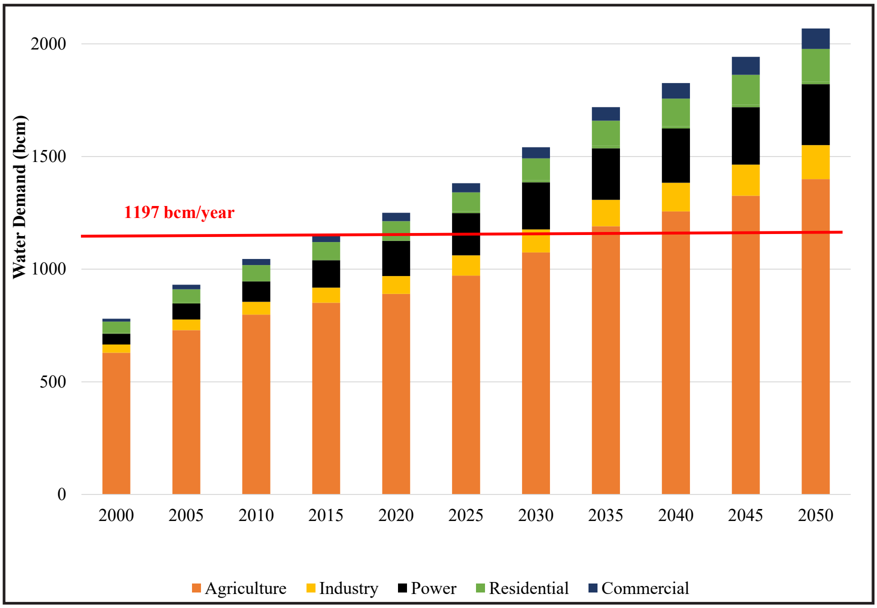

Figure 9.3: Water demand and supply under BAU

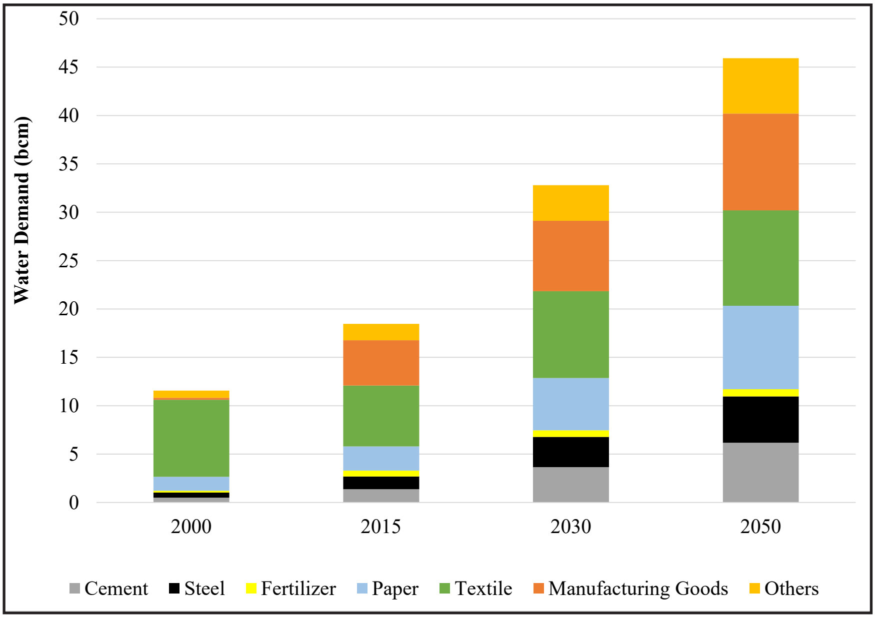

Figure 9.4: Water demand in industry sector under BAU

9.3.2. Water Demand under Alternate Scenarios until 2050

The share of water demand in the industry sector accounted for more than 5% of the total water consumption in 2000. At a growth rate of 2-3%, this share has raised to 10-12% in NDC and low carbon futures[13] (Figure 9.5) from 2015 to 2050. The demand exceeds the supply limit by 19% in 2030 and by 40% in INDC scenario in 2050. Similarly, in low carbon futures, the demand exceeds by 7-14% in 2030 and by 18-26% in 2050. The overall demand of water decreases by 16 bcm in NDC scenario between 2011 and 2050, however, it increases by 113 bcm in 2°C scenario and by 37 bcm in 1.5°C scenario over BAU scenario.

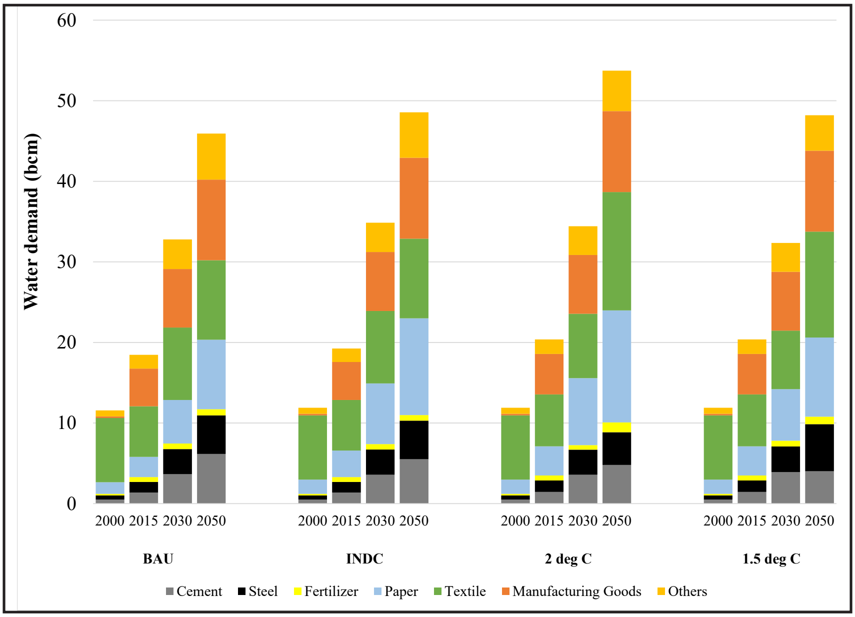

Figure 9.5: Water consumption in industry sector under alternate scenario

NDC scenario observes an increase in water use efficiency of industry sector to improve by 2-7% in 2030 over 2015 and by 10-28% in 2050 for fertilizer, paper and textile. In the INDC scenario, the demand for water decreases marginally when compared with BAU scenario due to the implementation of WUE measures (through notifications) in agriculture and power sector. For low carbon futures, even as recycled water is used, there is a decrease in water use efficiency due to addition on CCS in cement, steel and fertilizer industry by 14-59% over BAU scenario. Unlike, agriculture and power sector, without stringent efficiency policies, the water demand is expected to rise in the industry sector.

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[13] Low carbon futures in this chapter refer to 2^0C and well-below 2^0C (1.5^0C) scenarios.

The share of water demand in the textile industry is the highest (20-27%) under NDC and low carbon futures in 2050 (Figure 9.5). This is followed by paper and pulp (17-26%), iron and steel (8-12%) and cement (8-12%). The increase in water use under low carbon futures is due to the addition of CCS in cement and iron and steel industry, despite the increase in the share of recycled to 24-39% in 2050 (Figure 9.6).

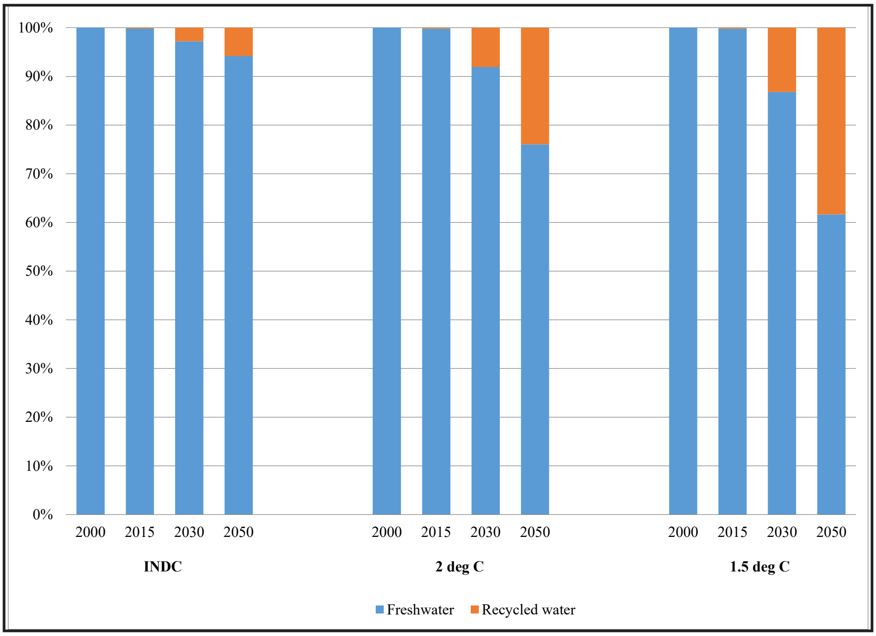

Figure 9.6: Share of recycled water in industry sector under alternate scenario

9.3.3. Impact of Water Constraint on Demand under Alternate Scenarios until 2050

When water supply limit (*1197 bcm*) is placed as a constraint on the water-energy system, it simulates the water stress to estimate its impact on final water demand and water-use efficiency. It is observed that overall water demand reduces in low carbon futures by 13% in 2030 and 36% in 2050 (Figure 9.7). The water productivity of fertilizers, paper and textile industry is most affected in the water-constrained scenario. To continue operations, fertilizer, paper and textile industry need to enhance its current overall WUE (NDC scenario) by 1.8 m^3/tonne (16%[14]), 54.8 m^3/tonne (22%) and 12.8 m^3/tonne (18%) in 2030 and by 7.6 m^3/tonne (36%), 75 m^3/tonne (29%) and 63 m^3/tonne (65%) respectively in 2050 under 2°C scenario.

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[14] The WUE of fertilizer reduced by 1.8 m3/tonne, which accounts for 16% reduction over NDC scenario in 2030.

