Doctor of Philosophy
Thesis

On

Unraveling discrepancies and overlooking risks: future climate analysis & decision-making in the Brahmaputra River Basin

Under the supervision of

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September 2024

INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

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DECLARATION

It is to declare that the content embodied in this thesis entitled **"Unravelling discrepancies and overlooking risks: future climate analysis & decision-making in the Brahmaputra River Basin"** is the result of investigations carried out by me at the **Centre for the Environment, Indian Institute of Technology, Guwahati, Assam, India** under the supervision of **Prof. Anamika Barua** & **Prof. Arup Kumar Sarma** for the award of the **Doctor of Philosophy**. The work has not been submitted elsewhere for any degree or diploma of any institute or university. I wish to state that to the best of my knowledge and undertaking nothing in this report amounts to plagiarism.

In keeping with the general practice of reporting scientific observations and outcomes of the research conducted, due acknowledgements have been made wherever the work described is based on the findings of other investigators.

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CERTIFICATE

This is to certify that the thesis entitled **"Unravelling discrepancies and overlooking risks: future climate analysis & decision-making in the Brahmaputra River Basin"** submitted by **Mr. Rupam Bhaduri (Roll No.: 176152005)** for the award of the **degree of Doctor of Philosophy,** is an authentic record of results obtained from the research work carried out under the supervision and guidance at the **Centre for the Environment, Indian Institute of Technology Guwahati, Assam, India.** The thesis has fulfilled all requirements as per the regulations of the Institute and has reached the standard required for submission. The work documented in this thesis has not been submitted to any other University or Institute for the award of any degree.

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Acknowledgement

I would like to express my sincere gratitude to my supervisor Prof. Anamika Barua, Professor, Department of Humanities and Social Sciences for her constant support and unparalleled guidance without which I would not have been here. Prof. Barua continued to believe in me and did not let me quit even when I lacked confidence in myself. She stood up for me whenever I was in need and I am in fact short on words to express my gratitude for her. I would also like to acknowledge my co-supervisor Prof. Arup Kumar Sarma, Department of Civil Engineering for his support, encouragement and invaluable suggestions during my work enabling the successful completion of the thesis.

I would like to thank my doctoral committee members Dr. Suresh Kartha from Department of Civil Engineering for his technical inputs during my progress reviews which helped me in ideating the co-relation analysis of the climate data with hydropower; Prof. Rajshree Bedamatta from Department of Humanities and Social Sciences for her inputs on my research methodology and introducing me to the concept of 'research positionality'. I remember and thank my former doctoral committee chairman Late Prof. Chandan Mahanta who believed in my work and was curious to learn the research findings. I really wish I could have shown him this thesis. I am greatly thankful to Prof. Lal Mohan Kundu from Department of Chemistry for agreeing to be my doctoral chairman and being a support whenever needed.

The work would have been incomplete without the guidance from Dr. Sumit Vij, faculty, Wageningen University, The Netherlands, which helped me shape my research. Dr. Sumit has been particularly helpful in breaking the academic block which enabled me to continue this thesis. I am forever going to be indebted for all the concepts I have learned from him which reignited the spirit of research within me.

My field work at Bhutan was particularly interesting as I was stuck in a foreign country during lockdown, imposed as a consequence of COVID-19 pandemic. Numerous people helped me before and during my field work and the thesis would be incomplete without thanking them. I extend my gratitude to Department of Hydropower, Department of Renewable Energy, National Centre for Hydro-Meteorology and National Environment Commission of Bhutan for supporting and cooperating during the interview. I also extend my thanks to Professors from College of Science and Technology, Phuentsholing, Bhutan for providing their perspectives during the interview. Special mention to Mr. Kinley from Babesa, Bhutan for being a kind heart *and helping me with the logistics and accommodation in Bhutan and Mr. Bharat Pradhan for his unconditional concern in ensuring I get food every time I returned from work. I am also grateful to the numerous Taxi drivers of Bhutan who helped me find my way whenever I was lost in the unknown land of Bhutan. Last but not the least, hearty gratitude to Dr. G K Choppel, National Environment Commission for helping me during the hours of emergency. I shall forever be indebted to him for his kind gesture.*

I thank Dr. Bhupen Mili of Arunachal Pradesh State Disaster Management for his support during my field work at Arunachal Pradesh.

A section of my research was conducted at Indian Institute of Tropical Meteorology Pune, Maharashtra and I take the opportunity to express my gratitude to Mr. Sudhir Sabade, Dr. Koteswara Rao Kundeti and Mr. Vinodh Kumar Buri who did not just train me in climate data analysis, but also ensured a smooth stay at Pune.

Beyond the academic content, I would also like to mention my special thanks to my amazing friends Ms. Vishaka Gulati, Ms. Arundhati Deka and Ms. Seema Lokhandwala for their constant support and motivation in professional and personal life. Numerous interactions of love and laughter with my friends Mr. Angshuman Sharma, Mr. Abhishek Singh, Dr. Aquib Jawed, Mr. Rahul Tiwari, Mr. Shashank Kulkarni and Ms. Pushpita Das during the lowest phase of my life maintained the sanity within me. I pray for their quick upgradation of titles.

I am also grateful to the Centre for Environment where I am enrolled as a Ph.D. candidate. I thank Mr. Mridul, and Mr. Rajib for all the help with the official paper work which enabled timely processing of academic formalities. I also thank Dr. Partha Bakal, Mr. Kaustav Rakshit and Dr. Deepmoni Deka for their administrative support. I extend my thank to administrative staffs from the Department of Humanities and Social Sciences for their support.

I extend this acknowledgement to my lab members and research juniors Ms. Surbhi Vyas, Mr. Shankar Ghosh, Ms. Krishna Deori and Ms. Chayasmita Basumatary who have been particularly helpful during the course of my thesis submission and viva-voce.

Without thanking Mr. Aniruddha Mahagaonkar, who played a pivotal role in instilling in me the values of conservation, nature education, and the pressing need to address climate change, this acknowledgement section would be incomplete. Even though Aniruddha left IITG to pursue his education soon after I joined Ph.D., his values and lessons remain with me.

Finally, I would acknowledge the encouragement received from my family to pursue this Ph.D. It was a dream for my late father Mr. Prasanta Bhaduri and late grandfather Mr. Durga Prasanna Roy Choudhury to see me complete this thesis, who were with me for half of this doctoral journey. My grandmother Mrs. Krishna Rani Roy Choudhury, who is still concerned *if I am eating on time during the course of writing this thesis, motivates me to stay strong and rise up against all the odds. My sisters-in-law Ms. Akanksha Patel and Ms. Prithivi Patel for just being there as a family, especially when I thought I could never have one. Last but not the least, I thank my wife Silky Patel who has been a driving force behind me to regain my mental health and give research another try. Had it not been her, I would have continued to stay lost staring at the infinite wall, as if time has never been a dimension.*

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Acronyms and Glossary

Abbreviation	Full form
ACCESS	Australian Community Climate and Earth System Simulator Coupled Model
ADB	Asian Development Bank
APHRODITE	Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation
BCC-CSM	Beijing Climate Center Climate System Model
BNU-ESM	Beijing Normal University Earth System Model
BRB	Brahmaputra River Basin
CanESM	Canadian Earth System Model
CCSM4	Community Earth System Model
CEC	Central Electricity Board
CEGIS	Institute for Global Environmental Studies
CESM1/CAM5	Community Earth System Model version 1.0/ Community Atmospheric Model version 5
CIBB	China, India, Bhutan, Bangladesh
CMIP	Coupled Model Intercomparison Project
CNRM-CM5	Centre National de Recherches Météorologiques-Coupled Model 5
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CWC	Central Water Commission
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory Earth System Model version 2G
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth System Model version 2M
GNH	Gross National Happiness
GOB	Government of Bhutan
GOI	Government of India
HEP	Hydro Electric Power Plant
ICIMOD	International Centre for Integrated Mountain Development
IMD	India Meteorological Department
INM	Institute for Numerical Mathematics
IPSL	Institute Pierre-Simon Laplace
MIROC-ESM	Model for Interdisciplinary Research on Climate-Earth System Model
MPI-ESM	Max Planck Institute-Earth System Model
MRI-CGCM	Meteorological Research Institute-Coupled Global Climate Model
NAPA	National Adaptation Programme of Action
NEC	National Environment Commission
NEX-GDDP	NASA Earth Exchange Global Daily Downscaled Climate Projections
NorESM1	Norwegian Earth System Model
RCP	Representation Concentration Pathway
SSP	Shared Socioeconomic Pathway
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
WB	World Bank
WRD	Water Resources Department
WWF	World Wildlife Fund

Abstract

The Brahmaputra River basin (BRB) is a fragile ecosystem at risk due to the changing climate. With over 1 million people relying on the river for their well-being and several water infrastructure projects being planned on the basin, understanding the impacts of climate change at the basin level is crucial. However, geopolitical complexities hinder comprehensive basin-wide research in the BRB, resulting in limited studies on the effects of climate change. With limited knowledge of climate change projections for the BRB, it is worrisome that several water infrastructure projects that are being planned may lead to maladaptation for the human and biophysical systems.

To overcome these challenges, rigorous scientific research is essential for comprehending the intricate relationships between hydropower dams and climate change. Such research endeavours will guide evidence-based decision-making to enhance hydroelectric infrastructure's sustainability and resilience. This thesis examines the relationship between transboundary flows and hydropower development on the BRB for climate change. To understand if the hydropower development initiatives are climate resilient, a fundamental question *"how hydropower projects in the Brahmaputra River Basin (BRB) incorporate scientific knowledge on future climate change?"* was asked in this thesis. Three objectives were defined to address the thesis question with specific methodologies for each.

To address the first objective, chapter 3 of the thesis uses a systematic literature mapping protocol ROSES, to systematically chart out the scientific literature on climate change projections on the basin and explain the scale and scope of biophysical research conducted to identify the knowledge gaps. Findings from the mapping exercise were further analysed qualitatively to generate an in-detail understanding of the literature. Chapter 4 of the thesis draws motivation from the findings of Chapter 3 and, thus, quantitatively investigates the future climate extreme events on BRB. The chapter aims to enhance understanding of climate change on the basin and comprehend its impact on hydropower. Focusing on the southwest monsoon season (June to September) under RCP 4.5 and RCP 8.5 emission scenarios, the research employs high-resolution, statistical downscaled data from NEX-GDDP project to understand the future changes. Observational data from the APHRODITE was used to validate the NEX GDDP data in the historical period. Findings from Chapter 3 and Chapter 4 set a context on the status of future climate change in the basin, which is a pre-requisite for addressing the third objective of the thesis in Chapter 5. Thus, to answer the objective, several policies and

documents related to hydropower development in India and Bhutan were reviewed to understand the inclusion of scientific knowledge on future climate change in hydropower development. The thesis further reinstated the findings from interaction with Indian and Bhutanese stakeholders. The interaction followed an unstructured and semi-structured protocol with the knowledge developers and government officials involved in the hydropower development. Content from the interaction was qualitatively analysed to generate themes based on the methodology developed by (Braun and Clarke, 2006). These themes formed the basis of the discussion, centred on narratives provided by the stakeholders.

The thesis found that most of the scientific literature published was on the Indian part of the basin (n=21), followed by studies on China (n=15), Bangladesh (n=11), and Bhutan (n=2). Basin-level studies were relatively lower (n=13) considering the existing literature (n=92). Most research publications were communicated by non-basin level countries (n=35). Chapter 3 of the thesis further analysed the collaborations within the basin-level institutions to qualitatively assess the status of collaborative research on climate change projections. It was found that not a single publication had collaboration from all the four basin countries. Limited studies on extreme climate events have been done on the basin level (n=1). The thesis answers the first objective by addressing the status of knowledge on climate projections on BRB and qualitatively analysing the publications in the last 30 years.

Findings from Chapter 4 indicate a projected 7.7% and 10.7% increase in monsoon precipitation by 2050 under RCP 4.5 and RCP 8.5, respectively. Subsequently, 18.1% and 38% increase by 2099 under RCP 4.5 and RCP 8.5, respectively. Various extreme precipitation indices exhibit an upward trend, with both scenarios predicting significant increases in maximum 1-day rainfall (2.2 mm decade-1 and 4.5 mm decade-1) and highest 5-day rainfall (2.33 mm decade-1 and 4.9 mm decade-1). Consecutive wet days (CWD) are also expected to become more frequent during the monsoon season. The findings from this chapter establish a concrete understanding of future climate change, demonstrating the uncertainties in climate extreme events.

Findings from the third objective demonstrated the discrepancy between scientific findings and policy implementation. One crucial finding was the absence of direct inclusion of any climate parameters in hydropower development. Analysis from stakeholder interaction further re-instates the absence of direct integration of scholarly knowledge on climate change in hydropower decision-making. The lack of participation from the meteorological department in drafting hydropower policies suggests that professional perspectives essential for climate resilience may have been overlooked.

Climate impacts are evident in the BRB; while there are gaps in academic knowledge, a better understanding of the climatic changes, especially studies related to extreme climate events in the BRB, is essential for future climate preparedness. Emphasis on the need to consider the growing risk of extreme precipitation events on water-infrastructure planning in the basin, especially concerning hydropower development, is essential. Understanding the hydropower vulnerability of a basin prone to climate change is indispensable from a multi-dimensional economic, socio-economy, ecology, and transboundary water governance perspective. Finally, findings from chapter 5 of the thesis highlight the gap in the science and policy interface, as it addresses the major thesis question and provides a qualitative assessment of the incorporation of scientific knowledge on climate projects in hydropower development.

Chapter 1

Setting the context and introducing the thesis

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1.1 Introduction

This introductory chapter aims to lay the necessary foundations for this thesis as a whole. The chapter provides a firm understanding of the thesis's landscape. To achieve this, the chapter pursues a dual purpose: firstly, to acquaint readers with the subject matter under examination, and secondly, to furnish a comprehensive framework that situates the significance and relevance of the thesis within its broader context. Subsequently, it delves into the motivations propelling the inquiry forward, shedding light on the gaps in knowledge that impel the investigation. The chapter ends by providing an outline of the structure of the thesis, along with a brief overview of each of the following chapters.

1.2 Transboundary waters and Hydropower development

Transboundary water resources are increasingly recognized as critical drivers of economic growth and regional cooperation. Transboundary water also stands as a pivotal resource in meeting the global demand for energy, with hydropower emerging as a prominent and environmentally sound solution (Llamosas and Sovacool, 2021). With industrial revolution taking place during 18th century, there has been need of enormous amount of energy. In today's scenario, with the global energy demand on the rise due to population growth and economic expansion in both developed and developing nations (Kaunda, Kimambo and Nielsen, 2012)there's a pressing need to address this escalating demand sustainably. Historically, fossil fuels have dominated the global energy supply, contributing to approximately 100% increase in total consumption since 1973, as reported by the International Energy Agency (IEA). However, the reliance on fossil fuels poses significant challenges due to their non-renewable nature and detrimental environmental impacts, including greenhouse gas emissions leading to climate change (Singh and Singh, 2012). To counteract these challenges, there's a growing imperative to transition towards renewable and sustainable energy sources. Use of clean energy from non-fossil based energy sources have been prioritized over the conventional energy sources with high carbon emissions, pertaining to Conference of Parties 21, Paris Agreement.
Hydropower stands out as a prominent renewable energy option, offering a reliable and environmentally friendly solution to meet the escalating energy demand (Shu et al., 2018).Harnessing the kinetic energy of flowing water, hydropower generation involves the

movement of turbines from higher to lower gradients, thereby producing electricity. Compared to other renewable energy sources like solar, wind, tidal, and geothermal, hydropower technologies are more established and efficient, boasting higher energy output per installation capacity (Owusu and Asumadu-Sarkodie, 2016). Moreover, hydropower projects offer multifaceted benefits beyond electricity generation, including irrigation, navigation, fisheries, and flood and drought control (Owusu and Asumadu-Sarkodie, 2016). Modern hydro turbines can convert up to 90% of available energy into electricity, far surpassing the efficiency of fossil fuel plants (Silva and Castillo, 2021).

Therefore, the significance of transboundary waters lies not only in their capacity to foster regional cooperation but also in their potential to serve as a crucial source of clean energy through hydropower generation. As nations seek sustainable alternatives to traditional fossil fuels, hydropower emerges as a beacon of promise, offering a renewable and eco-friendly source of energy. In this context, transboundary waters take on added importance, representing not only a shared resource for riparian states but also a reservoir of potential for meeting nations' growing energy needs while mitigating environmental impact. Furthermore, the transition to hydropower from fossil fuel-based energy sources aligns with global climate goals, such as Nationally Determined Contributions (NDCs), by significantly reducing carbon emissions. By embracing hydropower as a clean and sustainable energy source, nations can make substantial strides towards achieving their climate targets while ensuring a secure and reliable energy future.

However, hydropower development in Transboundary rivers is not devoid of challenges as it often intersects with geopolitical tensions and conflicting interests among riparian states. Disputes over water rights, allocation, and benefit-sharing can escalate, undermining regional cooperation and exacerbating political tensions (Wolf, 2007). Furthermore, hydropower development in transboundary river basins can have significant environmental and social implications, particularly for downstream communities and ecosystems. The construction of dams alters river hydrology, leading to changes in sediment transport, water quality, and aquatic habitats (Chong *et al.*, 2021). Moreover, large-scale dam projects can displace communities, disrupt livelihoods, and exacerbate social inequalities, raising concerns about human rights violations and social justice (Aboda *et al.*, 2019; Schulz and Adams, 2019). For example, in the Mekong River Basin, the construction of large dams, such as the Xayaburi and Don Sahong dams, has sparked controversy and raised concerns about their impacts on fisheries, agriculture, and downstream communities. In addition, climate change has led to an alarming situation due to changing hydrological patterns by altering precipitation patterns.

Such changes have led to shifts in river flow regimes and water availability (Payne *et al.*, 2020). This variability can affect the reliability and efficiency of hydropower generation, as dams rely on consistent water flows to generate electricity. Climate change is also associated with more frequent and intense extreme weather events, such as floods and droughts. These events pose significant challenges to hydropower infrastructure, including dam safety and reservoir management. Further, climate change can exacerbate existing socioeconomic vulnerabilities, particularly among community dependent on hydropower for energy and livelihoods. Drought-induced power shortages, flooding, and displacement of communities due to dam construction can have profound social and economic consequences.

To overcome these challenges, sound scientific research is indispensable for understanding the complex interactions between climate change and hydropower dams and informing evidence-based decision-making to enhance the resilience and sustainability of hydropower infrastructure. By integrating robust scientific research into planning, design, and management processes, engineers and policymakers can effectively address the challenges posed by climate change and ensure the long-term viability of hydropower as a clean and renewable energy source.

This thesis aims to highlight the nexus between transboundary waters and hydropower development, focusing on a River Basin called the Yarlung-Tsangpo–Brahmaputra–Jamuna Basin shared by four countries – China, India, Bhutan and Bangladesh. A relatively under researched river basin of South Asia with immense potential for hydropower development. The thesis argues that while hydropower projects hold the potential to drive economic growth and energy security of the riparian states, they must be approached with caution, taking into account environmental, social, and geopolitical considerations. The thesis aims to highlight the need for collaborative approaches, informed by sound science and stakeholder engagement, which are essential for ensuring the sustainable management of transboundary water resources and maximising the benefits of hydropower development for all the four riparian states.

This thesis endeavours to explore the intricate relationship between transboundary waters and hydropower development, with a particular focus on the Yarlung-Tsangpo–Brahmaputra–Jamuna Basin shared by China, India, Bhutan, and Bangladesh. Despite its significance, this basin remains relatively under-researched in the context of South Asia, yet holds immense potential for hydropower development. The central argument of this thesis is that while hydropower projects offer promising avenues for driving economic growth and enhancing energy security among the riparian states, their implementation necessitates a cautious approach. The thesis seeks to underscore the imperative for collaborative approaches, underscored by sound scientific research and robust stakeholder engagement, thereby paving the way for informed decision-making and policy formulation related to hydropower development. It asserts that only through such concerted efforts can the sustainable management of transboundary water resources be achieved while simultaneously optimizing the benefits of hydropower development for all four riparian states.

1.3 The Brahmaputra River Basin (BRB)

1.3.1 *The Geographical and Hydrological Dynamics of the Brahmaputra River Basin*

The river Yarlung-Tsangpo–Brahmaputra–Jamuna (henceforth to be referred as the Brahmaputra River Basin or BRB), is the largest transboundary river in the Hindu Kush Himalayan region (Tandon and Sinha, 2007) shared by China, India, Bhutan and Bangladesh. With a flow of about 20,000 m^3/s at its estuary, the Brahmaputra River is the fourth-largest river in the world by discharge. Before draining into the Bay of Bengal, the river travels 1625 km via China, 918 km through India, and 337 km through Bangladesh (Singh et al., 2004). BRB covers a total drainage area of 519,500 sq which is split by China (50.5%), India (33.6%), Bangladesh (8.1%), and Bhutan (7.8%) (Immerzeel, 2008a). The river rises from the glaciers of southern Tibet at an elevation of 5300 m and flows 2,900 kilometres across these nations before entering the Bay of Bengal (Wang *et al.*, 2020a). Almost 5.9% of the total land area of India is included of the catchment area, which includes states of Arunachal Pradesh, Assam, West Bengal, Meghalaya, Nagaland, and Sikkim. Arunachal Pradesh has a drainage area of 81,424 square kilometres; Assam has 70,634 square kilometres; West Bengal has 12,585 square kilometres; Meghalaya has 11,667 square kilometres; Nagaland has 10,803 square kilometres; and Sikkim has 7,300 square kilometres. Even though it doesn't pass through Bhutan, the basin covers an astounding 96% of the country's land as several tributaries from Bhutan join the BRB (Report on Brahmaputra Basin by GOI, 2014). Every one of these areas have a significant influence on the distinct topography and hydrological traits of the Indian Brahmaputra River Basin. In the higher part of the basin, there are mountain ranges and narrow valleys; in the lower part, there are hills, forests, and the floodplains. The distribution of rainfall varies as well; the southern Himalayan slopes receive over 6000 mm of precipitation annually. The higher altitudes of the basin experience heavy snowfall and cold temperatures. Because of its varied topography and climate, the region is a fascinating topic for geographical research (Rahaman and Varis, 2009a; China *et al.*, 2016; Kumar Sah *et al.*, 2022; Palash *et al.*, 2023).