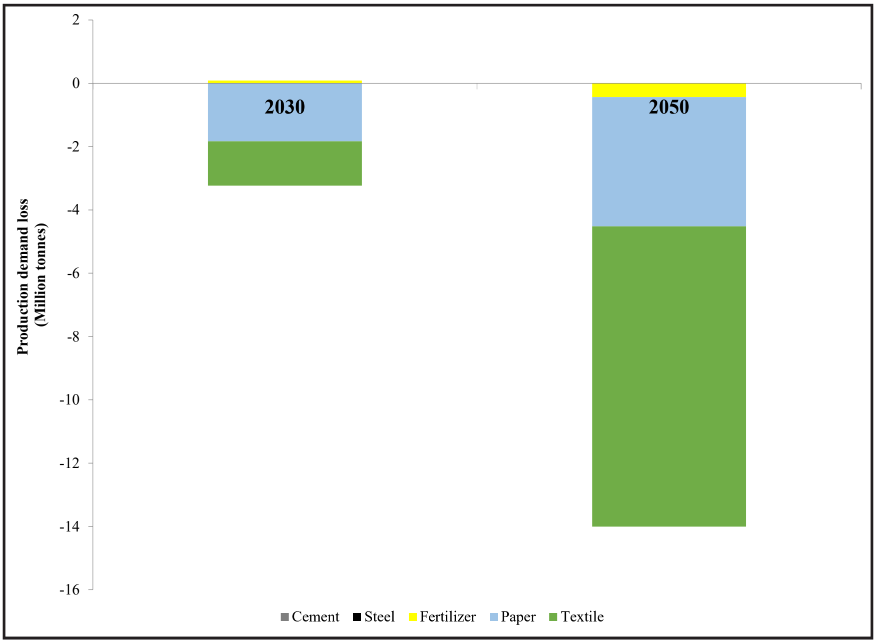

Figure 9.7: Reduction in water demand in a water-constrained system (2°C scenario)

If current specific water consumption (NDC scenario) is continued under 2°C scenario, the demand production in fertilizer, paper and textile industry will reduce by 0.08 million tonnes (MT), 1.8 MT and 1.4 MT in 2030 and by 0.4 MT, 4 MT and 9.5 MT respectively in 2050 (Figure 9.8). This may be due to a combination of reduced production or shut down of certain industries. Therefore, more stringent measures in major sectors and sub-sectors in place of the current mandated 20% improvement in water use efficiency is required when we move towards low carbon futures. These can be achieved through a combination of technological interventions and policy instruments.

9.4. Technological Interventions and Policy Recommendations

Industrial water use efficiency is quite low in India when compared to the global average in all the industries. There are three main reasons: a) weak regulatory standards, b) low cost of securing water, and c) low tariff structure[15]. Furthermore, lack of enforcement, a multiplicity of agencies (such as MOWR, MOEFCC, and MOUD), illegal water acquisition and tax violation issues are some of the challenges faced by states to implement water usage

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[15] Ranges from INR 15-720 per m^3 depending on the industry and State government. Some governments have a uniform rate for all industries.

policies. Currently, recycling and reuse are being conducted only in large cities, and desalination capacity stands at 0.33 bcm annually. Harvesting of rainwater is being made mandatory in many states. However, its contribution has been miniscule in comparison to its potential. About 73% of industrial water demand is met through the surface water while the rest is through groundwater resources.

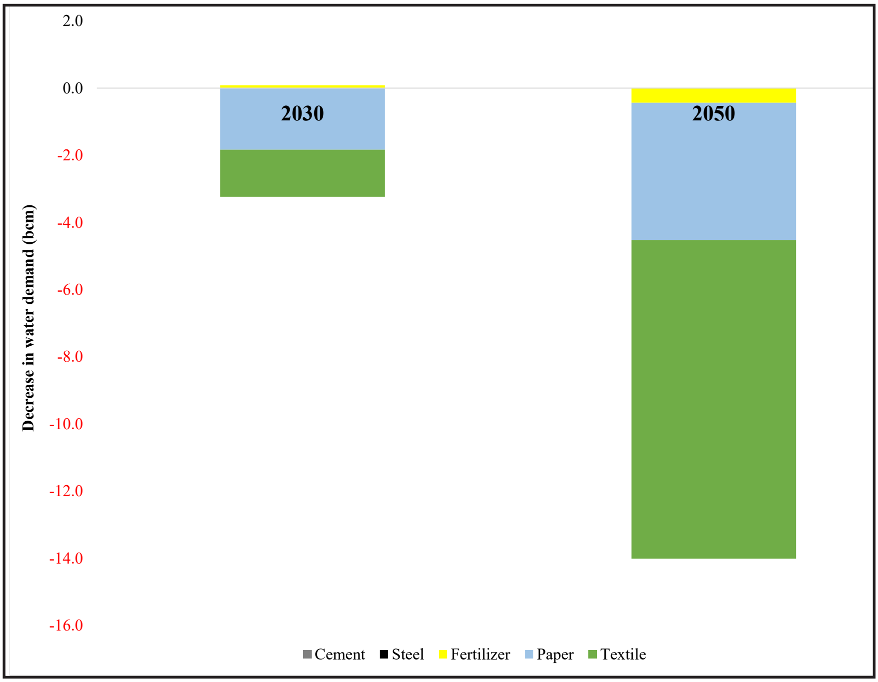

Figure 9.8: Production loss in 2°C scenario at 20% WUE

India needs to establish Bureau of Water-Use Efficiency to develop policies and strategies to push self-regulation and market principles to improve water-use efficiency to conserve water. There is an immediate need for laws and regulations for industry-specific water consumption similar to the ones created for the power sector in 2017.

Bemelmans-Videc et al. (1998) classified policy measures as a) regulations (sticks), also known as command and control (CAC) instruments include technology-based, performance-based and management based approach, and b) market-based instruments (MBIs) or economic incentives (carrots) can be of different categories including taxes, subsidies, and tradable permits and so on. The third kind of instrument using information can also be used as a substitute or complement to other instruments (regulations and MBIs). India has been using CACs (technology and performance-based) to regulate its resources (e.g., energy) and environment (e.g. pollution, emissions) with the recent introduction of some categories of MBIs through taxes, subsidies and tradable permits through pilot programmes. Information disclosure has been used to complement the CACs in some cases especially to promote energy efficiency or reduction of effluents/emissions. Table 9.6 presents a few examples of how these instruments can be used to improve water-use efficiency in the industry sector.

Table 9.5: Technology intervention to improve Water use efficiency

Industry	Technology Interventions
Industry	• Cooling purposes for captive electricity generation -> reduce specific water consumption below 4 m3/MWh • Recycling and reuse of wastewater from cooling and processes
Cement	- Shift to dry process for power - Rainwater harvesting - Water metering, Use of PVC instead of MS pipes to control leaks - Reuse cooling water for dust suppression - Deploy STP, ETP and RO[1]
Steel	- Shift to dry process for power - Reuse cooling water, condensate, process water
Paper	- Water metering to control leaks - Reuse cooling water, condensate, process water - Treat waste water and recover energy - Zero liquid discharge
Fertilizer	- Shift to dry process for power
Textile	- Hot water recovered and reused for bleaching - Reuse of scouring, jet-weaving, bleach, mercerizing rinse water - Use of automatic shutoff valves during continuous dyeing - Avoid overflow rinsing during VAT dyeing - Zero liquid discharge
Food	- Shift to improved wet cooling or dry process for power - Reuse cooling water, condensate, process water - Treat waste water and recover energy
Beverages	- Treat waste water and recover energy - Zero liquid discharge
Tanneries	- Treat waste water and recover energy - Zero liquid discharge

Source: IIR (2015), SIWI (2012).

The industrial sectors account for a small percentage of total water use directly when compared to agriculture and power. However, water constraint under different climate regimes will be a direct risk to major water-intensive industries as they require water uniformly throughout the year. These risks include: increase in overall production cost and shut down of industrial units due to non-compliance. Industry's gross value added contribution is more than 29% of India's GDP (manufacturing sector accounts for 16% of Indian GDP), at the same time, it is also one of the major sources of water pollution. Studies have shown that the release of one-litre effluent without wastewater treatment can pollute six-ten litres of fresh water, which decrease the availability of water in the future. In 2013-14, 8.7 bcm out of 14.4 bcm effluent was treated. So, roughly the remaining 5.7 bcm of effluent contaminated about 34-57 bcm of water. The lower range (34 bcm) is almost equal to the amount of water demand required for industry sector in 2030.

Table 9.6: Policy instruments to improve water use efficiency in the industry sector

Regulatory Instruments	Economic Instruments	Information Instruments
• Stringent Effluent Standards (ES) • Stringent Wastewater Treatment Standards (WTS) • Zero discharge	• Tariff based on manufacturing costs[2]	• WaterSense Programme for water billing • Standards and Labelling - Mandatory appliances (water-efficient pumps) - Voluntary appliances (water meters, shift to PVC pipes)

Improving the water-use efficiency to 30-35% will not only significantly increase conservation of water but also reduce effluents. At the same time, stringent effluent and water treatment standard will result in lesser pollution of surface and groundwater supply. Zero liquid discharge (ZLD) technologies have been available in Europe ever since the 1980s, and have been mandated in India from 2008 in textile, paper and pulp, distilleries and tannery industry. To install a five million litres per day capacity ZLD plant requires $4-5 million in capital expenditure and $0.9-1.5 million in operation expenditure annually. The reclaimed (treated and recycled) water is priced at $3 per litre while the cost of water supply from the municipality or groundwater extraction will range around $0.4-0.9 per litre. Many of the textile units in Tirupur, Tamil Nadu, were forced to shut down due to non-compliance in 2015 as the cost of installing ZLD was too high (Sustainability outlook, 2015).

A good tariff design balances economic efficiency, fairness, equity, revenue sufficiency, net revenue stability and resource conservation. It should be simple to understand (Boland, 2011). Therefore, to charge higher tariffs for industrial users the design needs to be based on the source of water, cost of supply, and manufacturing cost of the product, consumer market, revenues, and quality of treated effluent discharged. Implementation needs to be phased in over time and accompanied with information dissemination in the form of technical assistance and/or information campaigns.

9.5. Discussion and Conclusions

Rainfall variability already causes significant impacts on industry sector across the country. With climate change expected to amplify these impacts, the industry sector in India will have to adapt to increased uncertainty and growing water scarcity to meet the demands of a growing population. This chapter focussed on the impact of climate change on industrial water demand and presents that improving water use efficiency in various industries will play a significant role in low-carbon, water efficient futures.

Water has been termed as a 'public good' by conventional economists however Indian Water Policy 2012 defines it as a 'common pool resource'. Reforms to supply water to urban areas in the 90s transformed it into the 'economic good' status. Keeping in mind all its competing uses, water is a finite and vulnerable resource, especially in India. The economic value of water needs to be considered not only due to its use and scarcity value as a resource but also social, cultural and ecological significance it holds to the community, society and ecosystem. Only a few states (Andhra Pradesh, Karnataka, Orissa, Jharkhand, Rajasthan and Haryana) have policies to govern industrial water sector. Priority listing of industries for water allotment after human, agriculture and power based on industrial production, the scale of the industry and employment should be mentioned in national and state policies.