1.3.2 *The Ecological and Socio-Political Significance of the Brahmaputra River Basin*

BRB is a rich and diverse biological area with a vast range of flora and wildlife. The World Conservation Union (IUCN) has identified 12 hotspots of mega biodiversity on Earth, including the Brahmaputra basin, which is a part of the Indo-Burma biodiversity hotspot. BRB is home to several rare species of flora-fauna and their habitats (Biswas and Boruah, 2000; Pradhan *et al.*, 2021; Bhuyan *et al.*, 2024). Range of terrestrial and aquatic ecosystems support a rich tapestry of biodiversity, including wetlands, grasslands, tropical and subtropical forests, and riverine habitats. The work of (Sharma *et al.*, 2023), which highlights the existence of endemic and endangered species, further emphasizes the biological abundance of the Brahmaputra basin and highlights the basin's significant role in the preservation of biological diversity on a regional and global scale.

Many species flourish in these ecosystems, including a wide variety of bird populations, large mammals like the Asian elephant (*Elephas maximus*), greater one-horned rhinoceros (*Rhinoceros unicornis*), and Bengal tigers (*Panthera tigris tigris*), as well as a variety of reptiles, amphibians, and fish species. However, the basin is ecologically fragile and vulnerable to several environmental and geographical challenges (Debnath *et al.*, 2022; Tempa, 2022; Chen *et al.*, 2023; Mitra *et al.*, 2023; Wen *et al.*, 2023; Bhuyan *et al.*, 2024).

The basin also represents a unique combination of being densely populated, and politically sensitive transboundary river basin in South Asia (Rahman, 2017; Barua, Vij and Zulfiqur Rahman, 2018; Vij, Warner and Barua, 2020; Costanza Rampini, 2021; Deka *et al.*, 2023; Rogers *et al.*, 2023). It serves as a vital resource for approximately 130 million people of the riparian states (China, India, Bhutan and Bangladesh), catering to their needs such as for irrigation, hydropower generation, fisheries, and navigation (Rahaman and Varis, 2009b; Ray *et al.*, 2015a; Yang *et al.*, 2016a, 2016b; Rahaman and Hossain, 2020; He, 2021; Lyu *et al.*, 2023).

Various hydropower projects have already been constructed in the upstream of the river (predominantly in China and Arunachal Pradesh, India). The power plants have proved to be one of the major sources of energy generation in the respective countries. As Bhutan too holds the capacity of hydropower generation, India has also started to have its hydropower projects on the rivers of Bhutan through which both the countries can share the benefit. This has opened the scope for the co-management of the river and the development of trust within the countries.

Similarly, navigation is another crucial aspect which can be managed between the states of Bangladesh and India, as large amount of population across the boundary is directly dependent on it for livelihood. Therefore, the Brahmaputra is vital in maintaining a relationship among the countries sharing the river, China, India, Bhutan and Bangladesh (CIBB).

1.3.3 *Hydropower Development Plans in the Brahmaputra River Basin*

BRB is facing the impacts of changing climate, which has led to alarming climate-induced disasters such as floods and erosion (Mohammed, Islam, *et al.*, 2017a; Dutta *et al.*, 2021a; Sammonds, Shamsudduha and Ahmed, 2021; Kumar, Mondal and Lal, 2022) thus impacting the socially marginalized and economically vulnerable communities of the flood plains. While climate-induced disasters make the river and the riverine communities vulnerable, the river also provides ample opportunities for irrigation development, livelihood enhancement, and operations such as inland water navigation and hydropower development (Barua, Vij and Zulfiqur Rahman, 2018), with a potential for regional development. The basin countries, particularly India, China, and Bhutan, consider hydropower development to be the dominant mode of development for economic development and energy security. The countries have devised several plans for water infrastructure projects, particularly hydropower dams, which, along with energy generation, also aim to serve as flood control measures for the BRB.

Countries	Length of the Mainstream (km)	Drainage Area (103km2)	Share of the Drainage Area (%)	Annual Runoff (km3)	Hydropower Potential (103 MW)	Share of the Basin (%)	Population in the Basin in 2017 (million)
China	2057	332.4	50.5	307.1	113.5	54.2	1.8
Bhutan	0	35.7	5.7	71.6	30.0	13.1	0.8
India	918	186.1	29.7	158.6	66.1	28.8	50.8
Bangladesh	274	72.7	11.6	124.4	0	0	56.8

Table 1.1: Details of hydropower potential in the BRB Source: (Mahanta, Mahagaonkar and Choudhury, 2018; Pradhan et al., 2021)

While China, India, and Bhutan boast significant potential for hydropower development, Bangladesh, being a low-lying country, lacks the topographical conditions conducive to such endeavours. In the following sections, we delve into the hydropower development plans and progress of the riparian states within the Brahmaputra River Basin.

1.3.4 *Status of hydropower development in BRB*

a) ***China:*** The Yarlung Tsangpo River, originating from the Tibetan Plateau and flowing through China, India, and Bangladesh, holds immense hydropower potential. China's ambitious plans for harnessing this potential have sparked both excitement and concern. With the world's largest number of dams and the highest hydropower capacity, China's focus on large-scale hydropower development has been a cornerstone of its economic growth strategy. However, this rapid expansion has not been without controversy, as it has led to ecological and environmental concerns. One of the most contentious projects is the proposed "super-dam" at the Great Bend of the Yarlung Tsangpo, which could have a capacity of 60 GW, tripling that of the Three Gorges Dam. This project, if realized, could significantly impact downstream regions, particularly India, and raise questions about the environmental sustainability of large-scale hydropower projects.

As the river possess an enormous amount of hydropower potential upstream, China has planned five hydropower projects in its Yarlung-Tsangpo stretch of which Zangmu hydropower project, completed in 2014 is of 510 megawatt (MW). China is also pushing for carbon emission reduction and attain carbon neutrality by 2060. Large Hydro-Electric Plant (HEP) with dams will also utilise the freshwater in water scarce Southeastern China where the Yarlung-Tsangpo flows. For instance, 360 megawatt project at Gyatsa and 560 MW project at Jiexu are under construction in the basin. 3 more HEP are in advance stage of planning, 640 MW project at Dagu, 710 MW project at Bayu and 800 MW project at Zhongyu (Gohain, 2023).

Several such other hydropower projects are under construction, and about 11 dams will be functional by the end of this decade, including the gigantic Mutou hydropower project proposed to be constructed by China at the Great Bend of Yarlung-Tsangpo that is estimated to generate a mammoth 60-70 gigawatt (60-70,000 megawatt) of power — more than three times the Three Gorges hydro project located on the river Yangtze in China (Jyoti Das, 2022).

China has started focusing on its renewable energy plans as a part of its 14th five-year plan. One of the priority in this initiative is to develop more hydropower at the lower Yarlung-

Tsangpo basin. India has been concerned about China's long term plan for hydropower development at the upper reaches of the basin. While China has dismissed proposals of diverting the river water, it has been constructing hydropower dams since 2009. The 14th fiver year plan of China raises speculation on the construction of a super-dam at Medog. As per the narratives, this dam if functionalised could serve various energy and economic needs of China. China plans to achieve carbon neutrality by 2060 and with available water resources and plans to shift to clean energy, hydropower development is very likely to be under process.

Local interest from the Tibetan part of China to develop various hydropower sectors within the region, a three-step plan to strengthen the region's economy has been established. However, there are certain concerns regarding the ecological and geopolitical implications of China's hydropower plans. China being a hydro-hegemon and most part of the basin under its territory, has the major control over the basin. Impact on downstream countries India and Bangladesh are a matter of significant concern as very little knowledge about the basin is exchanged among the countries. Parts of Assam, India and Bangladesh being a floodplain, can face hydrological impacts leading to impact on several sectors which drive their economy, such as agriculture and fishery. Furthermore, there is scarcity of information on the demographic stress which could arise from the construction of dams. State of Arunachal Pradesh in India, is also situated in a higher elevation with high hydropower potential. Changes in the hydrological flow at the upstream of Yarlung-Tsangpo can severely affect the hydropower operations in Arunachal Pradesh. The nexus of energy demand, economic development and sustainability brings us to a complex situation where it will take more than a dialogue to facilitate co-operation (Zhang and Donnellon-May, 2021). Integrated water management with collaboration from all the four countries sharing the basin could possibly be one of the solutions.

b) ***India:*** *"The development of hydropower is of paramount importance as it is clean, green, sustainable, renewable, non-polluting and environmental friendly,"- R.K. Singh, minister of power and new and renewable energy, February 2022, PIB*

With 11% of the nation's installed capacity devoted to hydropower projects, India's electrical supply is derived primarily from coal (which accounts for 50% of the total) and renewable energy (30%). With a total installed capacity of 46.8 GW, India is home to 211 big hydroelectric projects (those with a capacity more than 25 MW). A total of 17 GW more of planned production from 41 more hydroelectric projects (HEP) are now under construction. 30 sizable HEPs that are now under construction are located in the vulnerable Himalayan region. The river Brahmaputra plays a pivotal role in maintaining India's water and energy security, as it has enormous potential to provide resources for water-infrastructure projects. As the national interest on clean and green energy sources rise, emphasis has also been put on the generation of hydro energy from rivers. Currently, there has been plans to construct 70 hydroelectric power projects in 18 states of India, among which 36 projects are already under construction.

"Commissioning of the sixth hydro power plant in the North East i.e. 600 MW Kameng Hydro Power Station in Arunachal Pradesh will be a major step towards fulfilling Nationally Determined Contribution (NDC) of the Government of India pledged under Paris Agreement 2015."-19th Nov, 2022, PIB India

BRB basin possess about 44% of India's total hydropower potential and plans are being carried out to harness the energy, primarily from the upstream state of Arunachal Pradesh. The sub-basin of the river in India lies in the States of Arunachal Pradesh, Assam, Nagaland, Meghalaya, West Bengal and Sikkim. Among these states, Arunachal Pradesh and Assam holds the maximum drainage area of 81,424 sq.km and 70,634 sq.km respectively Water Resources, Government of Assam (accessed 01 November 2023). Arunachal Pradesh is often dubbed as the powerhouse of the country and is home to 34 per cent (50,328 megawatts) of the country's 148,701 MW hydropower potential, according to estimates of the (Hydropower Policy, 2008; Annual Report and MOP, 2021)

BRB holds significant hydropower potential, with plans underway to harness this energy primarily from Arunachal Pradesh. Projects like the Kameng Hydro Power Station aim to contribute to India's commitments under the Paris Agreement, with a projected capacity addition of 30,000 MW by 2030. However, there are concerns about cost overruns, environmental impacts, and potential conflicts with China over upstream dam projects on the Yarlung-Tsangpo River, which could affect water availability and lead to flooding downstream.

The project is a part of projected hydro capacity addition of 30000 MW by 2030. The project stretches over more than 80 kilometers in West Kameng District of Arunachal

Pradesh at a cost of approximately Rs 8200 Crore. The Project has two dams and a powerhouse having 4 units of 150 MW to generate 3353 million units of electricity. Generation of 3353 Million Units annually from the project will make Arunachal Pradesh a power surplus state with huge benefits to the National Grid in terms of grid stability and integration and balancing of solar and wind energy sources in the grid.

This year, the Indian finance minister proposed an allocation of INR 350 billion (USD 4.27 billion) for the green transition, net-zero objectives and energy security in the 2023-24 budget, and specifically mentioned pumped hydropower. Arunachal Pradesh has the longest International Border in the country with a total length of 1,863 km. Out of the total international boundary, the State shares 1,126 km border with Tibet. Fears of Chinese dam-building upstream are invoked as another justification for large hydropower projects in Arunachal. the Lower Subansiri project which is scheduled to be operational later this year has overrun its original costs by more than 200%. The overrun cost is INR 132.11 billion (USD 1.61 billion) higher than the original cost.

According to the government sources, a 60,000 MW Chinese hydropower project on Yarlung-Tsangpo planned at MeDog on Arunachal Pradesh's border could be a cause for concern for multiple reasons-scarcity of water if China plans to divert it, floods affecting lakhs in Arunachal Pradesh and Assam if China suddenly releases water as well as environmental concerns.

"Ample presence of water resources such as rivers and natural springs along with heavy rainfall in the mountainous border regions of the State serve as a great advantage in extraction of energy from micro-hydel projects," Pema Khandu, Chief Minister, Arunachal Pradesh.

"Our fundamental mission is sustainable and equitable realisation of Hydro Power potential in Arunachal Pradesh. With that, we also believe in setting manageable short term targets to maximize productivity and thus we officially launched MISSION 3000 MW BY 2030 during our 15th Foundation day, which may be summarized as increasing our portfolio to 3000 MW of installed capacity by the year 2030." –Hydropower Development Corporation of Arunachal Pradesh.

Several Memorandums of Undertaking (MoUs) have been signed under Ministry of Power, between State Government of Arunachal Pradesh and public sector units (PSU's) which work around hydropower, to revive 12 stalled hydropower projects. The total estimated capacity of these projects is 11,517 MW. North Eastern Electric Power Corporation Ltd , Satluj Jal Vidyut Nigam Ltd.and National Hydroelectric Power Corporation were allocated projects totalling 2,620 MW, 5,097 MW and 3,800 MW respectively. Earlier, these projects were allocated to private developers however due to several economic and political challenges the projects were shelved for almost 15 years. Currently, these central PSU's have taken initiative to harness the hydropower potential of Arunachal Pradesh and align with India's target of achieving 500 GW (Gega Watt) of non-fossil energy capacity by 2030. A total investment of rupees 1,26,500 crores has been made on these projects. However, these rampant decisions to expand hydropower potential can have downstream impacts on the ecology and livelihood of people living on it. In an era of climate change, several climate induced disasters have been observed world-wide. The development plans have to be climate conscious to negate any kind of climate impacts.

c) ***Bhutan:*** Bhutan has prioritized energy in its development ambitions for a number of years. India and the country have collaborated closely on several hydroelectric projects, and a sizable amount of the output is shared between them. Bhutan has a capacity of about 1.6 gigawatts, with hydroelectric plants providing more than 99% of the installed capacity. The combined capacity of these facilities is 1,614 megawatts.

The Ministry of Economic Affairs now houses organizations like the Department of Energy and the Bhutan Electricity Authority, which were established as a result of later reforms. One important player in the country's energy scene is the Bhutan Power Corporation, which was, until recently, a publicly held company. The company is subject to regulations on project size and output when operating its multiple hydroelectric projects. The government recently combined a number of hydroelectric businesses to establish Druk Green Power Corporation, which is in charge of supervising and advancing the development of alternative energy sources and hydropower.

99 % of Bhutan's energy generation is still hydropower with a small amount accounting for thermal energy. Focus has also been towards renewable energy sources however, primarily hydropower remains to be the primary source of energy. A large portion of Bhutan's economy is from hydropower plants which are developed in collaboration from

India. India provides investments (partly loan and partly grant) to Bhutan for the development of hydropower. Chukha HEP, Mangdechhu HEP, Nikachu HEP, Kurichu HEP, Tala HEP, Dagachu HEP and Basochu HEP are among the major hydropower plants of Bhutan. It is observed that Bhutan produces surplus energy from its hydroelectric power plants during summer however during winter, Bhutan has also bought energy to India. Several investments on developing hydropower in Bhutan has also emerged from doner organizations like Asian Development Bank (ADB) and World Bank. However, with the country being prone to natural disasters like landslides and earthquake, development of large infrastructure on the rivers of Bhutan becomes a matter of concern. Studies on climate change of Bhutan has been low and very little is understood about the climate change impacts.

1.3.5 *Climate change on BRB*

Brahmaputra river basin is vulnerable to the impacts of climate change. The upstream of Yarlung-Tsangpo, middle reaches of Brahmaputra in India, and downstream of Bangladesh are impacted by the uncertainties in climate change. The country of Bhutan, which contributes several tributaries to the river, is not immune to the impacts of climate change.

Several studies have been conducted to assess the future climate change scenarios on the basin. For instance, (Immerzeel, 2008a) analysed the future climate projections on the basin, whereas, (Gain *et al.*, 2011)examined the effects of climate change on the hydrological streamflow of the river. Flood modelling was done by (Dutta *et al.*, 2021b) to forecast future flood vulnerability in the basin. (Lutz *et al.*, 2016) projected increase in runoff in the hydrological flow due to melting of glacier and precipitation changes. Shifts in precipitation was observed by (Pervez and Henebry, 2015a). Rainfall and temperature predictions for the basin and its impact on hydrology was studied in detail by (Palash *et al.*, 2023). All these studies underscore the immediate need for proactive adaptation to assess and address potentially significant impacts of climate change on BRB.

1.3.6 *Hydropower in the Context of Climate Change in BRB*

Globally, the consequences of impact of climate change on hydropower has been multifaceted. Impacts are laden upon reservoir size, hydrological flow, sedimentation rate, energy market dynamics etc. Depending upon the type of hydropower plant and geographical location, the short-term effect of climate change on hydropower can be positive, negative or negligible. For instance, during peak monsoon season, factors like hydrological flow, catchment area, energy demand, geomorphology of location etc. can all affect hydropower operations. Impacts can be severe such as landslides and GLOF (glacier lake outburst flood) which can further complicate the scenario. In one of the studies done by (Chuphal and Mishra, 2023), 46 hydroelectric power projects in India with large catchment and hydropower potential in them pertaining to the tropical wet and warm weather of the country, were expected to increase their production in future. However, the impact of climate variations on local regions is expected to be different from other. Which means, the climate impacts will essentially be different for different dams. If an increase in runoff is projected, it will lead to more frequent high reservoir storage conditions, posing challenges for reservoir operations (Gaudard, Gilli and Romerio, 2013). Although this study did not include BRB due to lack of data availability, the findings are crucial to understand impacts of projected climate changes on electricity generation.

As seen in previous section, hydropower plays one of the most important roles for economy generation in Bhutan (Uddin, Taplin and Yu, 2007; Alam *et al.*, 2017). The energy demand in Bhutan is increasing considering that Bhutan caters to Bhutanese and Indian energy market. (Tariq, Wangchuk and Muttil, 2021). However, Bhutan too witnesses the impact of climate change. This change in climate raises concern for the development of hydropower projects in China, India and Bhutan.

While glacier melting, precipitation during winter etc. might seem advantageous initially, long term impacts can lead to maladaptation and climate crisis. This could lead to various hydrological changes such as decrease in runoff, affecting the functional sustainability of the infrastructure (Mishra *et al.*, 2021; Wasti *et al.*, 2022). Studies on climate projections demonstrate glacial loss and reduced meltwater flux in South Asia, including China, Bhutan and upper reaches of Arunachal Pradesh (Sakai, 2012; Mahagaonkar *et al.*, 2017). These changes due to variations in climate can impact hydropower operations (Blackshear *et al.*, 2011; Schaefli, 2015; Li *et al.*, 2022). Although hydropower is an essential source of energy, its susceptibility to climate change means that long-term sustainability requires careful planning and adaptation measures.

1.3.7 *Occurrence of extreme events on BRB*

Several instances of extreme weather events have been reported from BRB. The upper reaches of the river with snow-capped and evergreen mountains have higher elevation and poses risk of flash floods, landslides and cloud burst. The region is also vulnerable to earthquake with frequent seismic activity happening at a miniature scale frequently. Tibet, which accommodates several large glaciers including the Purong Kangri Glacier, has remained dry, cold with specific vegetation supporting the environment. However, a recent scientific expedition at Tibet published a report "Qinghai-Tibet Plateau Scientific Expedition and Research" on August 19, 2017 according to which the region is getting wet, warmer with more forest cover (Phayul, 2024). The China Meteorological Administration has already issued a warning, stating that by 2050, the area covered by glaciers on the Tibetan plateau could decrease by 40%, raising the possibility of strong storms and flooding in places downstream (South China Morning Post, 2024). After traveling a few hundred kilometres towards the east and south, the river enters India at Arunachal Pradesh where it is known as Siang. Arunachal Pradesh has been witnessing some of the impacts of climate change. In 2004, a catastrophic flash flood washed away large landmass and vegetation cover of Seijosa district, Arunachal Pradesh. Currently, a shift in biodiversity has been observed due to change in the micro-climate of the region (Down To Earth, 2021). Evidence of extreme heavy rainfall (greater than 204.5 mm) has been witnessed in Arunachal Pradesh and in the sub-Himalayan region of Sikkim and West-Bengal (The Weather Channel, 2023). The Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) has preserved daily precipitation values from 1981 to 2020. These values demonstrate that at least 10 days per year in the Dibang river basin have seen above-normal rainfall (>2 standard deviation of the 40-year mean daily rain). There are currently 4–16 days each year with more than 100 millimeters of precipitation. There were sixteen days in 2015 with more than 100 millimeters of rain falling, the year the Anpum and Loklung rivers were destroyed. The region observed >200 mm of rain poured in one day—an extreme event (Dialogue Earth, 2021).

The river enters the floodplains of Assam and flows for X kilometres before entering Bangladesh as Jamuna. It is predicted that by the end of this century, there will be an increase in river run-off in the Brahmaputra river basin, according to the Intergovernmental Panel on Climate Change's (IPCC) forecasts (The Sentinel, 2024). Over the previous fifty years, the BRB floodplain experienced high magnitude floods in 1954, 1962, 1972, 1977, 1984, 1988, 1998, 2002, 2004, 2012, and 2020. Every year, three to four recurrent flood surges devastate the floodplain, claiming the lives of those who live there and their means of subsistence. Floods are projected to cause $2 billion in losses annually on average (WRD, 2022). Assam faces yearly flood, the intensity of which keeps increasing year by year. Because of the frequent occurrence of brief, strong rainfall episodes, floods are a major hydrological disaster in this region (Goswami et al., 2010; Varikoden and Revadekar, 2020). For instance, the 2012 floods effected at least 2 million lives, whereas, the 2020 floods took the tally to 5 million, with almost 100 people dead. The state received a continued spell of strong showers of 53.4 mm as of June 19, 2022. 528.5 millimetres of rain fell in total throughout the first 12 days of June, an excess of 109% (Down to Earth, 2022). The state is vulnerable to extreme climate events such as floods, flash floods, droughts and cyclone (CEEW, 2021).

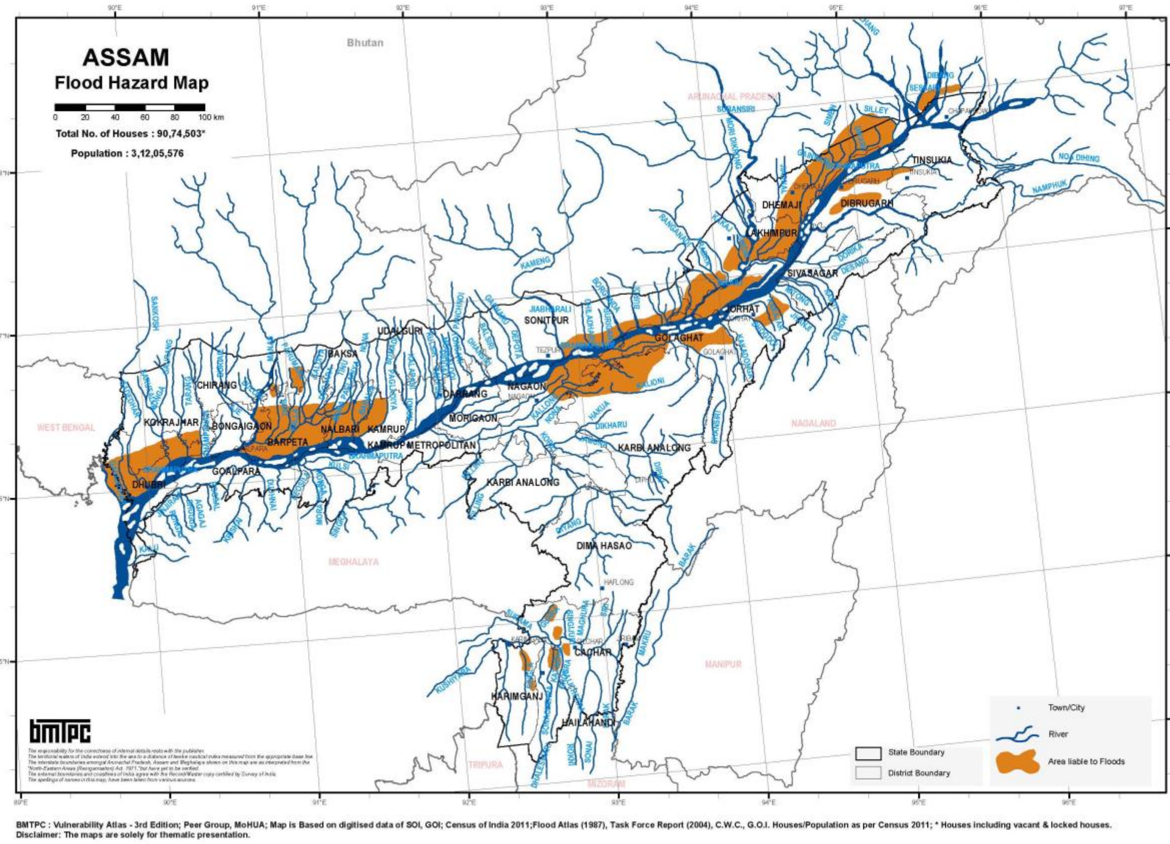

Fig 1.1: Flood Hazard Map of Assam (Source: https://vai.bmtpc.org/Assam.html)

Brahmaputra in Assam is joined by several tributaries from Bhutan such as Manas, Sankosh, Raidak, Beki etc. According to “Climate Change Projection Report” by National Centre for Hydrology and Meteorology, it is anticipated that over the next few decades, Bhutan will see a sharp rise in temperature and precipitation, which will lead to more flash floods and have an impact on forestry, hydropower, and agriculture. Among the recent noteworthy extreme weather occurrences in 2024 is the July 15 flash flood at the Begana Guru Lhakhang stream in Thimphu which led to severe damage at the downstream. On August 5, there was a flash flood near the Bumthang Lamay Gonpa stream. On August 10, Dechenphu stream was struck by another flash flood. On August 17, Isuna, Paro, and Gidakom regions of Thimphu experienced abnormal extreme rainfall. On August 18, torrential rains from Bayta Chhu triggered a flash flood in Gangtey that affected the villages of Beta, Gela, and Tokha in Gangtey gewog. For the duration of the monsoon season in 2024, the NCHM anticipates rainfall that is marginally above average with the possibility of extreme weather events (Kuensel, 2024).

2

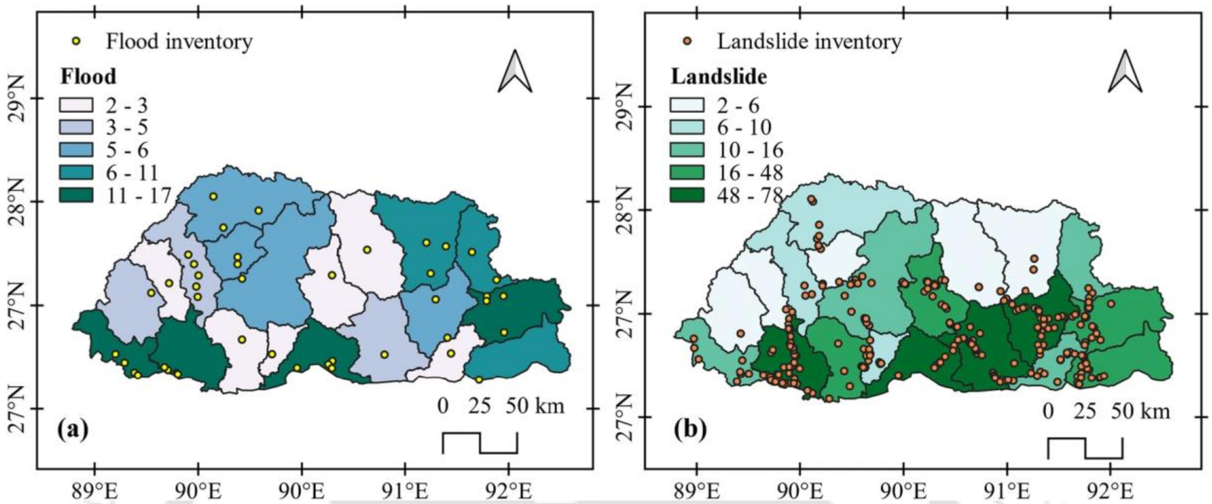

Fig 1.2: Flood and Landslide map of Bhutan (Source: Tempa and Yuden, 2023)

3

In Bangladesh, 60% of the country is affected by flooding (Chowdhury and Hassan, 2017). The current century has seen a number of devastating floods that have a negative impact on people's life in Bangladesh. These have occurred in the years 2000, 2004, 2007, 2018, and 2019 (Uddin, Matin, and Meyer, 2019).

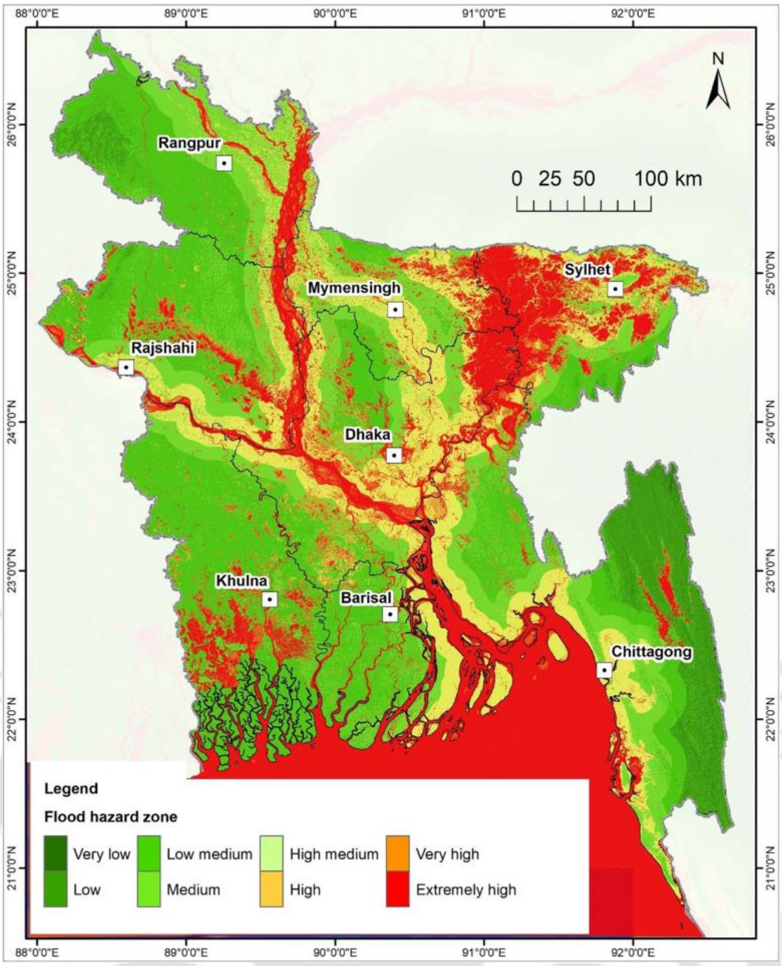

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Fig 1.3. Flood Hazard Map of Bangladesh [Source: Uddin and Matin (2021)]

The hydrology and water resources of the Brahmaputra River basin are anticipated to be significantly impacted by climate change. Additionally, a rise in mean peak discharge is projected to result in more frequent flooding (Nepal and Shrestha, 2015). Because of its increased exposure, risk of hazard, and susceptibility as transboundary river basins, the BRB is consequently more susceptible to flooding than other river basins (Vegad et al., 2023).

4.1 Research Gap

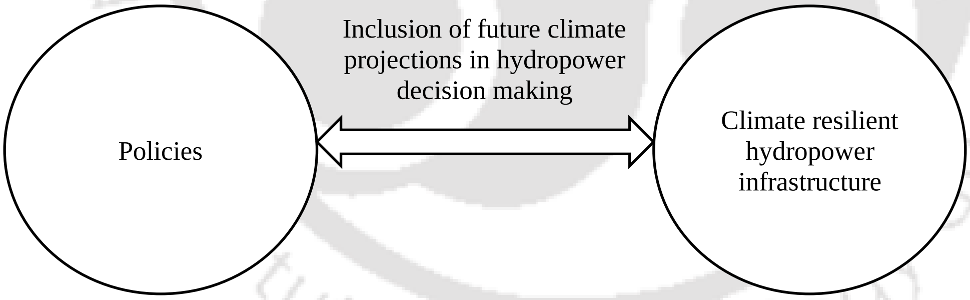
Climate change poses alarming challenges across the Brahmaputra River Basin (BRB), with riparian states already experiencing extreme consequences. Water, as a fundamental element of nature, is profoundly sensitive to these impacts. Despite this, there has been a striking lack of efforts to comprehend the repercussions of climate change on water infrastructure within the dynamic BRB.

During the course of this thesis, not a single study focusing on the impact of climate change on hydropower/water infrastructure in the BRB was found. This gap is particularly concerning given the multitude of hydropower projects planned for the basin's upper reaches, highlighting the urgent need to address how climate change influences hydropower development.

The lack of clarity regarding the scholarship of science at the basin level further exacerbates this issue. Existing literature fails to provide a comprehensive understanding of the relationship between climate change projections and hydropower development in the basin. Consequently, there is a significant opportunity to explore the development of climate-informed hydropower structures both at the research and policy levels.

While substantial scientific literature on climate change in the basin exists, questions persist regarding its adequacy, utilization in hydropower project development, challenges in basin-level science development, and the basin's preparedness for climate change uncertainties. Answering these questions is crucial for comprehending various factors such as challenges, benefits, vulnerabilities, resilience, knowledge gaps, and policy gaps associated with hydropower development in the context of future climate change. Without such understanding, the outcomes of interventions in the basin remain questionable.

4.2 Research Puzzle



The above identified research gaps led to exploration of concepts on climate change in BRB and hydropower decision making. Initial questions such as; Are climate change studies incorporated in hydropower policies? Are the hydropower infrastructures climate resilient? Are the decision makers aware of the climate uncertainties? Will the next hydropower plan in BRB be including climate parameters? What will happen if future climate projections are incorporated into hydropower policies?

These fundamental questions emerged as a puzzle. Thus, to solve this puzzle a larger research question was formulated, the answer to which can generate crucial insights on hydropower development in the basin.

4.3 Research objectives and questions

Deriving from the above-mentioned research gaps, the overarching aim of the thesis is to investigate *"how hydropower projects in the Brahmaputra River Basin (BRB) incorporate scientific knowledge on future climate change"*

This thesis is guided by the following three sub-objectives and questions, which are answered in this thesis based on a systematic review of literature, physical assessment of climate change scenarios on the basin and stakeholder interaction conducted in BRB as given in Table 1.2.

Sl. No	Research Questions	Research Objectives	Purpose	Research Tools
I	*How has the status of scientific knowledge on climate change scenarios evolved in the last three decades in BRB*	To analyze the academic scholarship on future climate projections in the BRB	*Helps in identifying the gaps in climate change research*	*Systematic Literature Mapping*
II	*How can the future climate scenario for entire BRB be assessed physically?*	To understand the future climate extremes over BRB using a globally downscaled model (NEX-GDDP)	*Feasibility analysis of climate change projections*	*Precipitation Analysis using NEX-GDDP dataset*
III	*How are the future climate projections included as a parameter in the hydropower decision making process*	To understand the inclusion of climate change in hydropower decision making process	*Identifying the involvement of 'Climate Change' in the hydropower decision making of Bhutan and India over BRB* *To frame policy suggestions on 'hydropower*	*Stakeholder interaction* *Qualitative analysis*

			decision making'	

Table 1.2: Representation of research objectives, research questions, purpose of research and tools used

4.4 Thesis outline

This thesis comprises eight chapters that delve into various aspects of knowledge production concerning climate change and hydropower in the Brahmaputra River Basin (BRB), examining their interconnectedness.

Chapter 2 outlines the methodology underpinning the thesis, emphasizing an interdisciplinary approach. It delineates how each objective necessitates specific methods and tools, while also addressing data challenges crucial for climate analysis, as explored in Chapter 5.

Chapter 3 investigates the evolution of scientific knowledge on climate change scenarios in the BRB over the past three decades. Utilizing the ROSES systematic literature mapping technique, it quantifies publications, assesses collaborations, sectoral focuses, and scientific parameters like emission scenarios. This chapter also highlights publication quality and research gaps, shaping subsequent research questions.

In Chapter 4, future climate scenarios for the entire BRB are examined, addressing Objective 2. This involves developing climate projections for the near (2050s) and far (2070s) future using the NEX-GDDP global climate dataset, with a focus on precipitation extremes. The chapter underscores the feasibility of climate change projections on the basin and their correlation with hydropower vulnerability.

Chapter 5 builds upon these findings to understand hydropower vulnerability from a policy perspective. Objective 3 is explored through content search, stakeholder interaction, and qualitative analysis, revealing the absence of climate considerations in hydropower decision-making processes. Interactions with academic practitioners and government officials in India and Bhutan further illuminate this gap.

Chapter 6 concludes the thesis, summarizing central findings and research objectives. Future research perspectives are also discussed.

Lastly, Chapter 8 serves as the bibliography, cataloguing peer-reviewed articles, reports, and grey literature utilized to support the research hypothesis and achieve the research objectives.

Chapter 2

Methodology

Chapter 2

Methodology

2.1 Research approach

In the early stages of formulating the overarching research question for the thesis, the study advocated for employing a mixed-method approach, blending quantitative and qualitative research methodologies. As the thesis progressed, an exploratory research approach was adopted, aligning with the need to delve into topics that remain relatively underexplored and warrant further investigation. Nonetheless, the sub-questions of the thesis were addressed using diverse research methodologies tailored to achieve the specific objectives. Objective 1 employed a mixed-method approach, Objective 2 was tackled through a quantitative approach, while the methods used to address Objective 3 encompassed qualitative and exploratory techniques.

For objective 1 (*To analyze the quantity of academic/scientific work done on BRB with respect to the future climate projections), a* systematic literature review mapping technique was used to quantify the state-of-the-art knowledge on climate projections on the basin. The study was further qualitatively analysed to understand the basin-level academic gaps. For objective 2 (To understand the future climate extremes over BRB using a globally downscaled model (NEX-GDDP), a quantitative analysis of climate datasets was used to project climate scenarios on the basin. For objective 3 (*To understand the inclusion of Climate Change in hydropower decision making process),* the fieldwork involved different research activities, including participant observation, unstructured and semi-structured interviews with relevant stakeholders. These activities enabled a better understanding of stakeholder's experiences by building meaningful relationships with them. It is important to note that the thesis specifically engaged with two categories of professionals working on the basin to address the third research question. Firstly, the engagement included scientific or academic practitioners who work on climatology or energy science and technology (specifically hydropower). Secondly, interactions were held with the government officials or decision-makers who play a role in developing hydropower decision-making. While most stakeholders agreed to interact, some did not, citing reasons for the securitisation of information on BRB. Thus, concerning the geo-political issues of the basin, challenges were observed in gathering ground data, interacting with stakeholders and facilitating collaboration.

2.2 Research location (Study area)

BRB is the largest transboundary river in the Hindu Kush Himalayan region, shared by China, India, Bhutan and Bangladesh (see figure 2.1). As discussed in section 1.3 in chapter 1 of the thesis, BRB is situated in the north-eastern part of the Indian Subcontinent, spanning latitudes from approximately 23.9˚N to 31.5˚N and longitudes from 82.1˚E to 97.7˚E. The BRB originates from the Angsi glacier, located in the southern region of Tibet Autonomous Region (TAR) at an elevation of 5300 meters. The river then traverses from west to east, followed by a journey of 983 KM in a northeast-to-southwest direction through the states of Arunachal Pradesh and Assam in India, where the river is accompanied by tributaries from Bhutan (Singh *et al.*, 2004). Eventually, it extends 230 kilometers southward into Bangladesh, referred to as the Jamuna (Palash *et al.*, 2023). The land cover within the Brahmaputra Basin is characterized by diverse components, including 44% grassland, 14.5% forested areas, 14% agricultural land, 12.8% a mosaic of cropland and natural vegetation, 11% covered by snow and ice, 2.5% barren or sparsely vegetated land, 1.8% occupied by water bodies, 0.05% representing permanent wetlands, and a mere 0.02% dedicated to urban areas (Palash *et al.*, 2023). The estimated annual water utilization within the Brahmaputra basin is approximately 27,457 million cubic meters, with China (specifically Tibet) accounting for 2% of this total, Bhutan for 1%, India for 43%, and Bangladesh for 54% (Tandon and Sinha, 2007; Shrestha *et al.*, 2015).