Water use in Indian industry is observed to be high when compared to global standards due to a combination of factors which include obsolete process technology, poor recycling and reuse practices and poor wastewater treatment. Conservation consciousness should be promoted through policy instruments[16]which will vary based on geographic location and climatic-hydrologic conditions. Water use efficiency is low-hanging fruits that need to be executed and optimized in all industrial processes to minimize water use. In short-term, this needs to be implemented through water-efficient technologies, however, in the long term, this needs to be realized through market-based instrument combined with regulatory and information based policies.

Short and Medium Terms – Water Efficient Technologies

Water efficient technologies will play a major role to reduce overall water demand in the industry sector. Recycling and reuse of treated water also offer a viable solution. However, this is expensive for industries due to the economy of scales, access to sufficient sewage at a reasonable cost and land to accommodate recycling plants. Stringent implementation of zero-discharge has been mandated for four industries and need to be up-scaled to other industries estates and clusters. These technologies need to be financed by

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[16] Regulatory, economic and information based incentives/disincentives

innovative business models, otherwise medium and small-scale industry will be forced to shut down due to non-feasibility. This technology will become extremely important if CCS needs to be installed to mitigate carbon emissions after 2020.

Long-Term – Water Pricing and Stakeholder Accountability through Metering

Price has played a major role in institutionalizing change in materialistic society. From an economic perspective, marginal pricing of water based on the value added to GDP and its importance to attain SDG 9 (industry) needs to be considered based on all-inclusive factors some of which include type of industry, its scale (market size, employment), geographic location, seasonality, and quality of water.

Footnotes

1 Standard Treatment Plant (STP), Effluent Treatment Plant (ETP), Reverse Osmosis (RO).

2 CII Report (2013): Textile (1.5-1.8%), Cement (0.775%), Paper (0.57%), Fertilizer (0.37%).

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Chapter 10

Implications of Climate Change on Water Quality: A Review on Perspective and Challenges

Manish Kumar[1*] and Pinky Taneja[1]

Abstract

Climate change has long been identified as a serious environmental issue. Although there exists a common notion that global warming is occurring, the effects of climate change on water quality have not been given due attention. In order to complement the knowledge-gap, this chapter presents the plausible relationship between climate change and water quality. Impact of climate change on water quality is manifested through the variability in temperature and hydrological variables. Ambient air temperature may cause fluctuation in water temperature thereby causing a variation in different water parameters, which in turn affects the bio/physicochemical equilibrium of aquatic environment such as metabolic activities of aquatic species and also determines the solubility, availability, and toxicity of certain bioactive compounds. Such slight variations in the temperature of water affect oxygen solubility, mineralization, and chemical equilibriums which in turn impacts the associated aquatic ecosystem. Frequent analysis of these modulations through climatic models could reveal significant information to help protect the affected population and develop an insight into the forthcoming events.

10.1. Introduction

Water is of fundamental importance for life on the Earth. With the current rise in water demand, all the efforts are made towards the sustainable conservation of water. However, maintaining the quality of water is equally important to ensure safe access to water to all. According to WHO and UNICEF 783 million people are still relying on unimproved water sources with increased microbial and chemical contamination (WHO/UNICEF, 2010). Sustenance of acceptable quality and long-term supply of drinking water to all is of national and international concern. Impaired water quality is a growing concern limiting resources for domestic, agricultural and industrial purposes (Krenkel and Novotny, 2012). The increased temperature and weather extremes are creating significant challenges in maintaining water quality.

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The global rise of temperature is a cause of concern presently. Global warming and climate shifts over the last 50 years have been directly linked to human emissions (IPCC, 2001). The panel on climate change has studied the effects of climate change on various components of the earth system. Potential impacts of climate change include temperature rise leading to urban heat build-up, more frequent rainfalls causing floods and rising levels of urban drainage systems, increased water demand, loss of soil moisture, increased stormwater discharges, inducing heat stress conditions and water quality deterioration. The IPCC fourth assessment report has documented the impact of climate change on water quality. They have pointed out that the climate-change-induced imbalances between water demand and water availability will directly/indirectly affect the water market transaction from rural to urban or environmental uses (Kundzewicz et al., 2008). Therefore, there arises a frequent need to study the water quality factors affected by changing meteorological patterns to allow disbursement of safe drinking water for all.

There are predefined norms for water quality parameters defined within a narrow range that are to be maintained for different purposes as described in Table 10.1. Increase in temperature is associated with changes in physicochemical characteristics of water. The global rise of temperature by 2°C assumes higher variations in weather pattern on a local scale and, a 2°C rise in temperature has the potential to alter the value of water quality parameters. Climatic variations are accompanied by the changes in these water quality parameters affecting the dependent population at large (Figure 10.1).

Table 10.1: Guidelines for different water quality parameters

Parameters	pH	Nitrate (mg/L)	Arsenic (mg/L)	Fluoride (mg/L)	BOD (mg/L)	Total suspended solids
Drinking water	6.5-8.5	45	0.05	1	nil	500
Sewage water	5.5-9	nil	0.2	15	350	600
Irrigation water	5.5-9	nil	0.2	nil	100	200
Marine coastal areas water	5.5-9	20	0.2	15	100	100

*CPCB, 2010

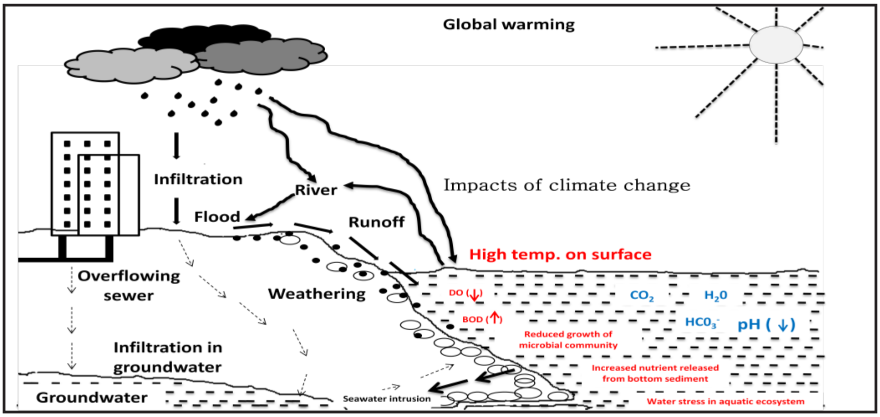

Figure 10.1: Implications of climate change on environmental components

This chapter envisages the effects of climate change on associated water quality and human health. The major implications of temporal variations and their associated environmental phenomena are studied at depth. Predictions of such events using different models have also been proposed as an initiative towards a safe future.

10.2. Climate Change Driven Processes

Environmental changes with due course of time as a result of climatic variability could influence the processes governing life on earth. Different parameters defining the quality of life are interrelated and depict significant changes in response to climate change. The changing climate has been predicted to increasing temperature altering the pH of water, decrease in the dissolution of oxygen, increased carbon dioxide (CO_2) absorption, loss of stability of calcium carbonates affecting the skeleton of corals and shelled animals (Fig. 10.2). Therefore, the acid-base chemistry of seawater determines the analytical parameter of the primary seawater acid-base kinetic equilibrium system involving carbonic acids and water as follows (Kumar et al., 2009):

$$CO_2+H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2H^+$$

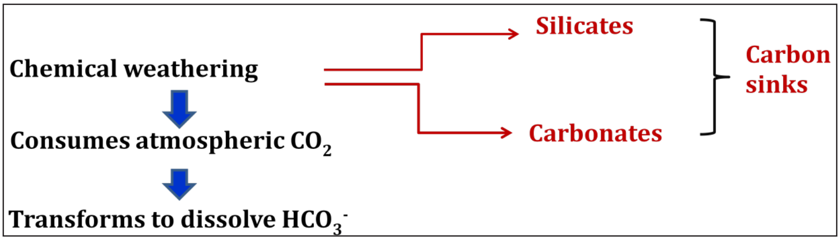

Figure 10.2: Change in Carbon dioxide flux in response to variations in climatic pattern

Along with the disturbance of marine life, such conditions would also impact human health by inherent mechanisms leading to a rise in diseases. Thus, arises the necessity to study the interrelationship among these factors.

10.2.1. Temperature

Sudden temperature rise is observed from 2001 to 2010 (Fig 10.1). The mean global surface temperature increased by 0.76°C in the last 150 years (IPCC, 2007). This temperature change is likely to affect oceans, weather patterns, snow and ice and plants and animals. The temperature increase alters growth rates of biological entities owing to increased CO_2 dissolution in oceans and reduced pH conditions (Fig. 10.3). Rising atmospheric concentrations of CO_2 are causing more gas absorption by oceans thereby increasing their acidity and impacting coastal and marine ecosystems.

A decrease in seawater pH of 0.15-0.35 units is expected by the year 2100. This could further impact the growth rate of aquatic organisms in response to reduced carbonates essential for marine calcifying organisms (Feely, 2004; Fabry et al., 2008).

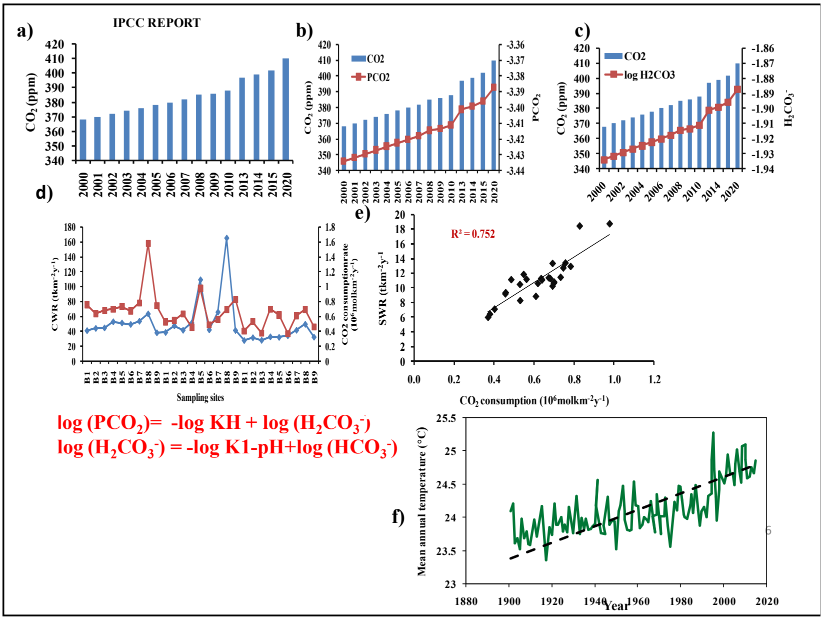

Figure 10.3 **Climate change induced impact on the River alkalinity a) rise in carbon dioxide concentration through years b) change in carbon dioxide concentration in relation to pH c) carbon dioxide concentration and bicarbonate formation d) carbon dioxide consumption rate e) plot of carbon dioxide consumption and f) mean rise in temperature in India**

10.2.2. Rainfall Intensity

Increased greenhouse gases and climate change patterns are projected to cause rainfall of variable intensity, frequency and duration. Increasing temperature is linked to variable precipitation levels on a global scale (Dore, 2005). The regional climate models have suggested an increase in intensities of rainfall in coming decades (Ekstrom et al., 2005) (Fig. 10.4). Increasing rainfall intensities is reported in many parts of the world in response to warming of the earth (Allan and Soden, 2008; Lenderink and Meijgaard, 2008; Wang et al., 2008). Ghosh et al., 2009 and Goswami et al., 2006 has also found a significant rise in precipitation intensity in various regions of India. This increase in spring runoff could further result into more nitrogen, phosphorus and other pollutants in coastal waters.