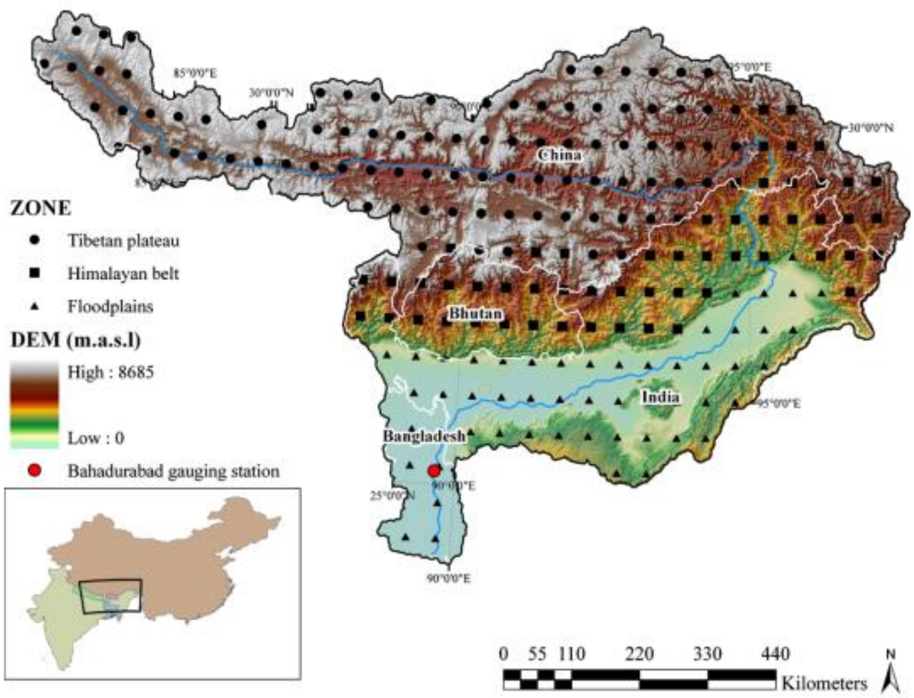


Fig 2.1: Map of Brahmaputra River Basin. *Source:* Indian Institute of Technology Guwahati

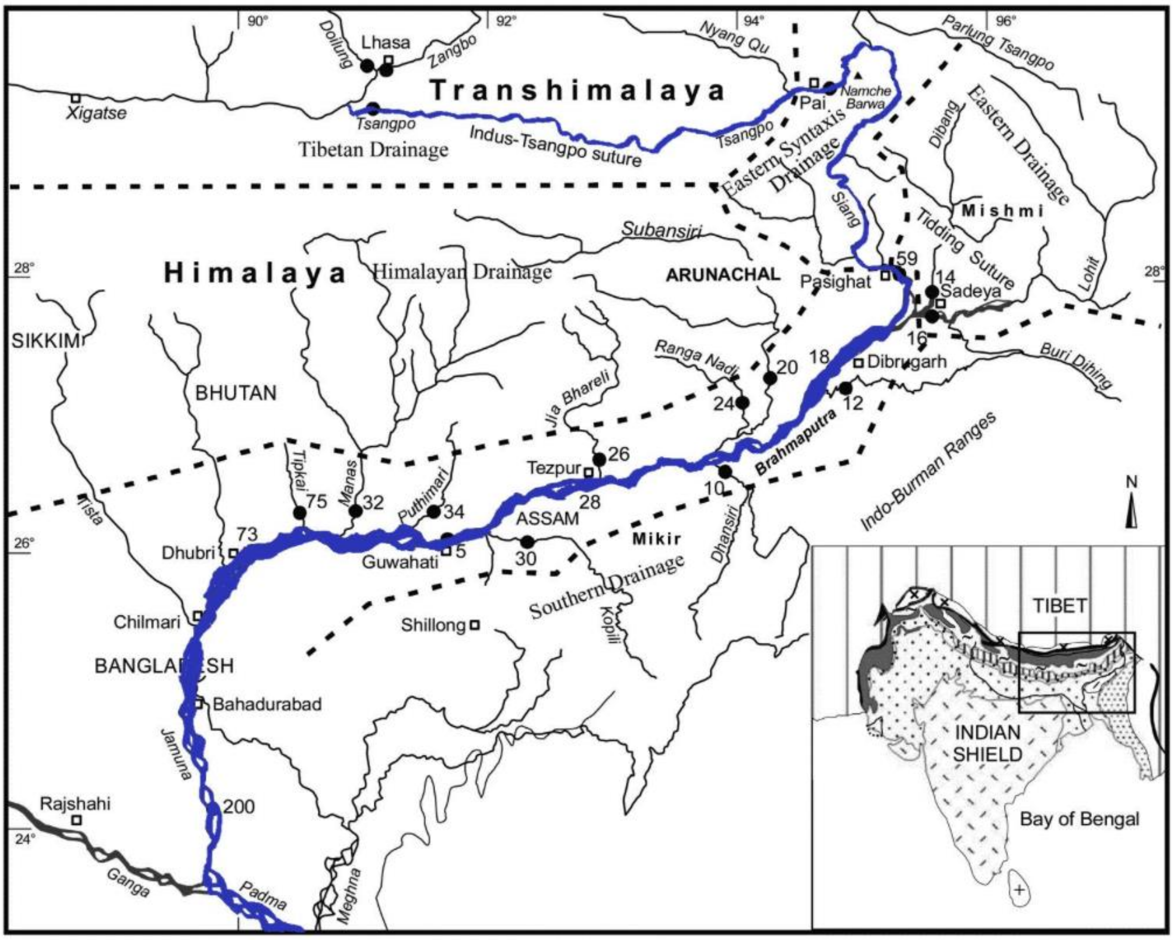


Fig. 2.2: Map of Brahmaputra river basin showing the drainage system along with tributaries (Source: https://www.indiawaterportal.org/articles/coping-floods-and-erosion-brahmaputra-plains)

Like every transboundary river basin, the BRB presents a complex geopolitical landscape shaped by the interests and interactions of riparian states. The strategic significance of the basin, given its vast water resources and economic potential, has led to heightened geopolitical considerations. As an upper riparian state, China holds a pivotal position in the basin and has pursued infrastructure development projects, including dam constructions, raising concerns among downstream riparian countries such as India and Bangladesh. The asymmetry in power dynamics and the potential for unilateral actions in the upper riparian region have exacerbated concerns about water resource management, environmental impacts, and downstream water availability (Barua et al. 2018; Feng et al. 2019). The interplay of geopolitical factors adds a layer of complexity to the sustainable management of the basin.

As discussed in Chapter 1, the BRB holds immense potential for hydropower development, prompting China, India, and Bhutan to outline several plans for hydropower projects in the region. However, these plans have sparked concerns among downstream communities and environmentalists due to the lack of comprehensive scientific studies assessing the potential impacts of these projects. Furthermore, with the increasing frequency of extreme events such as floods and flash floods attributed to climate change, these concerns have escalated, leading to protests and resentment among local communities towards the development of these projects. Despite these apprehensions, hydropower development projects are progressing, driven by the need to meet energy demands in the respective countries.

While Objectives 1 and 2 of the study focus on the entire basin, Objective 3, which involves stakeholder interviews on the inclusion of climate change parameters in hydropower decision making, specifically targets Bhutan and India. The exclusion of China from the stakeholder interviews was due to reluctance to openly discuss the country's hydropower plans through online channels. Additionally, the outbreak of COVID-19 in 2020, coinciding with the commencement of fieldwork for the thesis, made it impossible to visit China, further limiting the scope of the study. However, insights gathered from offline discussions with stakeholders in Bhutan and India have helped mitigate this limitation and provide valuable perspectives for the thesis.

2.3 Methodology

This chapter offers an outline of the methodologies employed to fulfil each study objective. A comprehensive discussion of the methodologies utilized for each specific objective is further elaborated upon in the respective chapters.

2.3.1 *Systematic literature analysis (objective 1)*

For our mapping study, we followed the ROSES (Reporting Standards for Systematic Evidence Syntheses in Environmental Research) protocol (Haddaway *et al.*, 2018). The systematic mapping exercise (see Figure 2.2) follows an organized and transparent mapping of journal articles (Vij *et al.*, 2021) and attempts to collate and catalogue available evidence (James, Randall and Haddaway, 2016). Unlike systematic literature reviews, systematic mapping attempts to collate, describe, and catalogue available scientific evidence on a selected topic, the details of which are provided in chapter 3 of the thesis. For our analysis, we have selected two authentic academic databases: (1) JSTOR and (2) Scopus.

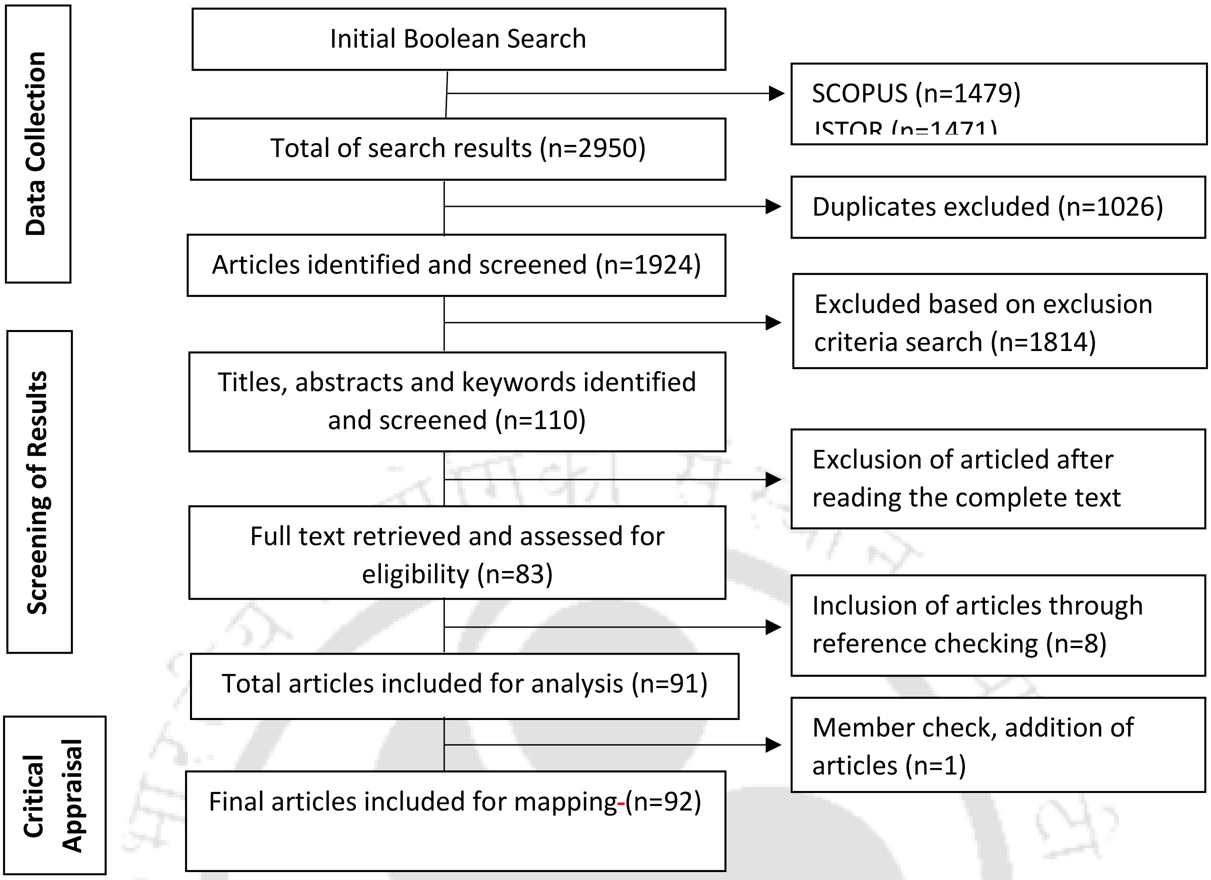


Fig 2.3: Steps involved in the systematic review for data collection

2.3.2 Physical assessment of climate data (objective 2)

a) *Dataset for analysis*

The study employed the NEX-GDDP dataset, which is obtained from CMIP5 models and applied to two different scenarios: RCP 8.5 and Representative Concentration Pathway (RCP) 4.5 (Thrasher *et al.*, 2012).We have just used precipitation as the parameter of interest in this investigation. The forecasts cover the years 2006 through 2099, and the historical runs cover the years 1950 through 2005. These high-resolution datasets are an invaluable resource for learning about processes that are sensitive to smaller spatial scales and comprehending how local topography affects climate conditions.

b) APHRODITE precipitation data and analysis

The observed precipitation data for our study has been obtained from Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) (Yatagai *et al.*, 2012).

The current study's climate projections are based on the Multi-Model Mean (MMM) mean values, which are derived from NEX-GDDP simulations performed by 20 GCMs. APHRODITE was used to properly test the outputs of the NEX-GDDP model. Using the South-West Monsoon season (June to September) as a baseline from 1976 to 2005, the analysis projects future changes in the precipitation indices.

2.3.3 Qualitative Analysis (objective 3)

a) Stakeholder identification and interactions

To identify the inclusion of scientific knowledge in hydropower decision making, it was necessary to identify the scientific community/knowledge developers and the decision makers/government officials involved in hydropower decision making. Hence, a detailed list of knowledge developers and decision makers was developed; the detailed method followed to identify the stakeholders and to conduct the interviews is mentioned in Chapter 5 of the thesis. The interviews in Bhutan were carried out in March, 2020, in their respective offices. The interview type was formal and followed by semi-structured questions. The interviews in India were carried out in Arunachal Pradesh in December 2022. Interactions in Assam in India were rather periodic, but followed a definite time step. Interviewees did not permit mentioning their names; hence, only the names of respective departments have been mentioned in the thesis.

b) Thematic analysis

Since the stakeholder interactions were done using semi-structured questionnaires, every interaction led to rigorous discussions, steering to generation of data which were diverse in nature. It contained beliefs, perceptions, scientific information and vision of the stakeholders. As the intention of the study was to identify and analyse patterns within data, a qualitative analysis method was necessary which could organise and describe the data. Method described by (Braun and Clarke, 2006) was found to be most suitable for the study, pertaining to several other similar studies being carried by this method. The method was particularly useful as it led to the construction of narratives which were used to qualify arguments, as presented in chapter 5 of the thesis.

The stakeholders were interviewed using semi-structured questions, the content of which was analysed qualitatively. The reason for strictly following a qualitative analysis with a 'Thematic' protocol was to understand the perspectives of academicians and government officials and segregate each concept perceived into themes. To pursue the analysis, the data generated through interviews was analysed by organising, exploring and condensing, the detailed steps of which are explained in chapter 6 of the thesis.

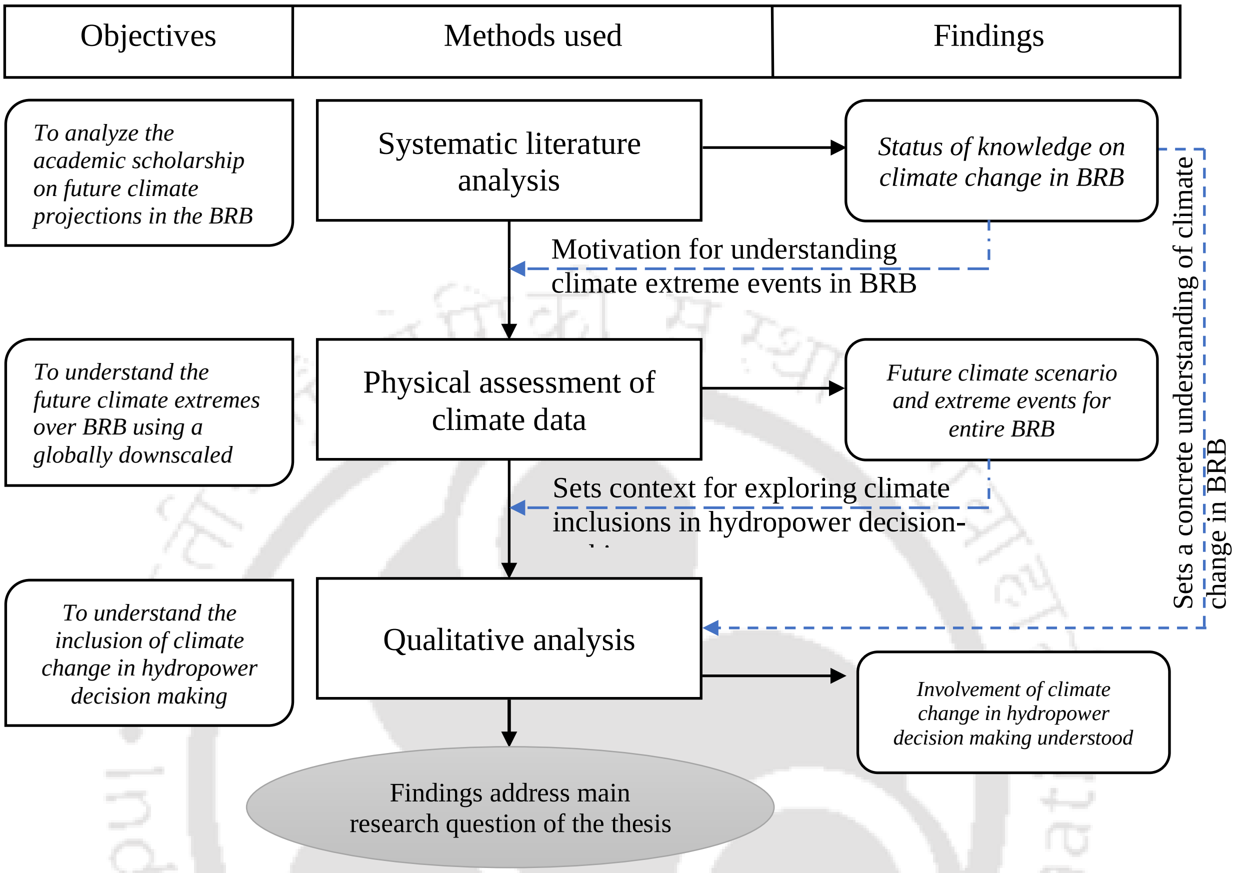


Fig 2.4: Flowchart showing methodological contributions to research questions

Chapter 3

Ignorance is not a bliss? A systematic mapping of climate change scenarios for the Brahmaputra Basin

Chapter 3

Ignorance is not a bliss? A systematic mapping of climate change scenarios for the Brahmaputra Basin

3.1 Introduction

The Brahmaputra in comparison to other river basins of South Asia, such as Indus and Ganges, is an under-researched river basin, with a limited number of studies conducted on socio-cultural aspects and climate change (Dutta *et al.*, 2021b). While there are, a few studies focusing on future climate projection in the BRB, the findings remain scattered and are not systematically collated, which makes it difficult to access the information for advancing research and policy formulation. This is worrisome because it has led to an absence of a reliable, and comprehensive network of scientific information about the basin (Biswas and Boruah, 2000; Ray et al., 2015a; Barua, Vij and Zulfiqur Rahman, 2018; Vij, Warner and Barua, 2020), raising concerns over the potential ramifications. Without a robust understanding of the basin's hydrological dynamics and future climate trends, any water infrastructure interventions on the basin become susceptible to questionable outcomes. Thus, the dearth of scientific information on climate projections and associated uncertainties not only hinders informed decision-making but also exacerbates mistrust and suspicion among stakeholders.

Scientific knowledge about the Brahmaputra River Basin is essential for making informed decisions and fostering climate-resilient development. By harnessing a robust understanding of the basin, we can navigate complex challenges and seize opportunities in a rapidly changing environment. Thus, scientific knowledge on BRB can serve as a cornerstone for devising evidence-based policies, strategies, and interventions aimed at enhancing the resilience of communities, ecosystems, and infrastructure in the face of climate change impacts.

To address this critical knowledge gap, our first imperative is to shed light on the current state of knowledge regarding future climate scenarios in the BRB by systematically mapping the existing literature on future climate change projections within the BRB. This study will collect and categorize the existing body of knowledge, while simultaneously identifying key gaps and areas for future research. Thus, this chapter of the thesis aims to map the landscape of published scientific articles pertaining to climate change projections in the BRB, employing a systematic literature mapping methodology, focusing on English-language scientific articles published between 1989 and 2023. We focus on three important aspects - firstly, discerning the key actors publishing research on BRB; secondly, examining the thematic content of these publications; and thirdly, evaluating the nature of collaborations fostering such scholarly output. Through this comprehensive analysis, we aim to shed light on the contributors, themes, and collaborative efforts driving knowledge production in this critical domain. The study thus addresses the first sub-research question of the thesis *"How has the status of scientific knowledge on climate change scenarios evolved in the last three decades in BRB?"* by providing a detailed status of knowledge on climate change projections on the basin. The findings from objective 1 help to understand the status of climate change projections on the entire BRB, based on which a quantitative analysis has been done to assess the climate scenario of the basin physically. The findings from this objective also provide a way forward to objective 3 of the thesis by opening a platform for discussion on climate change projections with stakeholders.

3.2 Method- Systematic mapping and ROSES protocol

As our first step to collect data, we created search queries, including the terms *Brahmaputra, yarlung, India, Bangladesh, China, Bhutan, climate, models, GCMs, RCMs, SSPs, RCPs* etc. The databases were searched for different Boolean configurations of a river basin (and related terms, such as ''tributaries,'' name of the river or stream) and climate change projections (and other related terms, such future climate change or future climate scenario). For instance, a search query such as

(brahmaputra OR yarlun*) AND (india OR china OR bangladesh OR bhutan) AND (climat* OR climate AND model) AND (gcm OR rcm OR rcp OR ssp OR a1 OR a2 OR a1b OR b1 OR b2) AND PUBYEAR > 1996 AND PUBYEAR < 2024 AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))

was used to generate results. Search queries were made specifically for China, India, Bhutan and Bangladesh, where the river is present, so as to understand the scale and intensity of research done by each of these countries. Our search was limited only to peer-reviewed journal articles with a full text written in English, published and/or accepted between January 1989 and December 2023. We limited our search to studies explicitly referring to ''climate change projections'' to capture future scenarios (RCPs), an approach used in most systematic reviews (Ford, Berrang-Ford and Paterson, 2011; Berrang-Ford, Pearce and Ford, 2015; Berrang-Ford *et al.*, 2021). The first search was implemented in June 2020, and after removing duplicates, we had a repository of 1924 articles. To keep the database updated, we conducted a second search in January 2022 and the last search in December 2023.

In the second step, data screening was conducted, entailing the reading of titles, abstracts, and keywords. Screening of the articles published in peer-reviewed scientific journals is based on the inclusion and exclusion criterion (see Table 3.1). Articles focusing on global climate models or regional climate models to generate future climate projections over Brahmaputra or any of its tributaries were taken into consideration. Research articles that concentrate on the projected impacts of future climate change on various biophysical components such as glaciers, soil, forests, wildlife, fisheries, etc., within the river basin were excluded from consideration if they did not directly address hydrology or climatology within the Brahmaputra River Basin (BRB). For instance, (Yang *et al.*, 2023) conducted an investigation into the effects of climate change on glaciers, specifically analyzing the cumulative reduction of glacial non-seasonal snow (GNS) within the Upper Brahmaputra basin, alongside other river basins. Employing 15 General Circulation Models (GCMs) and four Shared Socioeconomic Pathway (SSP) scenarios, their study delved into the response of glaciers to various climatic factors, yielding intriguing insights. However, the research did not extend its scope to examining the influence of snowmelt on the hydrological flow of BRB under both near and distant future scenarios. Consequently, the article did not align with the focus of our research.

Research articles with a focus solely on GBM (Ganga-Brahmaputra-Meghna) delta were not considered to be a part of this study, as their findings and analysis include the discharge data and other parameters from the other two basins. This is mainly because the study tries to understand how exclusive studies have been conducted in the Brahmaputra and its tributaries. After the first screening, 110 articles were selected for full-length reading.

Sr. No.	Inclusion criteria	Exclusion criteria
1	Time period between 1989 - 2023.	Not before 1989 and after 2023.
2	Focus on global climate models and regional climate models, generating future projections.	Exclude studies which are not focusing on BRB, rather focusing on GBM.
3	Articles included discussing the concept of climate change and related impacts.	Exclude articles focusing only on observed meteorological data and not discussing climate change projections.
4	Clearly defined ARs/RCPs used in the climate models (GCM and RCM) in the context of BRB.	Exclude articles not discussing the ARs/RCPs/SSPs and climate models in the BRB.

5	Only peer-reviewed articles published in English, including empirical studies.	Exclude scientific articles not published in English.
Screening of articles during critical appraisal		
6	Explanation of clear methodology used for downscaling or developing future climate scenarios with bias corrected downscaled dataset on the BRB.	Articles with unclear (not concrete) methodology are excluded.

Table 3.1: Inclusion and exclusion criteria for the screening of scientific literature

In the third step, a full-length reading of the selected articles was conducted. This critical analysis resulted in a list of 92 articles, and we recorded metadata such as author(s) name, affiliation of the author to the respective country, year of publication, journal title, geographical area of research and models used. Next, we tried to code the articles inductively on the following themes: categorization of the basin and extent of academic collaboration to develop research. Before finalizing the database, we included six articles through backward referencing and 1 article through member check.

3.3 Key findings

3.3.1 *Is there enough research to understand the BRB?*

a) Articles distribution over years

The articles we screened in our database suggest that the number of scientific publications focusing on climate change projections in the BRB has increased since 2009 (see Figure 2). Moreover, if we specifically focus on the articles that have sufficiently captured the analysis based on RCPs, the trend is also on the rise. The steady increase in publications post 2012 with a sharp peak in 2015, suggests an increase in interest of the researchers to understand the future climate scenario of the Brahmaputra Basin. There is a sudden decline between 2020 and 2021 which the authors speculate could have aroused due to the COVID-19 pandemic. However, post-pandemic, we see a surge in publications (Figure 2). Our analysis suggested that China and India are in the lead, followed by Bangladesh. However, China made a significant contribution to the publications, bringing back their focus on the BRB and their infrastructure development initiatives.

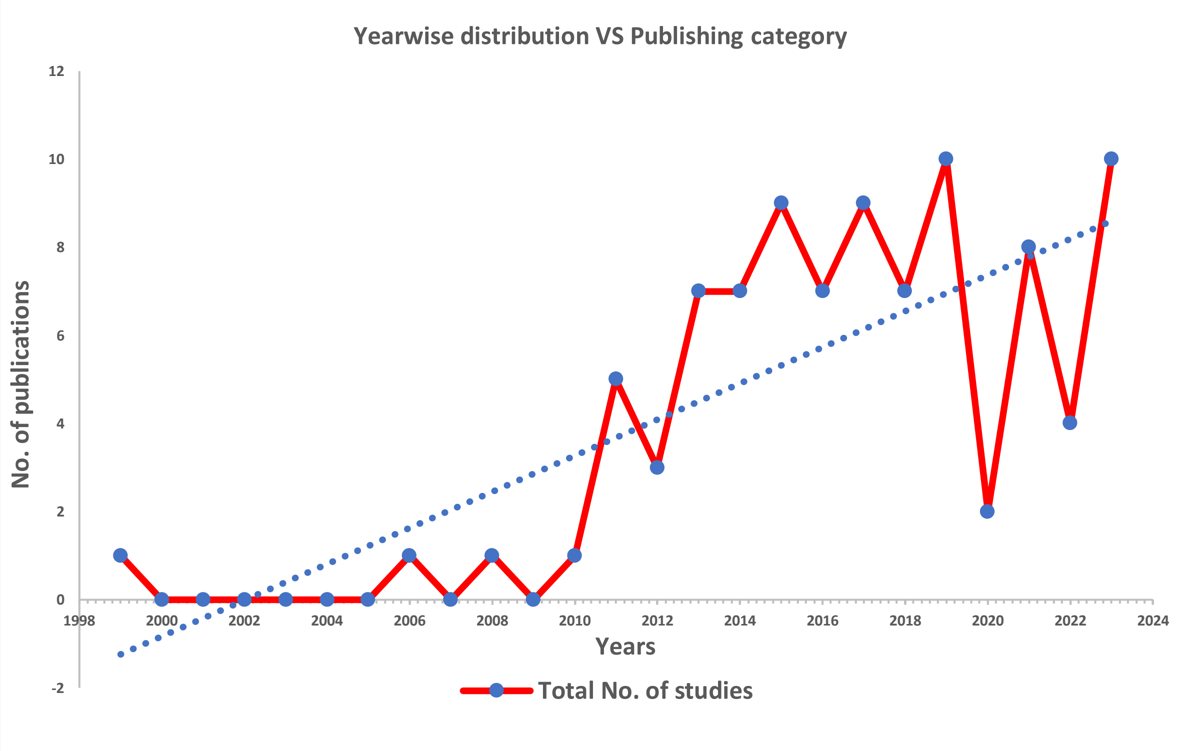


Fig 3.1: Year-wise publication in the BRB

b) Geographic spread

The analysis (Table 3.2) indicates that while there is a growing body of academic research on the Brahmaputra River Basin (BRB), the distribution of these studies across the basin's countries is uneven. We found that most of the studies were done exclusively for Indian part of the basin (n=21) followed by Chinese part of the basin (n=15). This suggests a concentration of research efforts within India and China, possibly due to factors such as greater availability of funding, research institutions and academic expertise and interest on BRB. This is for Bangladeshi part of the basin (n=11) and Bhutanese part of the basin (n=2). This indicates a relative paucity of research in these countries compared to India and China. A limited number of studies (n=13) focus on the entire BRB, addressing the basin as a whole rather than specific segments or countries within it. This suggests a need for more comprehensive, basin-wide research that considers the interconnectedness and complexities of the entire river basin system. A limited number of studies focused solely on the entire basin (n=13). However, it is interesting to note that a significant number of studies (n=31) compare the BRB or segments of it with other river basins such as (Dobler *et al.*, 2011; Biemans *et al.*, 2013a; Hagemann, Loew and Andersson, 2013; Lutz *et al.*, 2016). While such comparative analyses provide valuable insights, they may not fully capture the unique dynamics and challenges of the BRB itself. (please see Table 1 Annexure I).

Geographical regions	1999	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	Total
	No. of publications per year																			
China									1	1	1			1	2		1	2	6	15
India								1			2	2	3	2	2	2	3	1	3	21
Bangladesh						1	2		2	1	3		1							10
Bhutan											1						1			2
Comparative studies	1	1					2	2	4	4	2	2	2	3	5		1	1	1	31
Basin level studies				1			1			1	1	2	3	1	1		2			13

Table 3.2: Distribution of publications across various geographical regions

c) Focus of the published articles

The focus of these studies primarily revolves around evaluating the potential impacts of future climate change on the basin, with an integrated approach combining hydrological modelling and climate projections being prevalent (n=38) (see Figure 3.2). For instance, research by (Mohammed, Islam, *et al.*, 2017b) utilized CORDEX datasets under RCP8.5 to project climate changes across the Brahmaputra River basin from 1980 to 2099. Their findings suggest significant temperature increases (increase by 2 degrees and 4 degrees by the years 2046 and 2074) and rising annual precipitation (rise at the rate of 1.69 mm/year), which are critical insights for understanding hydrological responses and planning adaptation measures.

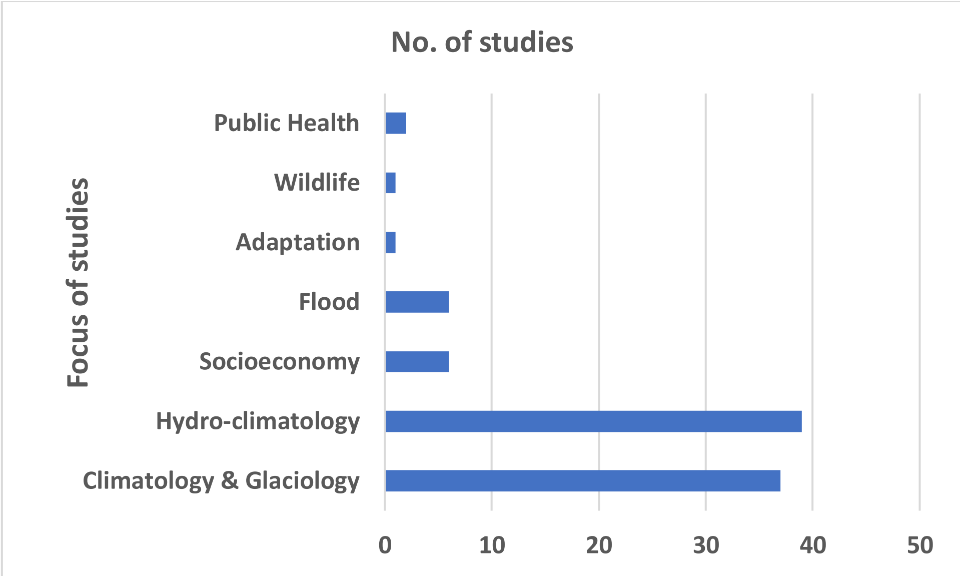


Fig 3.2: Focus of studies on different domains/sectors

Beyond climatology, some studies extend their scope to diverse domains such as glaciology, socioeconomic aspects, flood management, adaptation strategies, zoology, and public health. However, the research remains confined to climatological assessments, indicating potential areas for interdisciplinary exploration and knowledge transfer.

3.3.2 What is getting published?

Our analysis reveals a predominant use of emission scenarios in the studies conducted on the BRB, with notable emphasis on specific scenarios such as A1B, A2, and various Representative Concentration Pathways (RCPs) like RCP8.5, RCP6.0, RCP4.5, and RCP2.5 as shown in Figure 3.3. Additionally, there is emerging utilization of Shared-Socioeconomic Pathways (SSPs) introduced by the Coupled Model Intercomparison Project 6, although to a lesser extent (SSP1-1.9, n=1), (SSP1-2.6, n=22), (SSP2-4.5, n=6), (SSP3-7.0, n=3) and (SSP5-8.5, n=6).

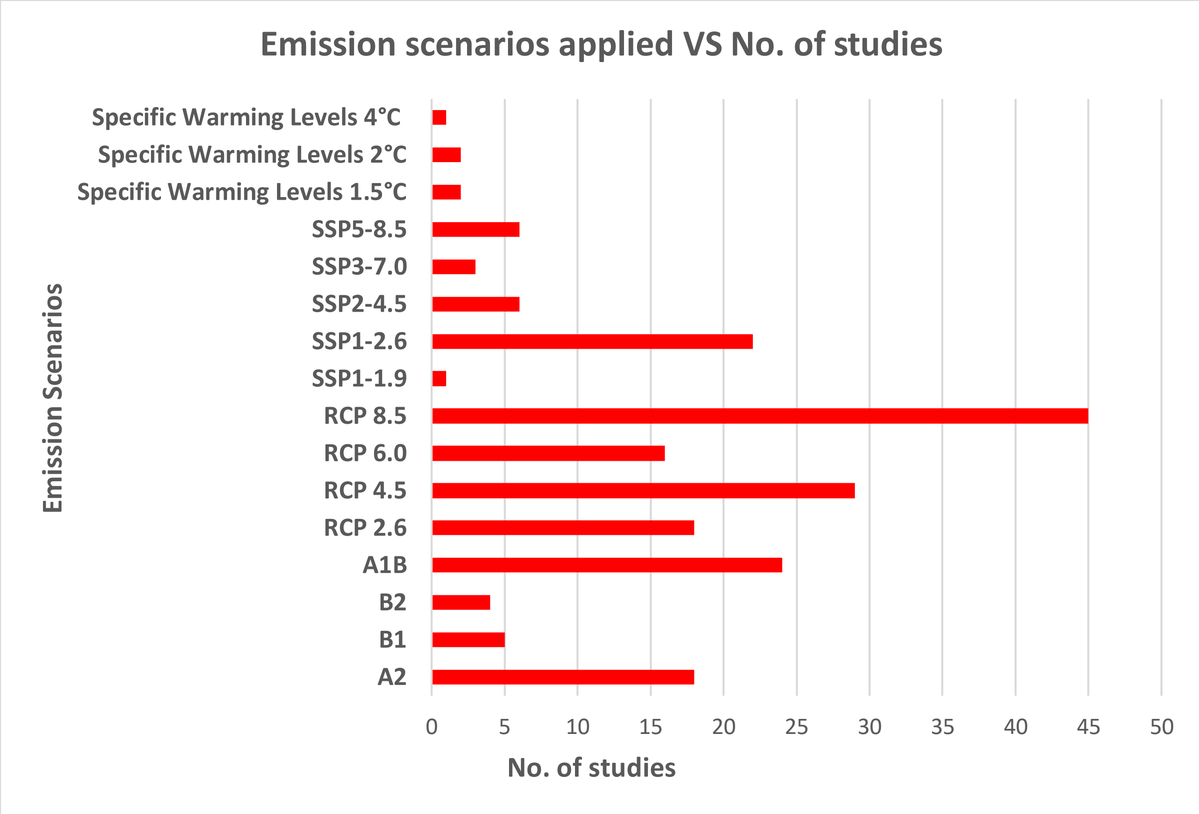


Fig 3.3: Use of RCPs in scientific articles

Only three articles have used integrated multi-sectoral models with climate and hydrological modeling to assess water demand within the Brahmaputra River Basin. For instance, (Wijngaard *et al.*, 2017a) conducted a comprehensive study focusing on the combined impacts of climate change and socio-economic development on water demand across the Indus, Ganges, and Brahmaputra basins. Employing cryospheric hydrological model SPHY and hydrology-crop production model LPJml, the study utilized an ensemble of 8 Global Climate Models (GCMs) under both RCP4.5 and RCP8.5 scenarios. Their findings reveal a projected increase in monsoon precipitation, indicating augmented water availability by the end of the 21st century. However, this positive trend is overshadowed by the rapid growth in socio-economic development, which is anticipated to create a future water deficit, underscoring the critical need for sustainable water management strategies amidst evolving climatic and socio-economic dynamics.

Study on climate extreme events are crucial for understanding the basin's vulnerability and resilience to extreme weather phenomena. Despite the comprehensive nature of many studies, there is a notable dearth of publications focusing on climate extreme events (accounts for only 16% of the total studies, figure 3.4). Moreover, disparities exist in the geographic distribution of research on precipitation and temperature extremes. For example, publications on the Indian part of the basin had the most studies on precipitation extremes (n=6) and temperature extremes (n=4), followed by China (Temperature, n=3) and Bangladesh (Temperature, n=1). No studies on precipitation extreme events were found on the Chinese, Bangladeshi part of the basin. A recent study on Bhutan considered both precipitation and temperature extremes while assessing the future climate scenario of Raidak river, which is a tributary of BRB (Zam, Shrestha and Budhathoki, 2021). At the basin level, we found only two publications on precipitation extremes, highlighting the need for more inclusive and regionally targeted investigations to capture the full spectrum of climate risks across the basin.

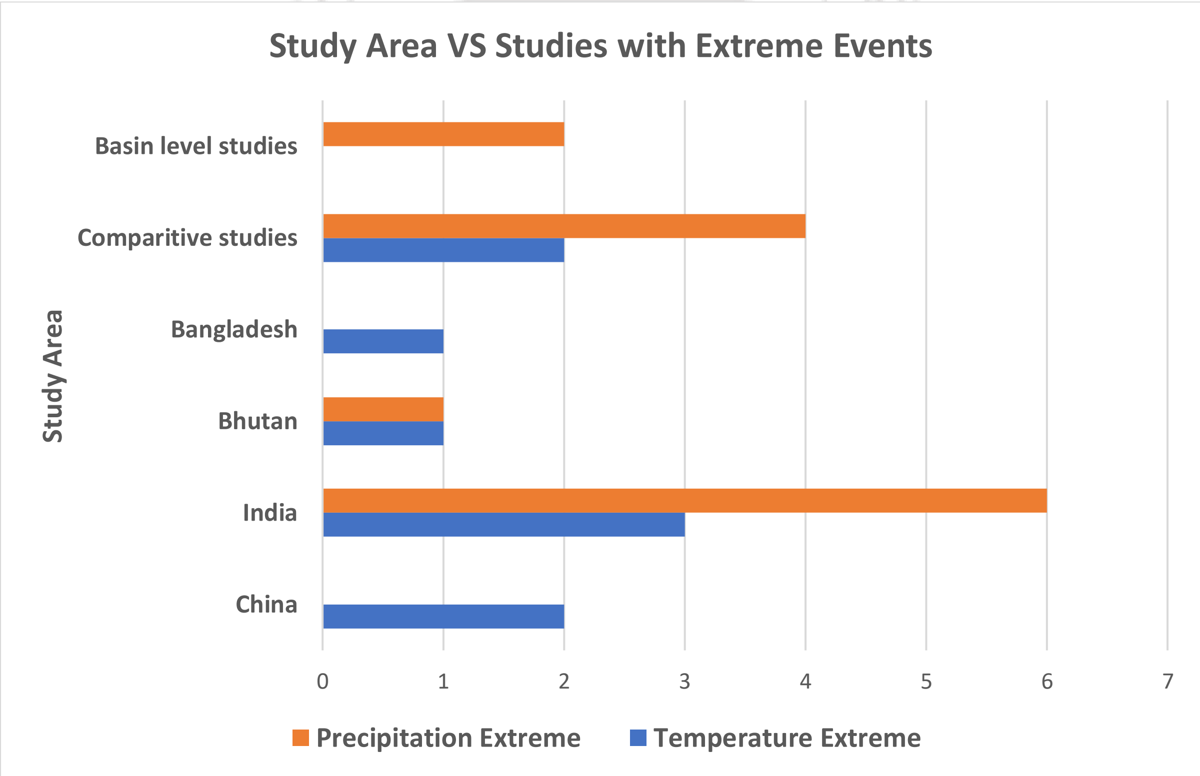


Fig 3.4: Projection of future extreme events in the scientific articles

Most of the publications in our database received funding from national or international organizations (n=65). All the publications for the Chinese part of the basin which were largely done by researchers from China received a grant. However, fewer publications from India received any kind of funding (n=9). Basin level studies on BRB had a moderate funding percentage (n=6). 90% of all the publications (n=27) on the comparative studies of BRB received funding. Note that 76.66% (n=23) of the total publications on comparative studies of BRB were communicated by authors with affiliation from non-basin level countries.

3.3.3 *What are we collaborating for? If we are?*

Our analysis reveals that a significant portion, (n=43), of the publications are joint endeavours, involving collaboration with organizations or institutions either within the Brahmaputra River Basin (BRB) region or from countries outside the region. These studies either centre on the BRB itself or constitute a comparative study of the BRB with other basins or within GBM Basins. Among the studies focusing on the BRB and involving collaboration beyond the region, (n=5) focus on the Chinese part of the basin, (n=7) on Bangladesh, and only (n=1) for India and Bhutan. However, none of the publications on the BRB had a collaboration with institutions spanning all basin-level countries (China, India, Bhutan, and Bangladesh).

To understand the collaboration extent, we refer to the corresponding authors of each publication (please see Table 1, Annexure I), aiding in determining the primary authorship of the paper. It's worth noting that in collaborative publications focusing on the China part of the basin, the corresponding authors were primarily Chinese (n=14), with the exception of one article with Australian affiliation (Li *et al.*, 2013). Conversely, all publications focusing on India were affiliated with Indian authors (n=20). Interestingly, publications on Bangladesh showed limited affiliations from Bangladesh (n=2). The sole publication on Bhutan had Norwegian affiliation, with collaboration from India. Basin-level studies were predominantly communicated by authors affiliated with basin-level countries (China, n=2; India, n=1; Bangladesh, n=5). However, comparative studies on the BRB were mainly communicated by researchers from non-basin-level countries (n=20) such as (Sperna Weiland *et al.*, 2012; Biemans *et al.*, 2013b; Hasson, Lucarini and Pascale, 2013; Mathison *et al.*, 2013; Van Vliet *et al.*, 2013; Wijngaard *et al.*, 2017b)

The research articles with all the authors affiliated from India and without any international collaboration (n=19) focused primarily on the Indian tributaries of the Brahmaputra. On the contrary, out of the total articles from China (n=15), only five articles were published with collaboration from outside basin level countries. Although there are limited articles from Bangladesh (n=11), 66 percent of them showed international collaboration. To note, there is only one article where Indian and Chinese academics have collaborated for developing future climate analysis for Brahmaputra along with researchers from Germany and Austria (Dobler *et al.*, 2011). Bhutan, which often collaborates with India and Bangladesh for developing scientific knowledge, had only one joint research article focusing on the future climate scenarios where the corresponding author belonged to a non-basin level country, Thailand.

Apart from the articles by the authors from basin level countries, there are articles where scholars from Europe, Australia and the US have studied the basin focusing on future climate change scenarios (n=21). For instance, (Immerzeel, 2008a) predicted an accelerated seasonal increase in precipitation and temperature between 2000 to 2100 where he also pointed towards the climate change threats on the flood plains. (Yang *et al.*, 2016c) used an ensemble of 37 GCMs, the CMIP5 (Coupled Model Intercomparison Project, fifth phase), from the four RCP scenarios and suggested a warmer and wetter climate condition in the basin to the year of 2050, leading to increase in streamflow. The effects on the water system of natural drivers and social drivers was also addressed by developing a hydro-economic model BRAHEMO (Brahmaputra Hydroeconomic Model).

Our analysis indicates that while there are research articles identifying climate projections for future preparedness at the country level, there hasn't been a study conducted in collaboration with researchers from all the riparian countries at the basin scale. This suggests that while individual countries in the basin may be undertaking research and planning efforts regarding climate projections and future preparedness within their own borders, there is a lack of collaborative efforts involving all the countries sharing the Brahmaputra River. Such collaboration could potentially yield more comprehensive insights and strategies for addressing climate change impacts and fostering a common knowledge base in managing shared water resources.

Despite China's efforts in installing meteorological stations on its tributaries, such as Lhasa, and bringing investments, the lack of regional-level study indicates that it has not engaged in sufficient collaborative research with the basin countries to understand the future climate scenario over the Yarlung Tsangpo. We found 15 research studies from China that assess the future climate scenario over their part of the basin (see Table 1, Annexure I). While considerable research has been conducted on other rivers originating from China, such as the Yangtze, Mekong, and Salween, the Yarlung Tsangpo remains under researched in the context of future climate preparedness. Given the numerous water infrastructure projects being planned by China, understanding the future climate around the Chinese part of the basin is crucial for informed decision-making downstream.

With a maximum number of articles on the Indian part of the basin (n=11), Indian collaboration with other basin level countries to explain the climate scenarios has been minimal (n=1). Being a middle riparian nation between China and Bangladesh, India needs to develop collaborative knowledge with the basin-level nations to tap the potential of the basin. No study presents the future climate projections for the tributaries of Brahmaputra that have academic collaboration with the Bhutanese academicians or their government or other basin-level countries. Out of the two articles, one of the studies focusing on the Bhutanese part of the basin (Chamkhar Chu basin) was a collaborative study by Indian and Norwegian academicians (Li *et al.*, 2016). The other was between Thailand and Bhutan (Zam, Shrestha and Budhathoki, 2021). Several tributaries from Bhutan join the Brahmaputra in Assam, over which hydropower development projects are being planned through a bilateral treaty between India and Bhutan (Saklani and Tortajada, 2019). Lack of understanding of the future climate impacts on the river will lead to unpreparedness not only for infrastructure development at Bhutan but also for the riparian downstream (Assam, India & Bangladesh).