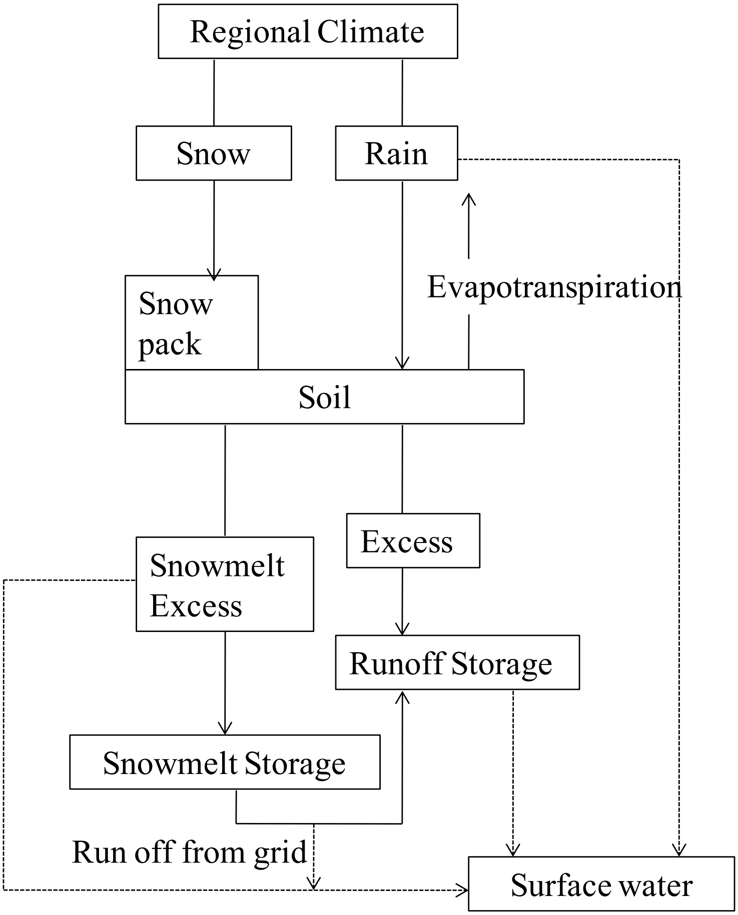

Figure 10.4 Effects on regional climate in response to excess rainfall and snowmelt

10.2.3. Extreme Events

Another major consequence of sudden temperature rise and climate change is explained in terms of extreme events such as drought, floods and avalanches. Relatively small shifts in average temperature are associated with an increased frequency of extreme weather events such as floods, cyclones, droughts and heavy rainfall patterns. Increased temperature speeds up glacier meltdown influencing flow and discharge regimes of rivers (Lutz et al., 2014). Changes in climate could result in droughts affecting agricultural production thereby limiting food sources availability. According to recent studies more frequent and intense flooding was reported in locations initially not at risk (Douglas et al., 2001 and Blankespoor et al., 2010, Hartmann et al., 2013). Hettiarachichi et al., 2018 studied the role of storm temporal patterns in an urban developed watershed depicting significant impact on urban flooding due to climate change events. Climate-induced flooding has also been linked with severe health risks to humans in cases of overflow from point sources further contaminating flood water in Nigeria (Gabreila and Alfred, 2016).

10.2.4. Combined Sewer Overflow

Changes in temperature through a due course of time have led to an increased extent/rate of storm-water influx into the combined sewer networks (CSO) thereby impacting the nearby water bodies. This untreated wastewater from residential and industrial areas finds its way into the freshwater bodies raising serious health concerns. Higher overflow frequencies have been predicted on the basis of rainfall-runoff simulations in Germany indicating an increase in the volume and duration of overflow at simple CSO structures (Bendel et al., 2013). Similar findings are reported by a study on combined sewer systems in Northwest England predicting a rise in spilling volume, duration and frequency in response to climate change by 2080 using three global climate models (Abdellatif et al., 2015). They have reported an estimated increase of 37% in spill volume and 12% increase in its duration. In Maryland, 82% of overflow volume comprised of rain-related overflows affecting the human population at large (Kenward et al., 2016).

10.2.5. Change in Land use Pattern

The vegetation and soils act as carbon sink aiding in the absorption of carbon dioxide through photosynthesis. The land disturbance leads to methane and nitrous oxide emission further contributing to an increase in global mean temperature. The future land use is predicted to have a significant influence on climate (Feddema et al., 2005). The variable land use and land cover can modify surface fluxes of heat (Fig. 10.5) Kumar et al., 2013. The water demand in the Upper Ganges region in India has been estimated to rise due to variable climate change and land use patterns. A 63% increase of streamflow is predicted under the combined land use and climate change scenario in this region (Tsarouchi G. and Buytaert W., 2018).

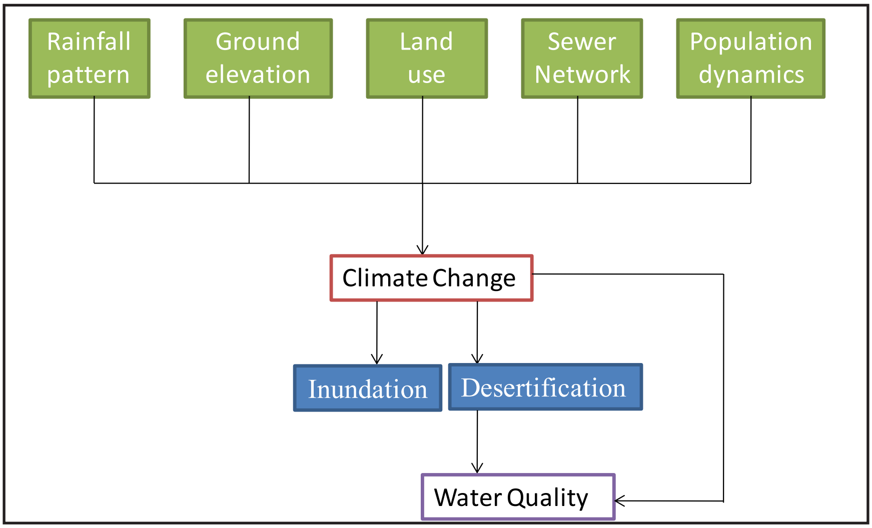

Figure 10.5: Factors affecting climate change and water quality

10.3. Climate Change Implications

The current shifts in meteorological patterns are accompanied by severe consequences on water quality of lakes, groundwater and abundance of biological communities (Table 10.2).

Table 10.2: Effect of climate change on water quality parameters

S.No.	Parameters	Effects	References
1	Temperature	Increase in air temperature will be accompanied by an increase of water temperature in lakes and rivers	Bates et al., 2008
2	pH	Temperature rise would lead to a decrease in pH. Absorption of CO_2 would further increase the formation of carbonic acid which dissociates giving H^+ and lowering pH	McNeil et al., 2005, Lenton et al.2018, Das et al., 2016
3	Dissolved Oxygen (DO)	Higher temperatures will reduce DO saturation levels	Matear and Hirst, 2003, Kumar et al., 2015.
4	Biological Oxygen Demand (BOD)	BOD will increase because of high temperature and reduced dilution effects	Whitehead et al., 2009

S.No.	Parameters	Effects	References
5	Total Suspended Solids	Increased surface water temperature increases total suspended solids	Murphy (2007)
6	Volatile Organic Carbon	Uncontrolled emission of volatile organic carbon may lead to build up of greenhouse gases and hence there may be climate change consequences	Murrells and Derwent, (2007)
7	Carbon dioxide levels (CO_2)	Increased atmospheric carbon dioxide levels result in increased ocean absorption of carbon dioxide	Soon et al., 1999
8	Nitrate	Higher temperature increases soil organic matter mineralization and a consequent increase of nitrates	Solheim et al., (2010)
9	Arsenic	Climate change will lead to high rainfall events which will lead to increased resuspension of contaminated suspended sediments and increase in heavy metal concentration as arsenic	Kibria, (2014)
10	Organic phosphates	Temperature rise and warm climatic conditions increase nutrient load in lakes and rivers	Seifert et al., (2010)
11	Bacterial population	Climate change triggers genetic changes in bacteria that enable them to survive in water	Costa et al., 2011
12	Viruses	Climate change will increase mosquito-virus borne disease due to increased intensity of close contact between humans and spoiled water	Schvoerer et al., (2008)

10.3.1. Lakes

Freshwater ecosystems account for 0.8% of Earth's surface with only 0.009% fraction available out of the total water. Therefore, the deterioration of the environmental quality of these lake ecosystems affects ecology and aquatic life (Vincent, 2009). The rise in temperature is accompanied by a reduction of ice-cover in lakes and variations in discharge capacity of lakes due to the melting of glaciers. Further, changes in volume and frequency of precipitation results in changes in water levels and transport of nutrients to lakes (Table 10.3). The nutrient loading along with warm temperature degrades the water quality of lakes. (Fig. 10.6). It has caused adverse impacts on ecological balance and aquatic species assemblage in the lakes of Europe, for example, the migration of cold water fishes in Lake Maggiore, Italy (Borre, 2014).

Table 10.3 Human impact in consequence to global flux in the biogeochemical cycle of elements (Schlesinger and Bernhardt, 2013)

Element	Juvenile flux[a]	Chemical weathering	Natural cycle[b]	Biospheric recycling ratio[c]	Human mobilization[d]	Human enhancement
B	0.02	0.19	8.8	42	0.58	2.8
C	30	210	107,000	446	8700	36.3
N	5	20[e]	9200[f]	368	221	8.8
P	~0	2	1000	500	25	12.5
S	10	70	450	5.6	130	1.6
Cl	2	260	120	0.46	170	0.65
Ca	120	500	2300	3.7	65	0.10
Fe	6	1.5	40	5.3	1.1[g]	0.14
Cu	0.05	0.056	2.5	23.6	1.5[g]	14.2
Hg	0.0005	0.0002	0.003	4.3	0.0023	3.3

[a] Degassing from the Earth's crust and mantle; the sum of volcanic emissions to the atmosphere (subaerial) and net hydrothermal flux to the sea

[b] Annual biogeochemical cycle to/from the Earth's biota on land and in the oceans in the absence of humans

[d] Direct and indirect mobilization by extraction and mining from the Earth's crust or (for N) industrial fixation

[f] Biological N fixation on land and in the ocean totals~300TgN/yr

[g] Human enhancement in the atmosphere and rivers

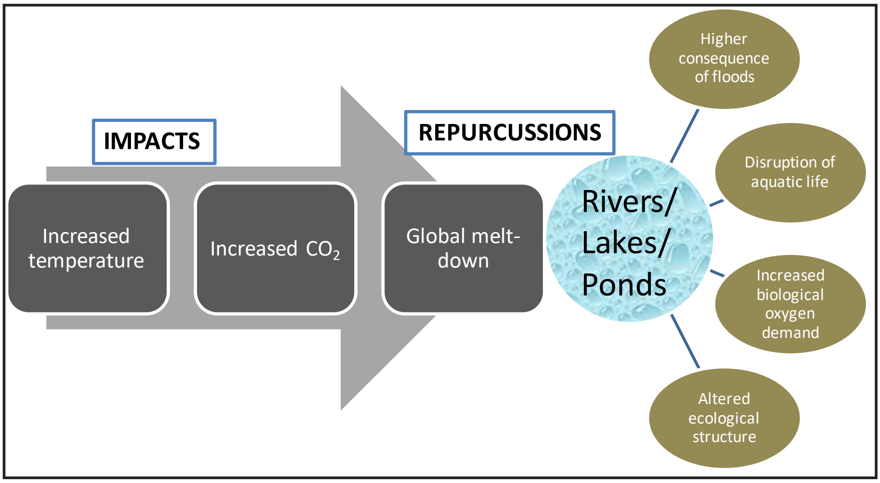

Figure 10.6: Effects of climate change on freshwater ecosystem

An incursion of invasive species facilitated due to the temperature changes would also possibly impact aquatic systems. Warmer water temperatures in northern latitude lakes would allow non-native warm water fishes to flourish and cause a significant loss of native species adapted to colder water temperatures (Sharma et al., 2007). Mooij et al. (2005), report the negative impact of climate change on macrophyte-phytoplankton community due to harmful consequences of eutrophication and other biomechanical limitations in shallow lakes of Netherlands. Therefore, the consequences of global change and eutrophication result in influxes of nitrogen, phosphorus and other pollutants in coastal and estuarine water bodies which further impacts the aquatic ecosystem.

10.3.2. Groundwater

Groundwater being an essential part of the hydrological cycle is valuable and provides a water source for domestic, agriculture and industrial use. The proposed possible ramifications of climate change include a decline in groundwater levels, increased droughts and floods, higher mobilization of pollutants and increased salinity. These effects could directly impact water supplies thereby hindering groundwater quality and availability. Environmental changes in hydrological conditions are anticipated in the course of global climate warming in Russia (Kovalevskii V.S., 2007). In southern Europe decline in groundwater recharge capacity and its increase in the northern part of Europe has been predicted (Hiscock et al., 2011).

10.3.3. Rivers

Global change in temperature and precipitation patterns affects the mass balances of the river ecosystem at various spatial scales. It results in an increased upstream movement of riverine networks impacting freshwater species abundance and distribution and may influence the biogeochemical/biogeographical cycling process. The principal changes associated with hydrological and water resource systems are considered as significant changes in the river basin morphology and flow morphology as suggested by Das et al. (2005). A potential change in channel morphology will bring hydrological changes due to changes in water and sediment discharges, hydraulic flow differences and so on. The depth of the channel will change in accordance with erratic rainfall distribution, different patterns of gradients and sinuosity, the width/depth ratio, the slope factor of the river beds, loading of sediments and so on. These independent variables are closely associated with indeterminate variables which is in turn connected to relief and valley dimensions as suggested by Jha et al. (2008).

Heavy rainfall is associated with increased headwater flow in river catchments leading to floods. The rate of chemical weathering and associated consumption rate of carbon dioxide has been studied in the river water to estimate the influence on climatic variations by several researchers (Dessert et al., 2001 and Das et al., 2005). The study on chemical weathering of Godavari river basin by Jha et al. (2008) reported that bicarbonate as major anion influencing weathering pattern which increased carbon dioxide consumption rate by 1.04%. There is a serious concern of rivers changing their course with respect to the increasing temperature. River Ganga has shifted by 35 to 50 Km, and Kosi river shifted westward by 125 Km (Singh 1971). Increased surface runoff from river basins has also been projected due to climate change in India (Gosain et al., 2006).

10.3.4. Biological Diversity

Climate change is identified as a significant driver of extreme biological changes. Microbial contamination of water from livestock faeces, *E.coli* and bacteria is of important concern. Transmission pattern of infectious diseases is likely to change in response to climate change. The temporal variations and warming of water will affect the growth and survival of such biological species. Changes in rainfall patterns accompanied by climate change are expected to influence the transmission of disease vectors affecting human health (Gogoi et.al., 2018). The diseases transmitted directly through physical contact are likely to increase in changing climatic conditions due to a significant decrease in sanitation and altered land-use patterns.

Environmental shifts and temporal changes could have implications on the *E.coli* growth within dairy faeces increasing contamination of catchment systems further affecting human health (Oliver and Trevor, 2016). Exploration of plant-microorganisms interaction under elevated CO_2, drought and warming conditions reveals an abundance of ectomycorrhizal fungi promoting the survival ability of plants in drought-like conditions (Compant et al., 2010). The abundance of Pseudomonas species and Rhizobium species is also predicted under enhanced CO_2 concentrations (Marilley et al., 1999; Drigo et al., 2009).

10.3.5. Emerging Contaminants

Change in climatic pattern affects the fate and occurrence of contaminants in environment. Recurring rainfall and erratic ocean currents influence the processes governing availability of different contaminants. Fluctuations in weather patterns as wind and temperature influence the degree of re-volatilization of emerging contaminants impacting associated population (Carlsson et al., 2016). Contaminants including plasticizers, pharmaceutical and personal care products, polychlorinated and polybrominated compounds, nanoparticles, hormones and algal toxins are currently rising in response to climatic shifts (Sauve and Desrosiers, 2014). Increased rainfall due to climatic variations leads to sewer overflows increasing the availability of emerging contaminants into different water bodies. These contaminants in turn affect the human health increasing the outbreaks of various types of diseases. The extensive exposure to pharmaceuticals and medicines is expected to increase the adaptability and resistance towards several drugs affecting behavior and patterns of animal community.

Melting of ice cover in response to increased temperature is likely to affect the degradation of contaminants as implied by the deposition of mercury in soil sediments released in past episodes (Point et al., 2011). Increased incidences of floods and drought has altered the transport pattern of contaminates as increasing concentration of metals and dioxins have been added to previously non-contaminated areas (Lake et al., 2005). Rising temperatures accompanied by potential rise in bioaccumulation and biomagnification of metals in marine organisms has been reported by Marques et al., (2010). Inhibition of growth of algae has also been reported as a result of increased exposure to antibiotics (Yang et al., 2008).

10.3.6. Wetland

Wetlands encompassing heterogeneous species of aquatic organisms are resilient and able to sustain the ecosystem despite changes in temperature conditions. However, rapid climatic variations induce environmental regimes exceeding their threshold resilience limits. Increase in temperature is followed by increased carbon dioxide production and methanogenesis activity affecting the oxygen holding capacity of water (Avery et al., 2012). Variable amounts of precipitation and shifts in evaporation pattern alter the wetlands structure. The excess floods inundate wetland and foster organic matter oxidation in soil (Choi et al., 2017). Freshwater wetlands turn to brackish water in response to the saltwater intrusion. This incident has negative consequences such as enrichment of water bodies through invasive aquatic species such as cyanobacteria which deteriorates the water quality, and further limits the freshwater usage for domestic and agricultural purposes (Beltman et al., 2000).

10.3.7. Landfill sites derived leachate

Frequent dumping of hazardous waste in landfill sites is causing newer challenges. Climate change is further expected to worsen the situation. Climate change related infiltration of water into landfill sites is expected to increase production of gas emissions in Kuala Lumpur and Selangor (Eusuf et al., 2007). Long-term methane emissions from landfills are anticipated in conjunction with slight changes in temperature. This landfill leachate may lead to increasing concentrations of metals, nutrients like nitrate, phosphate and chlorides affecting the water quality. Landfill sites have been estimated to allow 40 million methane emissions globally thereby influencing climate change (IPCC, 2006). In a case study in Dhaka, solid waste dumping in the open was linked to excessive methane and carbon dioxide emissions thereby contributing to climate change and a temperature rise of 4°C (Rahman et al., 2010).

10.4. Modelling Climatic Conditions: A Perspective towards Safe Future

Recent studies have focused on the development of climatic models to allow for future predictions of changing environmental conditions. These models represent the biological properties of a climatic system providing plausible predictions of forthcoming events using hydrological inputs (Goose et al., 2010; Loucks et al., 2017). Mean temperatures are studied as a function of environmental heat flux to incorporate the temperature variations through temperature modelling techniques (Stella, 2013). Water quality modules like Mike 11 have been developed to study the deterioration of river water quality through human interventions that end up in an increased organic matter loading (Radwan et al., 2003). Global circulation models have been used since long for studying future climate change projection models (Semadeni-Davies et al., 2008). Effects of climate change on temperature shifts promoting species invasions could be predicted using temperature models (Jackson and Mandrek, 2002). Paleolimnological methods have been developed to get a better understanding of the potential impacts of climate change on lakes by analysing and dating sediment cores of the lake. Therefore, the utility of these models in forecasting the change in weather and climatic patterns would be beneficial for the near future.

10.5. Conclusion

The tangible effects of climate change demand actions and policies to mitigate the situation in the near future. Potential impacts of varying climate and temperature rise include habitat loss of species, saline intrusion, frequent floods, droughts, the spread of infectious diseases and contamination of water. In view of the above consequences, mitigation measures to prevent greenhouse gases emissions and spills from landfills need to be undertaken. Execution of action plans to help reduce further degradation, and pollution load of the riverine ecosystem is necessary. The major focus of this chapter was to develop an understanding of the climate change implications to the associated environment. The interrelationship among several factors determines the quality of water and hence emphasises the current need to reduce greenhouse gas emissions. Climatic models can be used to predict the intricate variations of climate in the near future. Such modelling data would generate a platform which helps to simulate the impacts of future climate on water quality and develop a preparedness scheme to allow displacement of humans in cases of the extreme crisis.