Moreover, Bangladesh, who partnered with Indian institutions and academics to develop several future climate projections for GBM, did not have a single collaborative article to understand the future climate scenario for BRB exclusively. Similarly, Bangladesh did not have any collaborative research papers with China and Bhutan too. Being the lower riparian nation and prone to climate vulnerabilities, Bangladesh needs to develop collaborative future climate projection scenarios with the upper riparian nations.

3.4 Knowledge gaps and future research ideas

In this section, we will reflect on the knowledge gaps and present a few research ideas, a prerequisite for the Brahmaputra Basin.

First, we found that most studies in our database focused on sections (tributaries and rivulets) of the main river, instead of the entire basin. Most of the climate-based studies were conducted on the Indian part of the basin (n=19%). However, the focus of these studies was limited to certain tributaries rather than the entire river flowing through India. On the contrary, the articles focusing on Yarlung Tsangpo (n=10%) majorly studied the entire stretch of the river flowing through China. On the other hand, only 2% of the research articles studied exclusively the Bhutanese part of the basin. Bhutan being ecologically sensitive is vulnerable to natural hazards. With the accelerating climate uncertainties, studying the future climate scenario of the entire basin (at least within each country) is necessary, especially when multiple water infrastructure projects are being planned in the upper reaches of the river. We make a call for basin-wide research which considers socio-economic projections, governance issues.

Second, earlier studies on climate vulnerability suggest that the Brahmaputra basin will be impacted with the climate-induced disaster (Apurv *et al.*, 2015a; Yang *et al.*, 2019; Wang *et* *al.*, 2020b; Dutta *et al.*, 2021a; Sammonds, Shamsudduha and Ahmed, 2021; Kumar, Mondal and Lal, 2022). There is already a growing consensus among the riparian countries, that water infrastructure development can provide tangible solutions to the most fundamental problems of poverty and natural disasters in Brahmaputra and the perils of the rivers can be turned into prosperity (Crow and Singh, 2009). This has led to a keen interest among riparian countries to develop the under-developed hydropower resources and flood prevention infrastructure (Rahaman and Varis, 2009a) . China for example, being an upper riparian has several plans for harnessing the potential of the river by developing hydropower projects at the Yarlung-Tsangpo (Barua, Vij and Zulfiqur Rahman, 2018). Similarly, many water infrastructure projects are being planned in the tributaries of India and Bhutan (Uddin, Taplin and Yu, 2007; Kumar and Saxena, 2010; Alam *et al.*, 2017; Yaqoob, 2019). However, with limited knowledge on whether these projects include climate scenarios, there is a high possibility of maladaptation. Moreover, a lack of information and scientific knowledge may create suspicion and mistrust among riparians (Vij, Warner and Barua, 2020).

One of the primary reasons for the slow development of climate research on the basin is the dearth of meteorological stations. Lack of meteorological stations lead to lack of observed meteorological or atmospheric data which is mandatory for the calibration and validation while developing future climate projections using climate models. Without the observed data, the climate models remain as a dummy for future trend analysis of the climate. Lack of data sharing among the basin level countries has been another key reason for the existing research gap (Barua, Vij and Zulfiqur Rahman, 2018). Data (hydrological or climate), which is believed to be available for almost the entire basin to an extent, do not get shared within the basin level countries mainly because of the structure of the government with strict rules and regulations. The few Memorandum of Understandings (MoU) among the basin level countries related to Brahmaputra is limited to the sharing of flood data and very little or no sharing of the hydrological data (Vij *et al.*, 2020). China shares only a segment of the hydrological data during monsoon and similarly, India shares its data with Bangladesh, creating a platform for power interplay (Barua, Vij and Zulfiqur Rahman, 2018). This poor data sharing is a consequence of securitization of data and such mechanisms leads to lack of transparency and hinders the basin-level research (Ray *et al.*, 2015b). Another challenge which is observed here is access to Visa to conduct any research as face-to-face interaction is sometimes necessary in the inception of research design and execution. Although it is comparatively humbler for India-Bhutan, India-Bangladesh, Bangladesh-Bhutan and Bangladesh-China, access to Visa for India-China and

China-Bhutan is not always very laminar. Bhutan doesn't have a Chinese embassy due to which a Bhutanese researcher has to get the Visa via India. Similarly, access to Visa for India-China depends totally on the current political scenario of the country. Finally, the national agenda of harnessing the potential of the river only at the country level is leading to mismanagement of the transboundary river Brahmaputra at the basin level.

Such collaborative research will pave the path for cooperation and good governance within the basin. Bangladesh has several research institutes focusing on water resources management such as Institute of Water Modeling (IWM), River Research Institute, Centre for Geographical and Environmental Information System (CEGIS), Institute of Water and Flood Management (IWFM) etc. which have been actively involved in developing solutions to climate impacts on water. However, lack of collaborative projects on the Jamuna and the Brahmaputra (India) part of the basin will be challenging to develop adaptation options at the local and the transboundary level. BRB being topographically unique, has diverse geophysical conditions, and therefore, it is mandatory for all the four basin level countries to come together to understand the future impacts of climate change over the basin.

However, the authors do not deny the fact that Bangladesh has done significant amount of research in predicting the future implications of climate change on GBM at the GBM delta, as the confluence of the three rivers merge at Bangladesh after traversing from India, and the researchers are probably focusing on climate projection over entire GBM instead of BRB explicitly.

3.5 Conclusion

The study conducted a comprehensive systematic literature mapping to analyze research on the future impacts of climate change on the Brahmaputra River Basin (BRB). This assessment, the first of its kind for the BRB, holds significant importance due to the already evident climate-induced disasters affecting the river. A total of 92 articles were screened and selected for the study, which focused on future climate scenarios on the basin. Our analysis revealed that while some research has been undertaken at the regional level, there has been a noticeable lack of basin-wide studies. Although the Brahmaputra has been a subject of academic inquiry globally, the focus on developing a nuanced understanding specifically tailored to the river's unique parameters has been limited. Only a single research article focused on future extreme events for the entire the basin. Notably, the absence of collaboration among academic institutions within the basin emerged as a significant observation from our mapping-based analysis. The current trend of isolated research within basin-level countries could restrict growth and development to individual national interests. Collaborative research is essential for generating future climate projections, which are indispensable for making climate-informed decisions and achieving sustainable development goals. However, further work is needed to bridge the gap between science and policy at the basin scale. We recommend additional systematic reviews of gray literature, including policy and project reports, to address key questions regarding the basin's future climate scenario.

3.6 Limitations

There are three main limitations to the methodology used in this study. First, we used systematic review mapping to showcase the knowledge gaps in terms of climate change projections in the BRB. It is possible that an infinitesimal percentage would have been excluded as the entire process is based on the two search engines and specific search terms. There is a possibility that we might have missed certain literature that has used different terminology compared to the ones we have employed. Second, we used two search engines to cover the relevant literature landscape; it is possible that there might be more domain-specific databases that could yield additional results. We also did not consider databases that included non-English articles, although recognised that some literature could have been published in other languages (especially Chinese). Lastly, we have not included grey literature in the literature landscape, including unpublished and published government reports, project evaluations, and scientific reports from international non-government organisations and parastatals. Future research projects could expand the search to other databases and languages using the methodology in the article or otherwise.

Chapter 4

Unveiling Tomorrow's Deluge: Investigating Precipitation Extremes in the Brahmaputra River Basin using NEX-GDDP Datasets

Chapter 4

Unveiling Tomorrow's Deluge: Investigating Precipitation Extremes in the Brahmaputra River Basin using NEX-GDDP Datasets

4.1 Introduction

The ability to evaluate the potential impact of climate change on the Brahmaputra River Basin (BRB) remains constrained. The primary attributed reason for the scarcity of comprehensive basin-wide studies is the securitization of observed data, resulting in reduced transparency and hindrances to basin-level research (Ray et al. 2015; Barua et al. 2018). Access to data has been one of the major challenges in this transboundary river basin, which is subject to the state of diplomatic relation among the riparian nations. Given the data constraints, research endeavors tend to concentrate on particular sub-regions or facets within the Brahmaputra basin, resulting in fragmented research initiatives. Despite the data challenges, a few studies examined the possible consequences of climate change on the entire BRB. The findings from objective 1 have suggested the presence of only 13 articles with a focus on future climate projections over the entire BRB using GCMs and RCMs (see Table 4.1). For instance, (Immerzeel 2008) made an initial forecast regarding the accelerated seasonal rise in both precipitation and temperature spanning from 2000 to 2100 and then analyzed the potential threats posed by climate change to the floodplains in BRB. Later, (Yang et al. 2016) employed an ensemble of 37 General Circulation Models (GCMs) from the CMIP5 (Coupled Model Intercomparison Project Phase 5) across four Representative Concentration Pathway (RCP) scenarios. Their findings indicated a projected trend towards a warmer and wetter climate within the basin up to the year 2050, which is anticipated to result in an increased streamflow. So far the study done by (Dutta et al. 2021) is the only work on understanding the climate projections on BRB which included meteorological station data from a few measured gauge stations on Tibet along with India Meteorological Department (IMD), as an effort of academic collaboration. For the missing data stations on the basin, data from Climate Forecast System Research (CFSR) was used. However, the study too doesn't take into account the precipitation extreme indices, which is mandatory to understand a dynamic topographical region like Brahmaputra. Most of the articles focused on studying the hydro-climatological aspects of the basin (n=9), among which two studies (n=2) also focused on flood forecasting and a single research (n=1) was done on hydro-climatology and socioeconomic study of the basin. One of the study focused on climatology and sustainable development (n=1) and two (n=2) studies focused only on the climatological aspect. Focus of study on future climate extreme events have been significantly low with only one (n=1) research article focusing on an extreme precipitation index (Mohammed et al. 2017). No one study covering multiple future climate extreme indicators for the entire basin have been conducted. Furthermore, no research has been conducted to determine how future extreme climate scenarios may affect the water-infrastructure projects in the basin.

The study intends to close this knowledge gap by improving our understanding of numerous extreme climate occurrences and future climatology inside the BRB. By projecting future temperature scenarios along with precipitation extremes onto the basin, the study addresses the second research question of the thesis, which asks, "How can the future climate scenario for entire BRB be assessed physically?" Additionally, it has a qualitative relationship with the hydropower vulnerability in the basin, which offers a path forward for resolving the thesis' final research question. This study goes beyond the general trend analysis of precipitation using global datasets by investigating future changes in precipitation extremes over the BRB using 5 (five) precipitation indices across two distinct periods: the near future (2021–2050) and the far future (2070–2099). Also, quantification of monsoon precipitation and extreme precipitation events under RCP 4.5 and RCP 8.5 provides specific percentage and trends. Since the General Circulation Models (GCMs) usually have low spatial resolutions, they frequently fail to resolve sub-grid scale processes that are crucial to regional climate. Thus, for a data deficit region like BRB, the study was done using high-resolution, statistically downscaled, and bias-corrected NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) data, based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) model. Projections of this study are strengthened by the use of observational data from the APHRODITE (Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources) project to validate the NEX-GDDP data for the historical period. This ensures that the model outputs are grounded in real world observations. Prior to our study, there was no application of NEX-GDDP datasets to comprehend future climate extreme occurrences throughout the basin. The enhanced resolution of NEX-GDDP enables researchers to capture localized climate variations with greater precision, particularly in regions characterized by complex topography, such as river basins.

Research Article	Year	Model used for study	Scenarios considered	Observed Meteorological data obtained from	Focus of study	Focus on Climate Extremes

(Immerzeel 2008)	2008	6 GCMs (CCSR, CGCM2, CSIRO-Mk2, ECHAM4/OPYC3, GFDL-R30, HADCM3)	A2 and B2	CRU TS 2.1	Climatology	No
(Shi et al. 2011)	2011	RCM (RegCM3) and GCM(MIROC3.2_hires)	A1B	CRU	Climatology	No
(Pervez and Henebry 2015)	2014	CMIP5 (CGCM3.1)	A1B and A2	National Climate Data Center, 2001 (23 Station Data)	Climatology + Hydrology	No
(Gain and Wada 2014)	2014	3 GCMs (ECHAM5, HadGEM1, HadGEM2)	A1B and A2	CRU TS 2.1	Climatology + Future water availability and demand	No
(Alam et al. 2016)	2016	9 GCMs	RCP 2.6, RCP 4.5, RCP 6, RCP 8.5	MERRA-NASA POWER	Climatology + Hydrology	No
(Yang et al. 2016)	2016	37 GCMs	RCP 2.6, RCP4.5, RCP 8.5, RCP 8.5	APHRODITE and GPCC	Climatology + Hydrology + Socioeconomic Study	No
(Mohammed et al. 2017a)	2017	CORDEX-SA (11 Projections)	RCP 8.5	WFDEI dataset	Climatology + Hydrology + Flood Forecasting	Yes (99th percentile)
(Mohammed et al. 2017b)	2017	CORDEX-SA (11 Projections)	RCP 8.5	WFDEI dataset	Climatology + Hydrology + Flood Forecasting	No
(Islam et al. 2018)	2017	11 RCMs CORDEX-SA	RCP 8.5	ERA-Interim (Temperat	Climatology + Hydrology	No

				ure), TRMM (Precipitation)		
(Xu et al.)	2019	CORDEX (HadGEM3-RA (RCM1) RegCM (RCM2) SNU-MM5 (RCM3) SNU-WRF (RCM4) YSU-RSM (RCM5))	RCP 4.5 and RCP 8.5	WFD	Climatology + Hydrology	No
(Haque et al. 2021)	2021	CORDEX-SA	RCP 8.5	NASA POWER	Climatology + Hydrology	No
(Alam et al. 2021)	2021	BCC-CSM1.1, BCC-CSM1.1(m), GISS-E2-H, GISS-E2-R, HadGEM2-ES, MIROC-ESM, MIROC-ESM-CHEM, and MRI-CGCM3.	RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5	MERRA-NASA POWER	Climatology + Hydrology	No
(Dutta et al. 2021)	2021	CMIP5 (GFDL-ESM2M, HadGEM2-CC, and IPSL-CM5-1R)	RCP 4.5 and RCP 8.5	CFSR data, IMD data and Measured data from Tibetan gauge stations (Total 36 station data)	Climatology + Hydrology	No

Table 4.1: Existing studies on climate change projections over the entire BRB

4.2 Data and Method

3.5.1 Data

NEX-GDDP dataset offers a collection of 20 statistically downscaled models derived from CMIP5 models (Table 4.3) , which are applied to two distinct scenarios: Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 (Thrasher et al. 2012). To create these data products, the Bias Correction and Spatial Disaggregation (BCSD) statistical downscaling method, as described by (Wood et al. 2004), was utilized. The advantages of using NEX-GDDP over CMIP5, CMIP6 and CORDEX have already been studied (Jain et al. 2019; Kulkarni et al. 2020; Kumar Behera et al. 2023). For more detailed information, the data is accessible at https://cds.nccs.nasa.gov/nex-gddp/. The NEX-GDDP dataset encompasses three key climate variables: daily precipitation, maximum temperature, and minimum temperature. However, for this study, we have exclusively utilized precipitation as the parameter of interest. These datasets span historical runs from 1950 to 2005, while the projections extend from 2006 to 2099. GCM runs executed by the involved models to project the climate extreme events are included in the NEX-GDDP-CMIP5 dataset. These high-resolution datasets serve as valuable tools for gaining insights into processes sensitive to finer spatial scales and for understanding the influence of local topography on climate conditions.

The observed precipitation data for our study has been obtained from the APHRODITE project (Yatagai et al. 2012). APHRODITE is high resolution gridded precipitation data (0.25° x 0.25°) (Xie et al. 2007). Previous research has shown that APHRODITE data has been widely used for precipitation trends and extreme analysis in several regions and it proved to exhibit concordance with station data (Xu et al. 2016; Luo et al. 2020; Ji et al. 2020; Bhattacharyya and Sreekesh 2022). A study was also done on BRB by (Yang et al. 2016) using APHRODITE data along with Global Precipitation Climatology Centre (GPCC) data to understand the future climatology over the basin to explore future climatology across the basin. Description of data is provided in Table 4.2.

3.5.2 Data Description

CF variable name, units:	*pr*, Precipitation (mean of the daily precipitation rate) kg m-2 s-1
Spatial resolution:	0.25 degrees x 0.25 degrees
Temporal resolution and extent:	Daily from 1950-01-01 00:00:00 to 2100-12-31 11:59:59

Table 4.2: Description of the data used in the study

Model	Institute
ACCESS1-0	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia
BCC-CSM1-1	Beijing Climate Center, China Meteorological Administration, China
BNU-ESM	Beijing Normal University, China
CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada
CCSM4	National Center for Atmospheric Research, USA
CESM1/CAM5	National Center for Atmospheric Research, USA
CNRM-CM5	Centre National de Recherches Meteorologiques, France

CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization, Australia
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory, USA
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory, USA
INM-CM4	Institute for Numerical Mathematics, Russia
IPSL-CM5A-LR	Institute Pierre-Simon Laplace, France
IPSL-CM5A-MR	Institute Pierre-Simon Laplace, France
MIROC-ESM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan
MIROC-ESM-CHEM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan
MPI-ESM-LR	Max Planck Institute for Meteorology, Germany
MPI-ESM-MR	Max Planck Institute for Meteorology, Germany
MRI-CGCM3	Meteorological Research Institute, Japan
NorESM1-m	Norwegian Climate Centre, Norway

Table 4.3: List of 20 NEX-GDDP models used in this study (source: Thrasher et al. 2012)

3.6 Methods

The ability of the model to reproduce the long-term average of the meteorological variables during the given period and to simulate temporal trends are two key elements of the model's performance evaluation. The present study derives its climate projections from the Multi-Model Mean (MMM) mean values, which are determined from simulations carried out by 20 GCMs involved in the NEX-GDDP. The robustness of the analysis is improved by the MMM mean values, which offer an aggregated representation of the climate projections produced by several models. The entire specified period for the near future (2021–2050) and the far future (2070–2099) is considered to conduct the model studies. NEX-GDDP model outputs were thoroughly tested against APHRODITE during the baseline period of 1976-2005. The study estimates future changes the precipitation indices using the baseline period of NEX-GDDP during South-West Monsoon i.e., June to September. To gain an organized comprehension of the precipitation over the region, we first assessed the spatial distribution of trends of the climatological means of 5 (five) extreme precipitation indicators over BRB. The baseline observation data was retrieved from APHRODITE. These include: a) SDII (Simple Daily Intensity Index), b) RX1DAY (Highest 1-day Precipitation), c) RX5DAY (Highest 5-day Precipitation), d) CWD (Consecutive Wet Days), e) CDD (Consecutive Dry Days) as shown in Table 4.4. These indices are widely used in many GCMs to investigate severe precipitation occurrences in historical data and future climate predictions (Donat et al. 2013; Rao et al. 2014; Basher et al. 2018; Rao et al. 2020). Furthermore, they have been used to predict future precipitation trends in the BRB. While other climate indices could be considered, these five indices offer a balance between simplicity and comprehensiveness. In the context of the BRB, where monsoonal variations and extreme events play a significant role, these indices are particularly effective in capturing the most critical aspects of the precipitation regime. BRB has been subject to extreme precipitation events such as floods, landslides and droughts. Understanding the intensity of the extremes at a spatial and temporal scale will provide scope for climate preparedness. Thus, the selection of indices depended on its feature to directly relate to flood risks (RX1 and RX5), intensity of rainfall events (SDII) and occurrence of droughts (CDD). These indices, which include RX1 for flash flood risk and RX5 for sustained flood and river swelling, accurately reflect the risk of flooding. Persistent wet period indicating risk of soil saturation and landslide can be attributed by CWD, whereas, CDD captures the length of dry spells indicating drought risk.

3.6.1 Handling the data

Step 1: The globally downscaled climate dataset was acquired from NEX-GDDP, while observed precipitation data were obtained from the APHRODITE database. The downloaded data underwent conversion into the required format, specifically mm/day, using the CDO software on a LINUX platform (https://code.mpimet.mpg.de/projects/cdo/).

Step 2: Subsequently, the converted observed and climate data underwent masking using a shapefile with accurate latitude and longitude coordinates for the Brahmaputra region, employing the Ferret software. Ferret is an interactive computer visualization and analysis environment designed to handle large and complex gridded datasets.

Step 3: The data were then partitioned into 30-year time steps to develop projections for the historical period, mid-future (2050s), and far future (2080s). Calibration of the observed data was performed with the historical modelled data.

Step 4: The precipitation analysis was specifically focused on the months of June, July, August, and September (JJAS), as these months typically experience the highest rainfall in the Brahmaputra River Basin (BRB).

Step 5: Climatological analyses for the mid-future and far future (for RCP 4.5 and RCP 8.5) were conducted, comparing historical modelled and observed data to assess projection trends.

Step 6: Ensemble means of the models were calculated, and trends of individual models were analyzed by overlaying different General Circulation Models (GCMs) onto the ensemble mean.

Step 7: Climate extremes such as Consecutive Dry Days and Consecutive Wet Days were determined for different RCP scenarios (4.5 and 8.5) by developing a set of codes in Shell Script on the LINUX platform.

Step 8: Finally, maps for each projected scenario were generated and visualized to provide a spatial representation of the findings.

Indices	Description	Units
Simple Daily Intensity Index (SDII)	The ratio of seasonal total precipitation to the number of wet days (≥ 1 mm)	mm/day
Highest 1-day precipitation (RX1DAY)	Seasonal maximum 1-day precipitation	mm
Highest 5-day precipitation (RX5DAY)	Seasonal maximum consecutive 5-day precipitation	mm
Consecutive Wet Days (CWD)	Maximum number of consecutive days when precipitation > 1 mm	Days
Consecutive Dry Days (CDD)	Maximum number of consecutive days when precipitation < 1 mm	Days

Table 4.4: List of extreme climate indices analysed in the study

3.6.2 Visualisation of the data

Data visualizations for all the map projections depicting year-wise climatology and climate extremes for two distinct time periods (2040-2069 and 2070-2099) and two Representative Concentration Pathway (RCP) scenarios (4.5 and 8.5) can be accomplished using GrADS (Grid Analysis and Display System). GrADS is an interactive desktop tool utilized for easy access, manipulation, and visualization of earth science data. It facilitates two data models for handling gridded and station data and supports various data file formats, including binary (stream or sequential), GRIB (versions 1 and 2), NetCDF, HDF (versions 4 and 5), and BUFR (for station data).