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Glossary of Terms

Acidity: Tendency of a compound to act as an H+ donor

Actual evapotranspiration: Actual evapotranspiration or AET is the quantity of water that is actually removed from a surface due to the processes of evaporation and transpiration

Adaptation: Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.

Aeolian: Pertains to wind related activities, specifically to the wind's ability to shape the surface of the Earth.

Aerosol: An aerosol is a suspension of fine solid particles or liquid droplets, in air or another gas. Aerosols can be natural or anthropogenic.

Aggradation: Refers to deposition of sediment. Aggradation occurs in areas in which the supply of sediment is greater than the amount of material that the system is able to transport.

Algal toxins: Algal toxins are produced by various algae and are found both in seawater and fresh water. The algal toxins can be retained in shellfish or contaminate drinking water.

Alluvial aquifers: An aquifer comprising unconsolidated material deposited by water, typically occurring adjacent to rivers and in buried paleochannels. Alluvial aquifers are generally composed of clay, silt, sand, gravel or similar unconsolidated material deposited by running water.

Altimetry: Altimetry is a technique for measuring height. Satellite altimetry measures the time taken by a radar pulse to travel from the satellite antenna to the surface and back to the satellite receiver. Combined with precise satellite location data, altimetry measurements yield sea-surface heights.

Ambient air temperature: It refers to surrounding air temperature.

Anthropogenic: Anthropogenic is an adjective that describes changes in nature made by humans and human activities.

Anthropogenic warming: Due to emission of greenhouse gases such as carbon dioxide, methane, and nitrous oxide, human influence in the atmosphere has been increased. In view of the dominant role of human activity in causing it, the phenomenon is sometimes called "anthropogenic global warming".

Aquatic species assemblage: It refers to the variety and abundance of aquatic species in a given water body.

Aquifer: Permeable layers of underground rock, or sand that hold or transmit groundwater below the water table that will yield water to a well in sufficient quantities to produce water for beneficial use.

Aridity index: Ratio of long-term potential evapotranspiration to long-term precipitation

Atlantic multidecadal oscillation: The Atlantic Multidecadal Oscillation (AMO) is a climate cycle that affects the sea surface temperature (SST) of the North Atlantic Ocean based on different modes on multidecadal timescales.

Avalanches: An avalanche (also called a snowslide) is a cohesive slab of snow lying upon a weaker layer of snow in the snowpack that fractures and slides down a steep slope when triggered.

Badland: A barren plateau region with steep slopes, where softer sedimentary rocks and clay-rich soils have been extensively eroded by wind and water. It is usually uncultivable land with little vegetation.

Base flow: Streamflow which results from precipitation that infiltrates into the soil and eventually moves through the soil to the stream channel. This is also referred to as ground water flow, or dry-weather flow.

Bias correction: When an estimator is known to be biased, it is sometimes possible, by other means, to estimate the bias and then modify the estimator by subtracting the estimated bias from the original estimate. This procedure is called bias correction. It is done with the intent of improving the estimate.

Bioaccumulation: Substances that are very slowly metabolized or excreted by living organisms and thus increase in concentration within the organisms as the organisms breathe contaminated air, drink contaminated water, or eat contaminated food.

Biogeochemical/biogeographical cycling process: In ecology and Earth science, a biogeochemical cycle or substance turnover or cycling of substances is a pathway by which a chemical substance moves through biotic (biosphere) and abiotic (lithosphere, atmosphere, and hydrosphere) compartments of Earth.

Biological/biochemical Oxygen Demand (BOD): Biological/biochemical Oxygen demand is the amount of dissolved oxygen needed (i.e. demanded) by aerobic biological organisms to break down organic material present in a given water sample at certain temperature over a specific time period.

Biomagnification: It is the process whereby certain substances such as pesticides or heavy metals move up the food chain, work their way into a river or lake, and are eaten by aquatic organisms such as fish, which in turn are eaten by large birds, animals, or humans. The substances become concentrated in tissues or internal organs as they move up the chain.

Blue water: Blue water refers to the portion of precipitation falling on earth surface that either over flows into streams and rivers or percolates below the rooting zone into a groundwater aquifer.

Braided: Consists of a network of river channels separated by small, and often temporary, islands called braid bars. It usually occurs in channels with moderate slope to high slope and large sediment load.

Budyko model: A simple model often used to estimate first order evaporation as it requires only rainfall and potential evaporation as input. The model equation provides a concise and accurate representation of the relationship between annual evapotranspiration and long-term-average water and energy balance at catchment scales.

Business as usual (BAU) scenario: Corresponds to RCP 8.5 corresponding to zero climate mitigation efforts where emissions are not controlled.

Calibration: Process whereby the parameters of a model are adjusted to obtain a satisfactory agreement between model-generated results and measured variables.

Canal seepage: Water lost from an irrigation canal through percolation to soil, evaporation etc.

Carbon sink: A carbon sink is a natural or artificial reservoir that accumulates and stores some carbon-containing chemical compound for an indefinite period.

Catchment area: Refers to a drainage area with a single outlet for the surface runoff. It is also known as watershed, river basin etc.

Channel routing: The process of determining progressively timing and shape of the flood wave at successive points along a river.

Chemical weathering: Chemical weathering is caused by rain water reacting with the mineral grains in rocks to form new minerals (clays) and soluble salts. These reactions occur particularly when the water is slightly acidic.

Climate change: Long-term modification of the climate resulting from one or more of the following factors***:*** (i) internal changes within the climate system; (ii) interaction between the climatic components; (iii) changes in external forces caused by natural phenomena or by anthropogenic activities.

Climate impact assessment: The process of determining the impact of climate change on various sectors of economy as well as sections of society.

Climate projection: A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, generally derived using climate models.

Climate resilience: Climate resilience can be generally defined as the capacity for a socio-ecological system to***:*** (1) absorb stresses and maintain function in the face of external stresses imposed upon it by climate change and (2) adapt, reorganize, and evolve into more desirable configurations that improve the sustainability of the system, leaving it better prepared for future climate change impacts.

Climate variables: Climate variables include all hydrological variables like precipitation, temperature, evaporation, evapotranspiration and so on.

Climatic extremes: Refers to an event that is rare at a particular place & time, such as heat waves, cold waves, periods of droughts & floods, severe storms. It is drastic variations in meteorological parameters over a period of time.

Cloud contamination: In the context of remote sensing, cloud contamination refers to pixels on earth that are unable to be sensed from satellites due to cloud formation in the atmosphere.

Coarse resolution: In the context of datasets, it refers to data with low spatial or temporal resolution.

Correlation: The process of establishing a relationship or connection between two or more things

Coupled Model Intercomparison Project Phase 5 (CMIP5): It is the 5th phase of coordinated climate model experiments by 20 climate modeling groups from around the world.CMIP5 will provide a multi-model context for 1) assessing the mechanism responsible for model differences in poorly understood feedbacks associated with the carbon cycle and with clouds, 2) examining climate predictability and exploring the ability of models to predict climate on decadal timescales, and 3) determining why similarly forced models produce a range of responses.

Crop calendar: The Crop Calendar is a tool that provides timely information about seeds to promote local crop production. It contains information on planting, sowing and harvesting periods of locally adapted crops in specific agro-ecological zones.

Cultivable area: The sub-area of a particular area which can be used for cultivation. In a particular area, there might be some areas which are not suitable for cultivation due to various reasons. So cultivable area is total area minus the uncultivable area.

Cyanobacteria: Cyanobacteria also known as Cyanophyta, are a phylum of bacteria that obtain their energy through photosynthesis, and are the only photosynthetic prokaryotes able to produce oxygen.

Cyclic stress: Cyclic stress is the distribution of forces (aka stresses) that change over time in a repetitive fashion.

Cyclones: Cyclones can be the most intense storms on Earth. A cyclone is a system of winds rotating counterclockwise in the Northern Hemisphere around a low pressure center.

Decision Support System for Agro-technology Transfer (DSSAT): It is a software application program that comprises crop simulation models for over 42 crops (as of Version 4.7) as well as tools to facilitate effective use of the models. The tools include database management programs for soil, weather, crop management and experimental data, utilities and application programs. The crop simulation models simulate growth, development and yield as a function of the soil-plant-atmosphere dynamics.

Demand-supply gap: The difference between demand and supply of any resource.

Desalination: Removal of salts from water through any technology.

Digital elevation model (DEM): Digital Elevation Model (DEM) is the digital representation of the land surface elevation with respect to any reference datum. DEM is frequently used to refer to any digital representation of a topographic surface. DEM is the simplest form of digital representation of topography. DEMs are used to determine terrain attributes such as elevation at any point, slope and aspect.

Dioxins: Any family of compounds known chemically as dibenzo-p-dioxins. Concern about them arises from their potential toxicity and contamination in commercial products. Tests on laboratory animals indicate that it is one of the more toxic man-made chemicals known.

Directional-hemispherical reflectance: It is the reflectance of a surface under direct illumination

Dissolved Oxygen (DO): Dissolved Oxygen is the amount of gaseous oxygen (O_2) dissolved in water.

Downscaling: The procedure to infer high-resolution information from low-resolution variables.

Drip irrigation: An efficient way of providing water to root zone of crops resulting in higher efficiency as compared to other primitive ways of irrigation

Drought: A period of abnormally dry weather marked by little or no rain that lasts long enough to cause water shortage for people and natural systems.

Drought indices: Meteorological, hydrological, and vegetative parameters that can indicate the spatio-temporal patterns of drought are known as drought indices.

Dune: A mound or ridge of sand or other loose sediment formed by the wind, especially on the sea coast or in a desert.

E. coli: Escherichia coli (abbreviated as E. Coli) are bacteria found in the environment, foods, and intestines of people and animals.

Effective Precipitation: Effective Precipitation (EP) is the amount of precipitation that is actually added and stored in the soil. During drier periods less than 5mm of daily rainfall should not be considered effective, as this amount of precipitation would likely evaporate from the surface before soaking into the ground.

Effluent: Liquid waste or sewage discharged into a river or the sea.

El Nino: A natural variability in ocean water surface pressure that causes periodic changes in ocean surface temperatures in the tropical Pacific ocean. El Niño Southern Oscillation (ENSO) has two phases: the warm oceanic phase, El Niño, accompanies high air surface pressure in the western Pacific, while the cold phase, La Niña, accompanies low air surface pressure in the western Pacific.

El Nino Southern Oscillation (ENSO): El Nino, in its original sense, is a warm water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fisheries. This oceanic event is associated with a fluctuation of the intertropical surface pressure pattern and circulation in the Indian and Pacific oceans, called the Southern Oscillation. This coupled atmosphere-ocean phenomenon is collectively known as ENSO.

Elevation data: In the context of dataset used for climate studies, it refers to elevation of a terrain represented in spatial grids. Digital elevation data are sets of elevation measurements for locations distributed over the land surface.

Emission: In the climate change context, emissions refer to the release of greenhouse gases and/or their precursors and aerosols into the atmosphere over a specified area and period of time.

Emission scenario: a plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change) and their key relationships. Concentration scenarios, derived from emissions scenarios, are used as input into a climate model to compute climate projections.

Energy flux: Energy flux is the rate of transfer of energy through a surface.

Escarpment: A steep slope or long cliff that forms as an effect of faulting or erosion and separates two relatively leveled areas having differing elevations.

Eutrophication: Over-enrichment of water by nutrients such as nitrogen and phosphorus. The two most acute symptoms of eutrophication are hypoxia (or oxygen depletion) and harmful algal blooms.

Evaporation ratio: Ratio of long-term actual evapotranspiration to long-term precipitation

Evapotranspiration: Combination of evaporation from free water surfaces and transpiration of water from plant surfaces to the atmosphere.

Flood: The inundation of a normally dry area caused by high flow, or overflow of water in an established watercourse, such as a river, stream, or drainage ditch; or ponding of water at or near the point where the rain fell.

Flood irrigation: A method of irrigation in which water is applied in the furrows; it is the least efficient method of irrigation.

Flood routing: Flood routing is the technique of determining the flood hydrograph at a section of a river by utilizing the data of flood flow at one or more upstream sections.

Floodplain: Area of land adjacent to a stream or river which stretches from the banks of its channel to the base of the enclosing valley walls.

Gauge stations: Location on a stream where measurements of water level and/ or discharge are made systematically.

General Circulation Models (GCMs): A general circulation model (also known as a global climate mode) is a numerical weather prediction (NWP) model that numerically simulates changes in climate. GCMs are one of the most advanced tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentration.

Geological: Related with the solid earth, the rocks of which it is composed, and the processes by which they change over time. Geology can also refer to the study of the solid features of any terrestrial planet or natural satellite such as Mars or the Moon.

Geomorphic connectivity: The efficiency of transfer of materials (mainly water and sediment) between system components.

Geomorphic sensitivity: The nature and rate of adjustments in geomorphic systems.

Geomorphic threshold: Geomorphic thresholds refers to the condition at which there is a significant landform change without a significant change of external controls such as base level, climate and land use. Also pertains to abrupt landform change as a result of progressive change of external controls.

Geomorphological: Related to the origin and evolution of topographic and bathymetric features created by physical, chemical or biological processes operating at or near the Earth's surface

Glaciers: Accumulation of ice with an atmospheric origin which usually moves slowly on land over a long period.

Global warming: A gradual increase in the overall temperature of the earth's atmosphere generally attributed to the greenhouse effect caused by increased levels of carbon dioxide, Chlorofluorocarbons (CFCs), and other pollutants.

Gradient: The gradient (also called slope, incline, grade, pitch or rise) of a physical feature, landform or constructed line refers to the tangent of the angle of that surface to the horizontal.

Green water: Green water refers to the portion of precipitation falling on land surface which is stored in soil and potentially available for uptake by plants.

Greenhouse gases: Gases that absorb heat in the atmosphere near the Earth's surface, preventing it from escaping into space, for example, carbon dioxide, water vapor, and methane.

Grey water: The volume of water that is required to dilute pollutants to such an extent that the quality of the water remains at or above agreed water quality standards.

Gross domestic product (GDP): The total value of goods produced and services provided in a country during one year.

Groundwater: Groundwater is the water found underground in the cracks and spaces in soil, sand and rock. It is stored in and moves slowly through geologic formations of soil, sand and rocks called aquifers.

Groundwater abstraction: Groundwater abstraction is the process of taking water from a ground source, either temporarily or permanently.

Groundwater draft: The groundwater draft is the quantity of groundwater withdrawn artificially

Gully: A landform created by running water, eroding sharply into soil, typically on a hillside. Gullies resemble large ditches or small valleys, but are metres to tens of metres in depth and width.

Habitat loss: Natural habitats are the physical, chemical and biological systems that support living things. Habitat is lost and degraded when natural or anthropogenic activities damage and destroy habitat to such an extent that it is no longer capable of supporting the species and ecological communities that naturally occur there. It often results in the extinction of species and, as a result, the loss of biodiversity. Perhaps the greatest threat to organisms and biodiversity is the process of habitat loss.

Hadley cell/circulation: The Hadley cell, named after George Hadley, is a global scale tropical atmospheric circulation that features air rising near the Equator, flowing poleward at 10–15 kilometers above the surface, descending in the subtropics, and then returning equatorward near the surface.

Headwater flow: Headwater streams are the smallest parts of river and stream networks. It includes first order streams.

Hydro-climatic study: A study that describes the effects of large bodies of water upon the climate

Hydrologic model: A hydrologic model is a simplification of a real-world system (e.g., surface water, soil water, wetland, groundwater, estuary) that aids in understanding, predicting, and managing water resources. Both the flow and quality of water are commonly studied using hydrologic models.

Hydrological cycle: The hydrologic cycle begins with the evaporation of water from the surface of the ocean. As moist air is lifted, it cools and water vapor condenses to form clouds. Moisture is transported around the globe until it returns to the surface as precipitation.

Hydrological regime: Hydrological regime refers to variations in the state and characteristics of a water body which are regularly repeated in time and space and which pass through phases

Hydrology: The study of the distribution & movement of water both in time & space is known as hydrology.

Inter Tropical Convergence Zone (ITCZ): The Inter Tropical Convergence Zone, or ITCZ, is a belt of low pressure which circles the Earth generally near the equator where the trade winds of the Northern and Southern Hemispheres come together.

Indian summer monsoon rain (ISMR): Total rainfall accumulation in Indian monsoonal season (June to September).

Infiltration: The percolation of water through the ground surface into subsurface soil

Intended Nationally Determined Contributions (INDCs): Intended Nationally Determined Contributions (INDCs) is a term used under the United Nations Framework Convention on Climate Change (UNFCCC) for reductions in greenhouse gas emissions that all countries that signed the UNFCCC were asked to publish in the lead-up to the 2015 United Nations Climate Change Conference held in Paris, France, in December 2015.

Inter-Sectoral Impact Model Intercomparison Project (ISIMIP): It is a project to establish a long-term, community-driven process of cross-sectoral climate-impact model intercomparison and evaluation.

Intermontane: A wide valley between mountain ranges that is partly filled with alluvium.

Invasive species: An invasive species can be any kind of living organism—an amphibian (like the cane toad), plant, insect, fish, fungus, bacteria, or even an organism's seeds or eggs—that is not native to an ecosystem and causes harm. They can harm the environment, the economy, or even human health.

Inverse Distance Weighting (IDW) Interpolation method: Inverse distance weighting (IDW) is a type of deterministic method for multivariate interpolation with a known scattered set of points. The assigned values to unknown points are calculated with a weighted average of the values available at the known points.

Irrigation: The artificial application of water to plants.

Irrigation penetration: It refers to the percentage of farming area irrigated by artificial means like canal, tanks, wells etc.

Irrigation return flow: Return flow is surface and subsurface water that leaves the field following application of irrigation water.

La Niña: La Niña is the positive phase of the El Niño–Southern Oscillation and is associated with cooler-than-average sea surface temperatures in the central and eastern tropical Pacific Ocean.

Land cover: Physical characteristics of the land surface such as crops, trees & concrete.

Landfill: 1. Sanitary landfills are land disposal sites for nonhazardous solid wastes at which wastes are spread in layers, compacted to the smallest practical volume, and covered at the end of each operating day. 2. Secure chemical landfills are disposal sites for hazardous wastes that are selected and designed to minimize the chance of release of hazardous substances into the environment.

Land use: Activities taking place on land such as growing food, cutting trees or building cities.

Last Glacial Maxima: The Last Glacial Maximum (LGM) is conventionally defined from sea-level records as the most recent interval in Earth history when global ice sheets reached their maximum integrated volume.

Latency period: It refers to the time lag in compiling data products like reservoir storage, river stage etc.

Leachate: A liquid that results when water collects contaminants as it trickles through wastes, agricultural pesticides, or fertilizers.

Lithostratigraphy: The geological science associated with the study of strata or rock layers.

Live storage capacity of reservoirs: Active or live storage is the portion of the reservoir that can be used for flood control, power production, navigation and downstream releases.

Mann Kendall test: The Mann-Kendall trend test is a non-parametric way to detect a trend in a series of values.

Mass balances: A mass balance, also called a material balance, is an application of conservation of mass to the analysis of physical systems. By accounting for material entering and leaving a system, mass flows can be identified which might have been unknown, or difficult to measure without this technique.

Meso-scale: An intermediate scale between those of weather systems and of microclimates, on which storms and other phenomena occur.

Meteorological drought: Meteorological drought happens when dry weather patterns dominate an area. It mainly occurs due to lack of precipitation.

Microbial contamination of water: Contamination of water due to the presence of microbial organisms like bacteria, virus and protozoa. Microbial pollution in aquatic environments is one of the crucial issues with regard to the sanitary state of water bodies used for drinking water supply, recreational activities and harvesting seafood.

Mitigation: A human intervention to reduce the sources or enhance the sinks of greenhouse gases(GHGs).

Mixed pixel effect: In the context of remote sensing, it refers to errors that occur in identifying pixel characteristics. Mixed pixel occur often at the edges of large parcels, or along long linear features, such as rivers or highways, where contrasting brightness are immediately adjacent to one another. The mixed problem cannot be solved simply by increasing the spatial resolution.

Modified angular distance weighting interpolation method: It is an interpolation method which weights the data points by distance relative to a correlation decay distance and gives more weightage to isolated data points.

Monsoon: Seasonal change of wind direction, from sea to land or vice versa, associated with widespread changes in temperature and rainfall in subtropical regions.

Nanoparticles: Nanoparticles are particles between 1 and 100 nanometres (nm) in size with a surrounding interfacial layer.

Ocean warming: The Ocean absorbs most of the excess heat from greenhouse gas emissions, leading to rising ocean temperatures which is referred to as ocean warming.

Organic phosphates: Organic phosphates are organic compounds with phosphate group. It is also referred to as an ester of phosphoric acid salt.

Orographic precipitation: Orographic precipitation, rain, snow, or other precipitation produced when moist air is lifted as it moves over a mountain range. As the air rises and cools, orographic clouds form and serve as the source of the precipitation, most of which falls upwind of the mountain ridge

Paleoclimate: Refers to climate events in the geological past.