3.7 Key findings

3.7.1 Model validation and precipitation variability analysis

To evaluate the accuracy of model simulations, we examined the monthly precipitation cycles (mm day−1) across the BRB from 1976 to 2005, as illustrated in Figure 4.1. The monthly mean precipitation, depicted by the black line from APHRODITE and the red line representing the Multi-Model Mean (MMM) of NEX-GDDP models, is presented in Figure 1. The red shading indicates precipitation variability (± standard deviation) among the 20 models of NEX-GDDP, while the gray shade highlights the monsoon season, June to September (JJAS). Visual inspection reveals that the model simulations adequately capture the seasonal precipitation patterns. The mean monthly precipitation patterns from the MMM closely align with those observed in APHRODITE. APHRODITE exhibits its maximum peak at 7.4 mm day−1 in July and a minimum of 0.3 mm day−1 in November. In comparison, the MMM peaks in July at 10 mm day−1 and records a minimum of 0.2 mm day−1 in November. The variability in MMM precipitation corresponds with the quantity of precipitation in the specific period. These findings suggest that the MMM effectively reproduces the monthly mean precipitation patterns over the BRB.

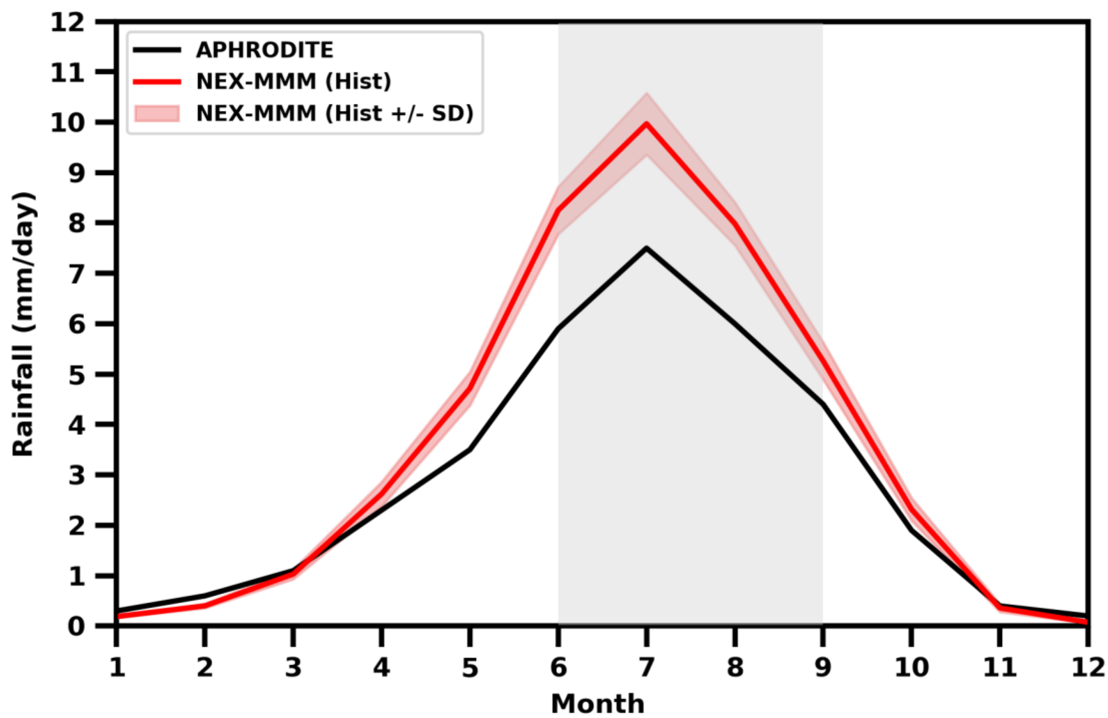


Fig. 4.1. Annual cycle of monthly precipitation (mm day−1) over BRB during 1976–2005 from APHRODITE (black) and NEX- GDDP MMM (red line). Gray-shaded region denotes the SW monsoon season (JJAS)

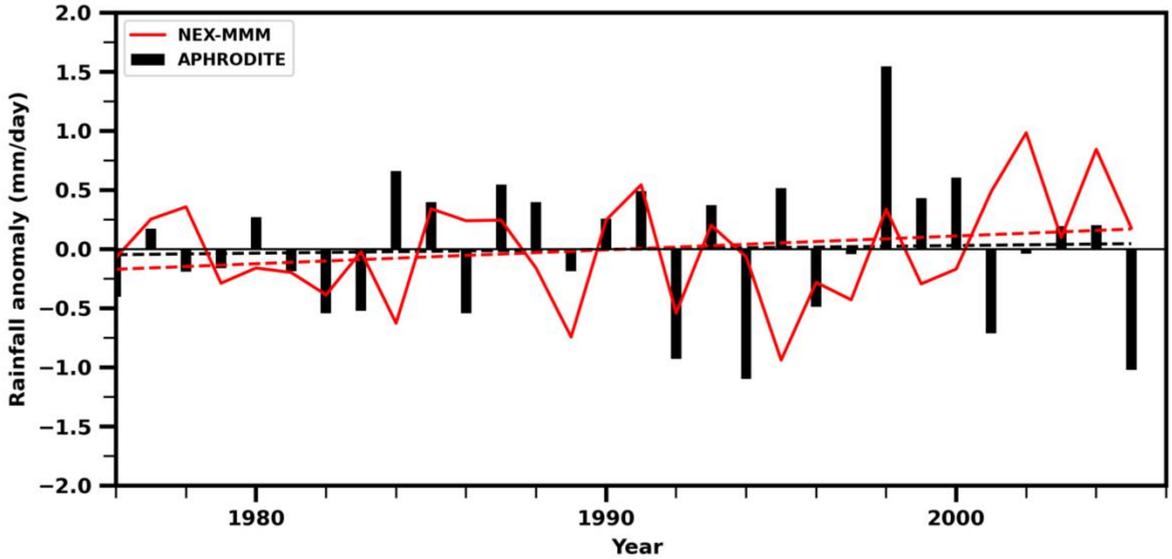


Fig 4.2. Inter-annual variability of SW monsoon rainfall (precipitation) over BRB during 1976–2005 from APHRODITE (black) and NEX- GDDP MMM (red line).

Figure 4.2 presents an analysis of the SW monsoon mean precipitation anomalies over the BRB for the period 1976 to 2005, utilizing data from both the APHRODITE dataset and the NEX-GDDP MMM. It is observed that both sources indicate an upward trend in SW monsoon precipitation throughout the study period. Specifically, APHRODITE demonstrates a modest positive trend of 0.006 mm day−1, whereas the MMM shows a more pronounced trend of 0.0125 mm day−1. These trends are statistically significant, achieving a confidence level of 90%. The analysis underscores an increase in the variability of SW monsoon precipitation in recent years as per the APHRODITE data. Notably, the MMM data suggests that recent years have experienced higher levels of precipitation, depicting a comparatively wetter period relative to the APHRODITE observations.

Figure 4.3 compares the mean precipitation during the southwest monsoon season across the Brahmaputra River Basin (BRB) from 1976 to 2005, derived from the Multi-Model Mean (MMM) of individual models, with data from APHRODITE. In Figure 4.3 (a), the APHRODITE dataset displays noticeable north-south variability in precipitation over the BRB, with higher rainfall levels (> 7 mm day−1) observed in the southern region compared to the northern region (< 4 mm day−1). Figure 4.3 (b) presents the MMM derived from all models for the same geographical area, accurately replicating the observed north-south precipitation patterns. However, minor variations in precipitation (approximately -2 to -3 mm day−1) are evident.

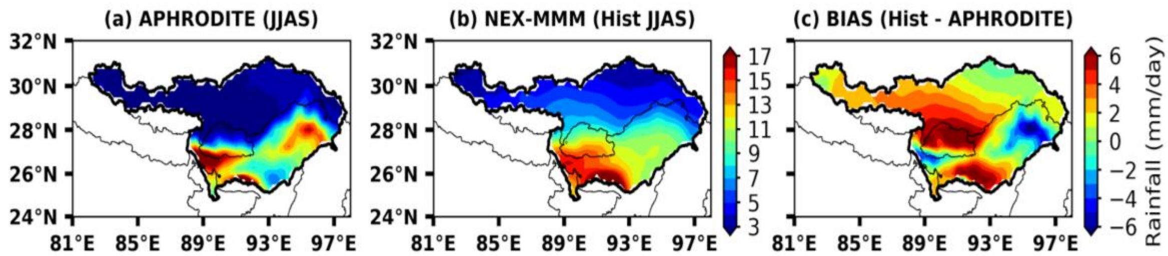


Fig. 4.3. Spatial distribution of SW monsoon mean rainfall from APHRODITE (a), NEX-GDDP's 20 individual model simulation's MMM (b), and the bias of MMM against APHRODITE for the period 1976–2005 (c)

Furthermore, Fig. 4.3 (c) illustrates the mean bias of the MMM, indicating a wet bias across the study region, especially for the extreme northern part (around the Tibetan and Bhutanese part of the basin), where a wet bias of 2–6 mm day−1 is observed. This comparison underscores the ability of the MMM to capture and reproduce the observed north-south precipitation patterns across the BRB, despite minor discrepancies in precipitation levels.

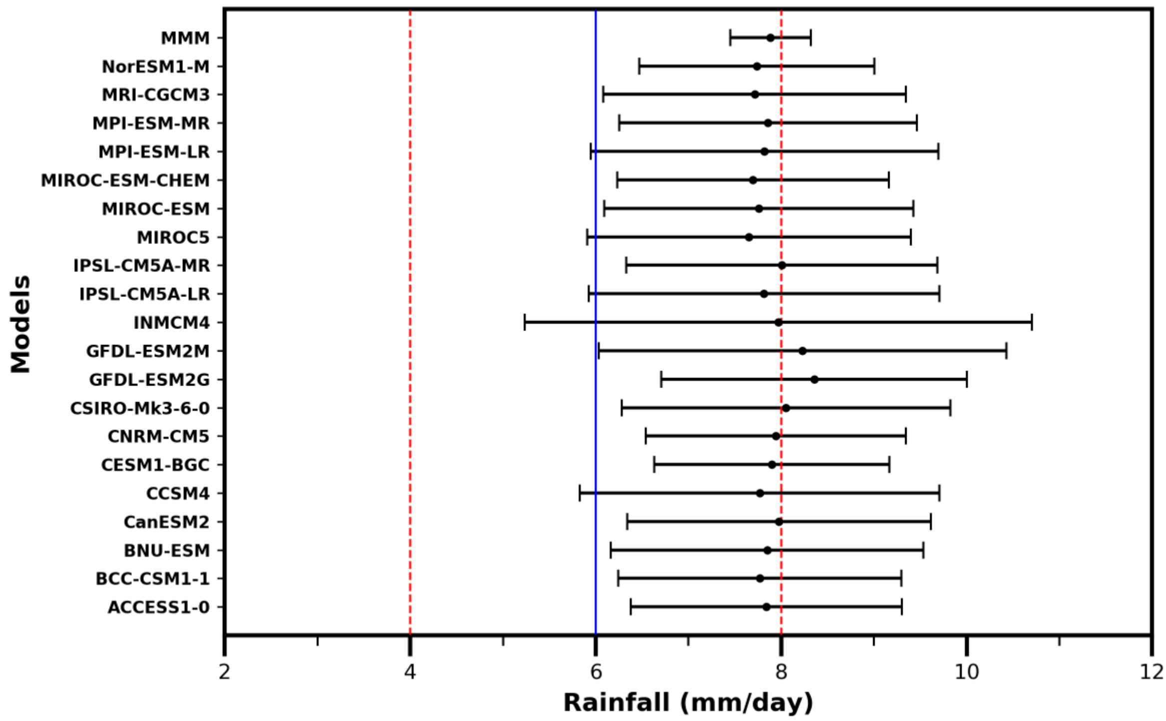


Fig. 4.4 Evolution of SW monsoon rainfall by NEX-GDDP's individual models and MMM during 1976–2005. The blue line shows the observed mean rainfall. Red dashed line shows ±

2 standard deviation of observed rainfall. Black dots are mean rainfall of individual model

Figure 4.4 compares monsoon precipitation and its variability across the BRB using data from individual models, the MMM, and observed data from 1976 to 2005. The observed precipitation's mean and ± 2 standard deviations are represented by blue and red dotted lines, respectively. Each black dot represents the mean precipitation of individual models, with the associated right and left limits indicating the standard deviation. The observed mean precipitation is documented at 8 mm day−1. While the mean precipitation values from individual models and the MMM do not precisely match the observed mean, they fall within the range of observed precipitation variability. This suggests that the bias-corrected models hold promise in accurately depicting precipitation patterns over the BRB. As depicted in Figures 4.1 to 4.4, the precipitation values simulated by the GCM models consistently exceed the observed values, particularly during the monsoon season. This overestimation is indicative of a wet bias.

3.7.2 Projected changes in seasonal mean rainfall

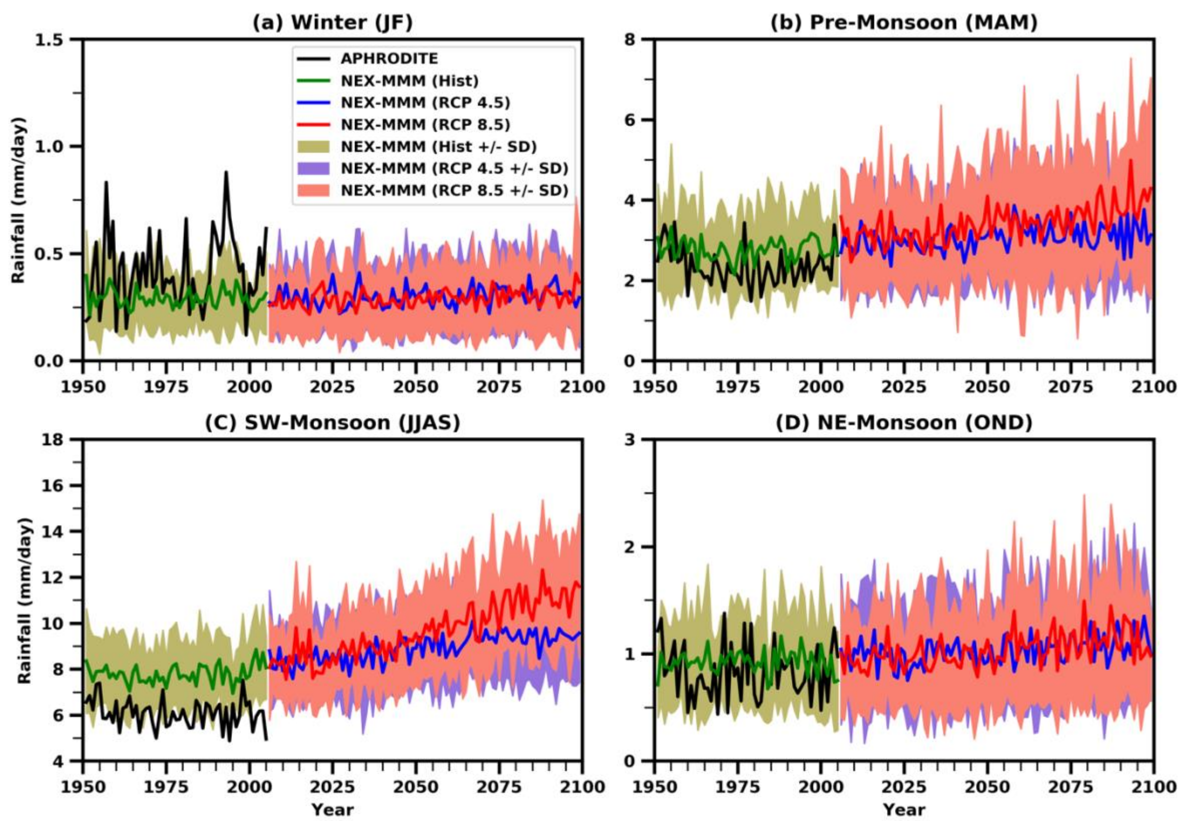


Fig. 4.5. Projected changes (%) in the mean precipitation over BRB for four different seasons; Winter (a), Pre-Monsoon (b), SW-Monsoon (c) and NE-Monsoon (D), with respect to the baseline period of 1976–2005 under the RCP 4.5 and RCP 8.5 scenarios

This segment delves into the projected future shifts in average seasonal precipitation across the

Brahmaputra River Basin (BRB) within two greenhouse gas concentration trajectories (RCP 4.5 and RCP 8.5), over two distinct periods: the near future (2021–2050) and the distant future (2070–2099). As depicted in Figure 4.5, the data shows the changes in seasonal average precipitation from the near to the distant future, using a baseline period for reference. The findings indicate a significant and uniform rise in precipitation during the South-West Monsoon season for both RCP 4.5 and RCP 8.5 scenarios, in both the upcoming and distant future. The Pre-Monsoon and North-East Monsoon seasons display a minimal increase in precipitation levels. Conversely, the Winter season is not expected to experience any notable changes in precipitation in the near or distant future.

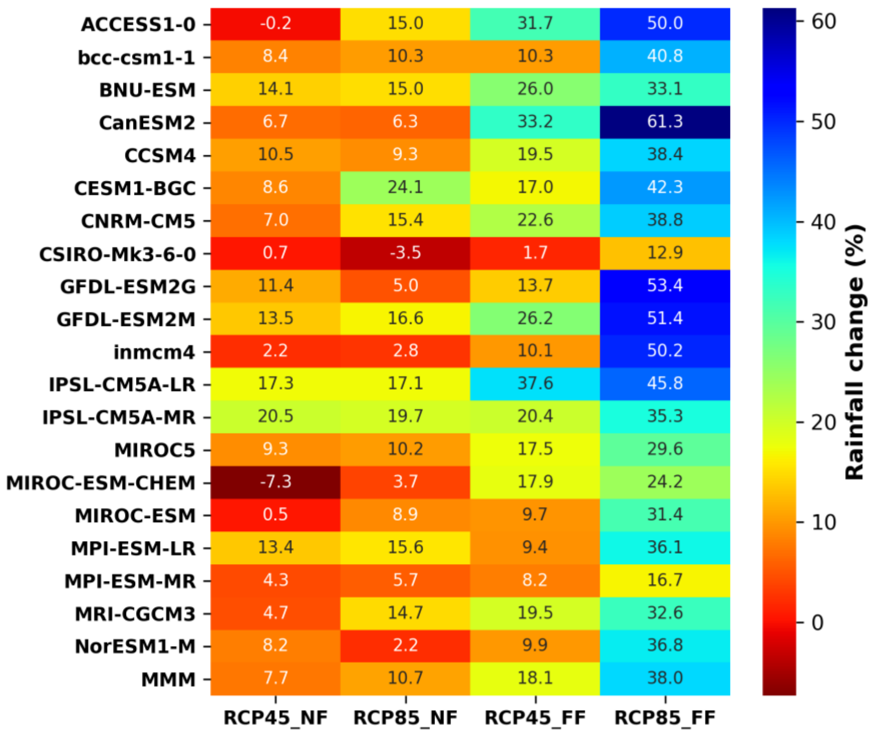


Fig. 4.6. Projected changes (%) in the SW monsoon rainfall over BRB. NF refers to near future (2021–2050), FF refers to far future (2070–2099), with respect to the baseline period of 1976–2005 under the RCP 4.5 and RCP 8.5 scenarios

Figure 4.6 details the anticipated shifts in average precipitation during the South-West Monsoon, highlighting the percent change in precipitation as predicted by individual models. Specifically, there is an increase of 7.7% under the RCP 4.5 scenario and 10.7% under RCP 8.5 in the near future, as indicated by the Multi-Model Mean (MMM). For the distant future, the MMM projects a significant rise in precipitation by 18.1% under RCP 4.5 and 38% under RCP 8.5, relative to the baseline period. Although a minority of models predict a decrease in precipitation across both scenarios, the majority forecast an increase in precipitation events in both the near and distant future. The model CanESM2 predicts the largest percentage change in average precipitation, while CSIRO-Mk3-6-0 predicts the least.

This overall trend towards increased future precipitation is consistent with the expected intensification of precipitation events under global warming scenarios, as corroborated by previous research (Immerzeel 2008a; Gain et al. 2011; Apurv et al. 2015b; Mohammed et al. 2017a; Ren et al. 2019; Khan et al. 2020; Kamal et al. 2021; Palash et al. 2023b; Singh et al. 2024). These findings are in line with research suggesting that despite a weakening circulation, the South Asian summer monsoon is projected to see an uptick in precipitation (Ueda et al. 2006; Christensen et al. 2013; Herring et al. 2019; Li et al. 2021).