Paleolimnology: Paleolimnology is the multidisciplinary science that uses the physical, chemical, and biological information preserved in sediment profiles to reconstruct past environmental conditions in inland aquatic ecosystems.

Parsimonious model: A parsimonious model is a model that accomplishes a desired level of explanation or prediction with as few predictor variables as possible.

Percolation: The movement of rain water through soil layers.

Perennial rivers: A stream or river that has continuous flow in parts of its stream bed all year round during years of normal rainfall

P^H: The negative logarithm of the concentration of [H+] ions in a solution.

Potential evapotranspiration (PET): Potential evapotranspiration (PET) is defined as the amount of evaporation that would occur if a sufficient water source were available.

Precipitation: As used in hydrology, precipitation is the discharge of water, in a liquid or solid state, out of the atmosphere, generally onto a land or water surface. It is the common process by which atmospheric water becomes surface, or subsurface water. The term “precipitation” is also commonly used to designate the quantity of water that is precipitated. Precipitation includes rainfall, snow, hail, and sleet, and is therefore a more general term than rainfall.

Precipitation intensity: It is the rate of precipitation (in the form of rain).

Pseudomonas species: Pseudomonas is a genus of Gram-negative, Gammaproteobacteria, belonging to the family Pseudomonadaceae and containing 191 validly described species.

Rainfed agriculture: Agriculture field solely dependent on rain without any form of irrigation

Renewable freshwater resource (RFWR): includes all flowing surface waters as well as hydrologically active groundwater***:***

Replenishable groundwater resources: It refers to groundwater resources that will get replenished with precipitation.

Representative Concentration Pathway (RCPs): "Representative Concentration Pathway" RCPs are scenarios that describe alternative trajectories for carbon dioxide emissions and the resulting atmospheric concentration.RCP2.6 and RCP8.5, which represent different trajectories of radiative forcing, culminating in 2.6 W/m^2 and 8.5 W/m^2 of radiactive forcing by 2100.

Reservoir: A large natural or artificial lake used as a source of water supply.

Reservoir storage capacity: The maximum water that can be stored in a reservoir.

Return period: When the time to the next occurrence has a geometric distribution, the return period is equal to the inverse of probability of the event occurring in the next time period, that is, $T = 1/P$, where T is the return period, in number of time intervals, and P is the probability of the next event's occurrence in a given time interval.

Rhizobium species: Rhizobia are bacteria that fix nitrogen (diazotrophs) after becoming established inside root nodules of legumes (Fabaceae). Species of plants that host these bacteria in their root nodules are called rhizobium species.

River Basins: A river basin is an area of land drained by a river and its tributaries.

River health: Refers to river condition, often seen as being analogous with human health, giving many a sense of understanding. Relationships between environmental variables that affect aquatic biota, such as habitat structure, flow regime, energy sources, water quality and biotic interactions and biological condition, are required in the study of river health.

River process: Deals primarily with flow and sediment dynamics in alluvial channels. It emphasizes water flows (basic principles and characterization), fluvial sediment, processes of erosion and sediment.

Riverscape: A landscape comprising the features of the landscape which can be found along a river and by river processes.

Routing Model: Hydrological or hydraulic model used for routing flood flows.

Runoff: That part of precipitation that flows toward the streams on the surface of the ground or within the ground. Runoff is composed of baseflow and surface runoff.

Salinity: The degree of salt in water.

Sea surface temperature: Sea surface temperature (SST) is the water temperature close to the ocean's surface

Seasonal rivers: A seasonal river is one that exists only after some seasonal occurrence such as the monsoon season in India

Seasonally: Seasonality is a characteristic of a time series in which the data experiences regular and predictable changes that recur every calendar year.

Sedimentation: Sedimentation is the deposition of particles carried by a fluid flow.

Sediment: A naturally occurring material that is broken down by processes of weathering and erosion, and is subsequently transported by the action of wind, water, or ice, and/or by the force of gravity acting on the particles

Sediment calibre: Refers to maximum size of sediment which can be transported by a flow.

Sediment flux: Volume of bed load, suspended sediment particles crossing a vertical surface per unit time per unit width of channel.

Sedimentary archives: Sediments deposited in lake, wetlands, estuaries, oceans, and on land that preserve evidence of past changes in climate or other environmental conditions.

Severe drought: Severity of drought can be explained by the extent of precipitation deficit and the extent of impacts caused by this precipitation deficit. When there is a high deficiency of water content in atmosphere or/and beneath the soil for a longer duration, it leads to a severe drought.

Sinuosity: A series of regular sinuous curves, bends, loops, turns, or windings in the channel of a river, stream

Snowmelt: Surface runoff produced from melting snow

Soil moisture: Water content in the soil layers in the upper regions near the earth's surface.

Solar cycle: The solar cycle or solar magnetic activity cycle is the nearly periodic 11-year change in the Sun's activity and appearance

Spatial variability: Variability of a physical quantity with space. For example spatial variability of precipitation refers to variation in the distribution of precipitation over an area.

Specific yield of aquifer: The ratio of the water which will drain freely from the material to the total volume of the aquifer formation. This value will always be less than the porosity.

Sprinkler Irrigation: Sprinkler Irrigation is a method of applying irrigation water which is similar to rainfall. Water is distributed through a system of pipes usually by pumping. It is then sprayed into the air and irrigate the entire soil surface through spray heads so that it breaks up into small water drops which fall to the ground.

Standardized Precipitation Evapotranspiration Index (SPEI): It is a drought index established by Vicente-Serrano et al (2010) which depends upon precipitation and temperature data. For computation, it also includes evapotranspiration data as an input. In case of unavailability of actual evapotranspiration (AET), Potential evapotranspiration (PET) is evaluated using temperature data for input.

Standardized Precipitation Index (SPI): It is a drought index developed by McKee et al (1993) to define and monitor meteorological drought. SPI is most widely used index for drought monitoring and prediction all around the globe. SPI can be termed as a tool to help decision makers to understand about the probable drought events likely to take place.

Stream power: Stream power is the rate of conversion of potential energy of water to kinetic energy as water descends downstream. The energy of flowing water is expended on the bed and banks of a channel and is utilized in performing geomorphic work

Streamflow: Streamflow is the volumetric discharge expressed in volume per unit time that takes place in a stream or channel and varies in time and space.

Sub-Himalaya: The southernmost mountains in the Himalayan range. Their average height varies between 600 and 1200 meters, it is bonded to the north by the Main Boundary thrust and to the south by the Main Frontal thrust.

Surface reflectance: It is the fraction of incoming solar radiation that is reflected from earth's surface.

Surface runoff: The runoff entering stream channels promptly after rainfall or snow melt. Superposed on base runoff, it forms the bulk of the hydrograph of a flood.

Sustainability: Sustainability is the process of maintaining change in a balanced fashion, in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations.

Sustainable Development Goals (SDGs): They are a collection of 17 global goals set by the United Nations General assembly (UNGA) in 2015. The SDGs are part of resolution 70/1 of UNGA.

Sustainable management: Taking proactive actions, even sacrifices, to manage, protect, conserve and restore our environment so that the resources can be sustained for future use.

Temperature lapse rates: The lapse rate is the rate at which temperature in Earth's atmosphere decreases with an increase in altitude, or increases with the decrease in altitude.

Total Runoff (TR): Total runoff, in hydrology is the quantity of water discharged in surface streams. It includes not only the waters that travel over the land surface and through channels to reach a stream but also interflow, the water that infiltrates the soil surface and travels by means of gravity toward a stream channel.

Total Suspended Solids (TSS): Total suspended solids (TSS) are the dry-weight of suspended particles that are not dissolved, in a sample of water that can be trapped by a filter that is analyzed using a filtration apparatus.

Unimproved water sources: Unprotected dug well, unprotected spring, cart with small tank/drum, tanker truck, and surface water (river, dam, lake, pond, stream, canal, irrigation channels), bottled water.

Unit hydrograph: Unit hydrograph is a direct runoff hydrograph resulting from one unit (one inch or one cm) of constant intensity uniform rainfall occurring over the entire watershed. The concept of unit hydrograph is based on linear systems theory and follow the principles of superposition and proportionality.

Urbanization: Urbanization refers to the population shift from rural to urban residency, the gradual increase in the proportion of people living in urban areas, and the ways in which each society adapts to this change.

Variable Infiltration Capacity (VIC) Model: VIC Model is a large-scale, semi-distributed hydrologic model that solves full water and energy balances. As such, it shares several basic features with the other land surface models (LSMs) that are commonly coupled to global circulation models (GCMs). Basically The VIC model is a computation tool that is used to answer hydrologic sciences question.

Virtual water: The water used directly or indirectly in producing a good is known as virtual water.

Volatile organic compounds: Volatile organic compounds (VOCs) are organic chemicals that have a high vapor pressure at ordinary room temperature.

Water management: Development and operation of regional water resources, taking into account hydrological and technical aspects, as well as socio-economic, political and environmental dimensions.

Water pricing: Water pricing is an important economic instrument for improving water use efficiency, enhancing social equity and securing financial sustainability of water utilities and operators.

Water scarcity: Water scarcity is the lack of sufficient available water resources to meet the demands of water usage within a region.

Water-intensive crops: These refer to crops with high water requirement. Crops like paddy, sugarcane, cotton etc. are water-intensive.

Watershed: Refers to a drainage area with a single outlet. It is also known as catchment area, river basin etc.

Wetland: A wetland is a place where the land is covered by water, either salt, fresh or somewhere in between. Marshes and ponds, the edge of a lake or ocean, the delta at the mouth of a river, low-lying areas that frequently flood—all of these are wetlands.

Zero liquid discharge (ZLD): Zero-liquid discharge (ZLD) is a water treatment process in which all wastewater is purified and recycled; therefore, leaving zero discharge at the end of the treatment cycle. Zero liquid discharge is an advanced wastewater treatment method that includes ultrafiltration, reverse osmosis, evaporation/crystallization, and fractional electrode ionization.

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Subject Index

Climate Change and Water Resources in India

Understanding of changes in water resources in India in response to the warming climate is vital to ensure the food and freshwater security. Impacts of climate change are already visible in different sectors that affect socioeconomic conditions and livelihood of the people. However, climate change impacts on the water sector can have profound implications in the coming decades in India. This book provides a comprehensive assessment of the implications of climate change on water resources in the country. The book has ten chapters written by the expert authors that cover a wide-range of the topics. The book highlights the current state and the potential of surface and groundwater in India. Moreover, the book provides information on the projected changes in the Indian summer monsoon, streamflow, water availability, and water demands in the agriculture and industry sectors. The linkage between climate change and water quality of surface and groundwater resources in India is also explored. Overall, the book will be an excellent resource for policymakers, government and non-government organizations, and the scientific community working in the areas related to water resources.

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