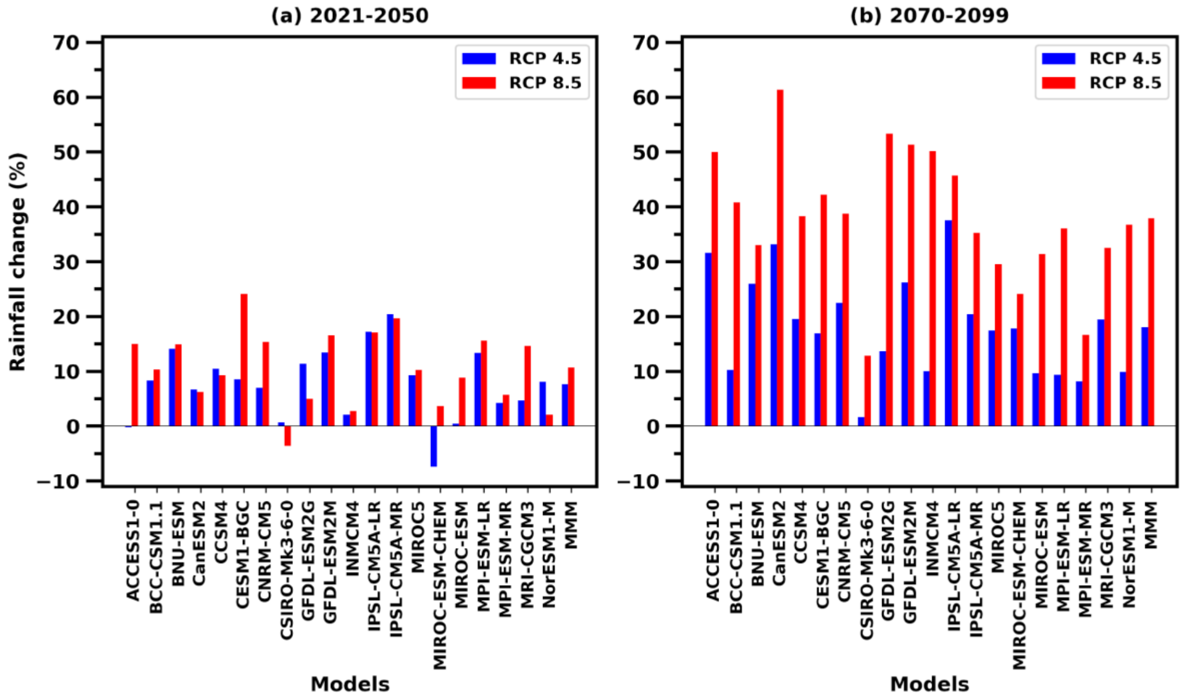


Fig. 4.7. (a) and (b) Projected changes by individual models for change in rainfall percentage in the near future (2021–2050) and far future (2070–2099) under the RCP 4.5 and RCP 8.5 scenarios relative to 1976–2005.

Moreover, spatial analysis reveals that the most considerable precipitation change is expected in the northern regions of the BRB under both lower and higher emission scenarios by the century's end. This observation resonates with the findings of Sharma et al. (2015), who also documented rising rainfall patterns for the BRB in future projections using multiple linear regression analysis and artificial neural networks.

3.7.3 Future changes of precipitation extremes

SDII represents the intensity of daily precipitation received in a given region. Figure 4.8 illustrates the inter-annual variability in SDII under the RCP 4.5 and RCP 8.5 scenarios from 1976 to 2099. The MMM variability is compared with APHRODITE precipitation for the baseline period. Notably, the MMM tends to higher compared to observations throughout 1976–2005, exhibiting a wet bias of 1 mm day−1 compared to the observations. No significant trend is observed from 1976 to 2005 in both observed data and MMM, with comparable patterns and tendencies. However, the MMM displays an increasing trend of 0.2 mm decade−1 (99.9% significance level) under the RCP 4.5 scenario and 0.6 mm decade−1 (99.9% significance level) under the RCP 8.5 scenario. This increase in SDII under both emission scenarios implies a future scenario with wet days featuring intense precipitation.

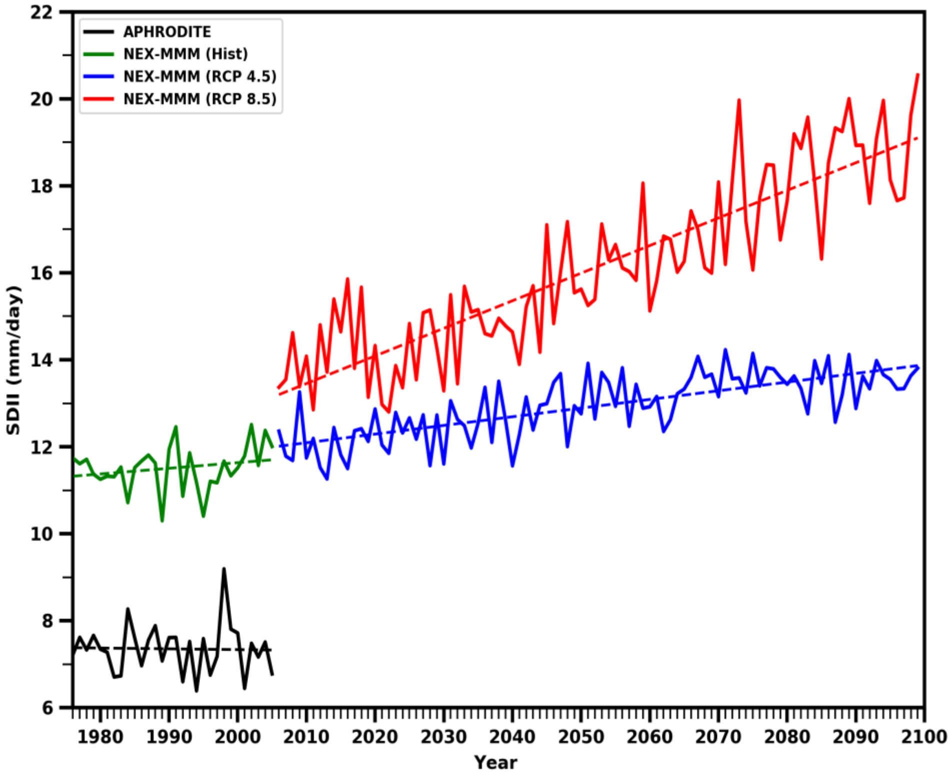


Fig. 4.8. Inter-annual variability in Simple daily intensity index (SDII) over BRB from 1976 to 2099

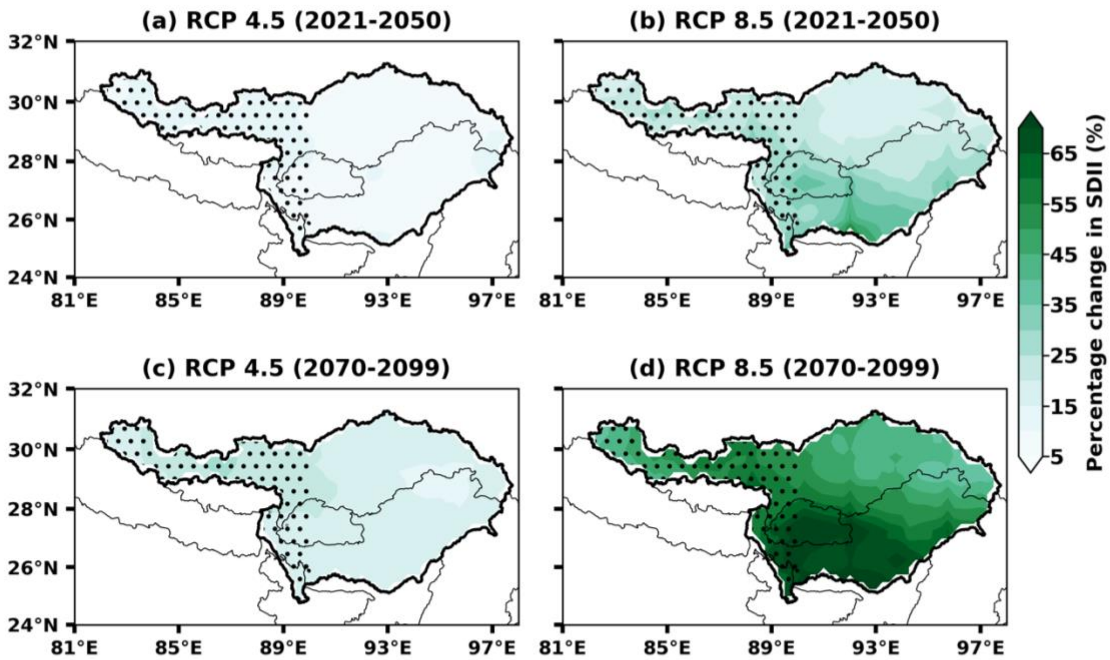


Fig. 4.9 a-d Future changes in the MMM of SDII in the near future (2021–2050) and far future (2070–2099) under the RCP 4.5 and RCP 8.5 scenarios relative to the baseline period of 1976–2005. Dotted regions represent significant changes at a 90% significance level.

In Figure 4.9, the future changes of SDII has been displayed. The spatial map is consistent with the trend lines depicted in Figure 4.8, which indicate an increase in the extreme precipitation indices. The RCP 8.5 scenario exhibits significant alterations, with a precipitation increase of approximately 50 % in the far futures, respectively. Lower part of the basin shows increase in overall percentage increase, indicating an increase in rainfall intensity. Black dots indicate the 90% significance level which was done using Student's T-Test (Decremer et al. 2014).

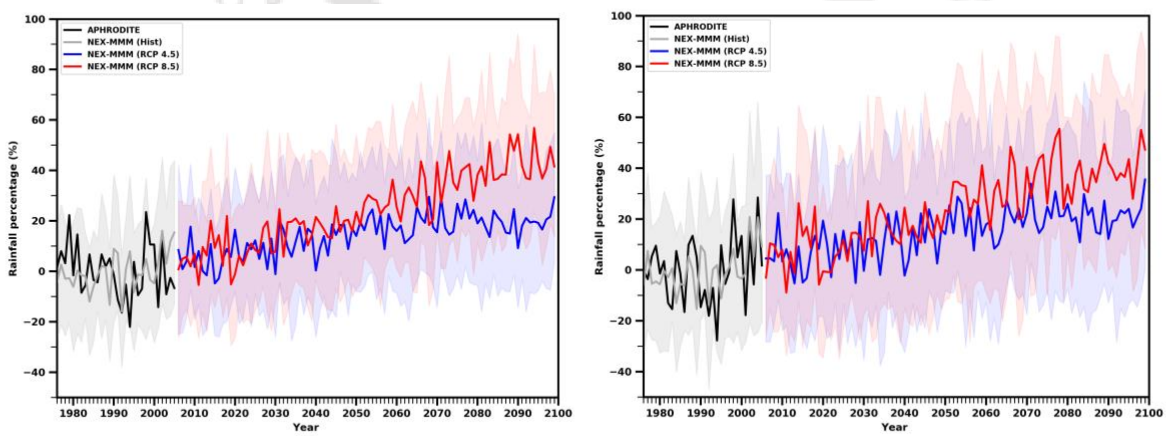


Fig. 4.10. Future projections of (a) RX1DAY and (b) RX5DAY (area averaged over BRB). Solid lines show the MMM, and shaded regions indicate the range of the standard deviation between the models

Figure 4.10 displays the relative projections of the highest 1-day (RX1DAY) and 5-day (RX5DAY) precipitation in the BRB. The results reveal an anticipated increase in RX1DAY and RX5DAY precipitation from the middle of the twenty-first century. Under the RCP 4.5 scenario, RX1DAY is projected to increase by 2.2 mm decade−1; under the RCP 8.5 scenario, the increase is 4.5 mm decade−1. Similarly, RX5DAY precipitation is expected to rise by 2.33 mm decade−1 under the RCP 4.5 scenario and 4.9 mm decade−1 under the RCP 8.5 scenario. This escalation in extreme precipitation intensity is identified as the primary contributor to the overall increase in total precipitation.

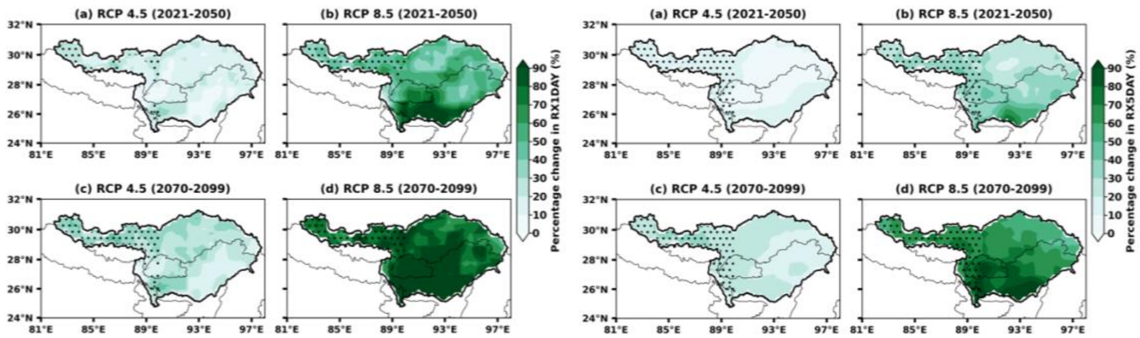


Fig. 4.11 Future changes in the MMM of RX1 and RX5 in the near future (2021–2050) and far future (2070–2099) under the RCP 4.5 and RCP 8.5 scenarios relative to the baseline period of 1976–2005. Dotted regions represent significant changes at a 90% significance level.

In Figure 4.11, the future changes of RX1DAY and RX5DAY have been displayed. The spatial map is consistent with the trend lines depicted in Figure 4.10, which indicate an increase in the extreme precipitation indices. The RCP 8.5 scenario exhibits significant alterations, with a precipitation increase of approximately 50-90% in the near and far futures, respectively.

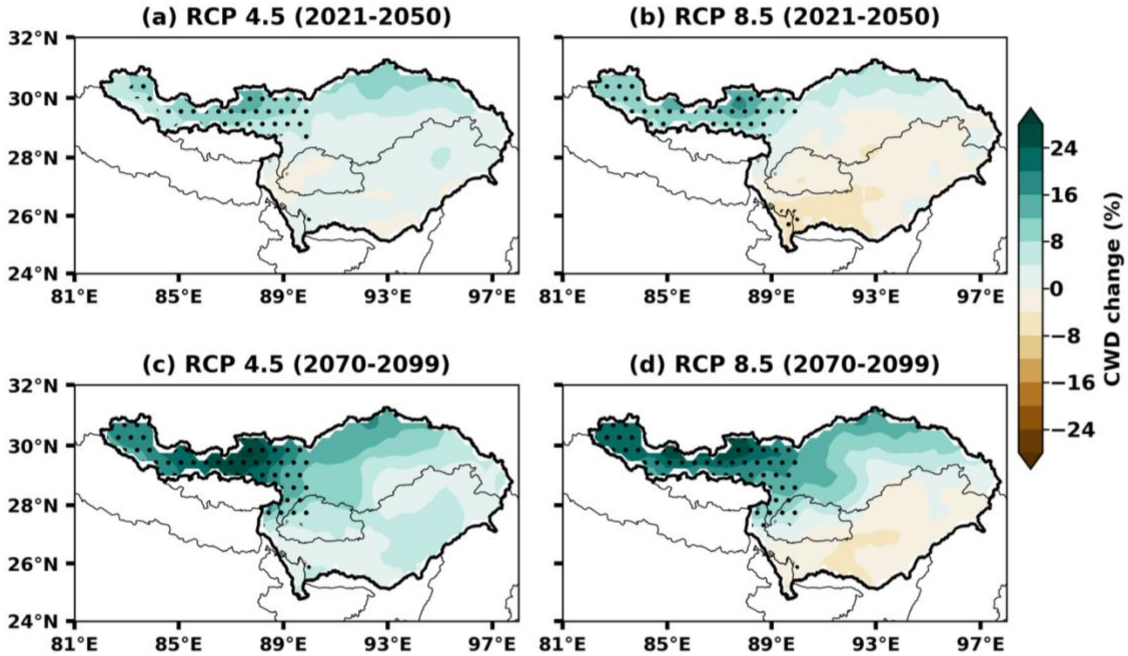


Fig. 4.12 a–d Future changes in the MMM of CWD in the near future (2021–2050) and far future (2070–2099) under the RCP 4.5 and RCP 8.5 scenarios relative to the baseline period of 1976–2005. Dotted regions represent significant changes at a 90% significance level.

Figure 4.11 illustrates changes in the number of Consecutive Wet Days (CWDs) for both near- and far-future periods under different emission scenarios (RCP 4.5 and RCP 8.5). Black dots indicate the 90% significance level. In the far future, the northern parts of BRB show an increase in CWDs under both scenarios, as indicated by the multi-model mean (MMM). Conversely, the northern parts may experience more CWDs in the near-future period than the southern parts.

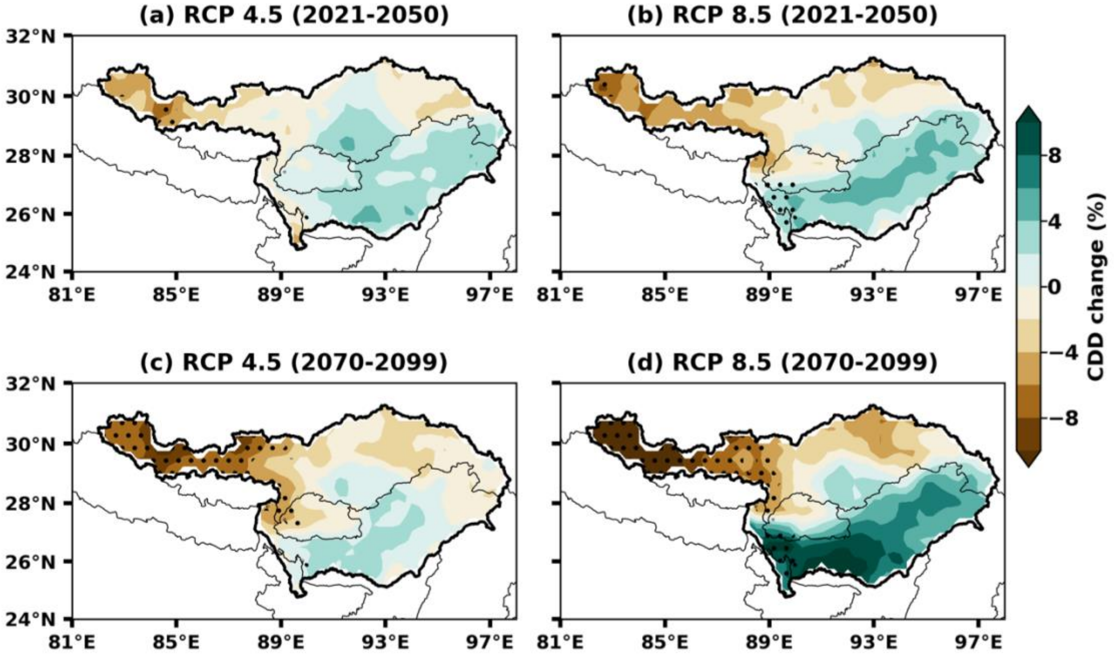


Fig. 4.12 a–d Future changes in the MMM of CDD in the near future (2021–2050) and far future (2070–2099) under the RCP 4.5 and RCP 8.5 scenarios relative to the baseline period of 1976–2005. Dotted regions represent significant changes at a 90% significance level.

Figure 4.12 presents changes in the percentage of Consecutive Dry Days (CDDs) for the near and far future under the RCP 4.5 and RCP 8.5 scenarios compared to the baseline period. Many parts of BRB exhibit a decrease in CDDs in both the near (around 5%) and far future (> 6%) under both scenarios.

3.8 Discussion

3.8.1 Climate Change scenario in BRB

The comprehensive analysis using NEX-GDDP MMM indicates an up-rise in precipitation over BRB, with a further increase expected by the end of the twenty-first century. Variability of individual models closely resembles observed patterns, despite a slight dry bias in the seasonal mean precipitation. This suggests that bias-corrected models hold the potential to reasonably depict precipitation dynamics over the BRB reasonably, thereby enhancing our ability to understand and predict monsoon behaviour in the region. Most individual models accurately capture the seasonal mean rainfall in BRB, closely aligning with observed values of 6 mm day−1 and a standard deviation (SD) of 1.1 mm day−1.

Future projections exhibit increased precipitation during the BRB monsoon season by the century's end. This aligns with studies done by (Immerzeel 2008c; Gain et al. 2011b; Dutta et al. 2021b). A study by (Mohammed et al. 2017c) observed an increase in precipitation in the BRB region due to global warming, particularly with a higher increase in northern BRB compared to the southern parts. Moreover, the upward trend in the SDII under warming conditions signifies heightened precipitation intensity over the BRB under RCP 4.5 and RCP 8.5 scenarios. The general rise in SDII suggests the likelihood of fewer rainy days with heavy rains in various parts, aligning with global observations indicating an increase in the intensity of daily heavy precipitation events (Kostopoulou and Jones 2005; Rao et al. 2014; Sun et al. 2020). On a global scale, this observed increase is attributed to the fact that with each 1 °C increase in temperature, the air's water-holding capacity increases by about 7%, leading to a higher concentration of water vapour in the atmosphere (Trenberth 2011; Trenberth et al. 2011) The projected intensification of RX1DAY and RX5DAY throughout the twenty-first century consistently indicates increased precipitation over BRB. RX1DAY and RX5DAY precipitation under the RCP 8.5 scenario exhibit severe increase, potentially contributing to intense downpours in the BRB region. Consequently, the study suggests a heightened risk of future flooding due to increased extreme precipitation (Geetha et al. 2019; Khan et al. 2020b).

Noticeable changes in CWDs between RCP 8.5 and RCP 4.5 scenarios are observed in both the near and far future, with a higher spatial gradient in the far future. The northern part of the basin which is predominantly mountainous, is likely to experience more number of wet days, than the southern part of the basin which is majorly a plain with lower elevation. Increasing CWD raises concerns about natural hazards like flash floods and landslides, particularly in a region already prone to such events. The decrease in CDD suggests shorter dry spells in the future, notably under the RCP 8.5 scenario. Lower part of the basin, mainly the floodplains of Assam and Bangladesh exhibit increase in CDD. The decrease in CDDs and the increase in CWDs indicate an overall increase in total precipitation, reduced occurrence of drought, and an extended duration of wet spells over BRB.

3.8.2 Hydropower Vulnerability in BRB

Numerous initiatives have been implemented within the BRB to harness its water resources, particularly for hydroelectric power generation. Currently, there are 12 operational mega hydropower dams in the upper Brahmaputra in China, eight (8) in the middle Brahmaputra in Bhutan, and 19 in the middle and lower Brahmaputra in India (Yang et al. 2016). While precise figures regarding planned and under-construction large dams are challenging to ascertain, (Alley et al. 2014) suggest that the number could exceed 30. The number of small and micro hydropower projects in the basin will be considerably higher.

However, both the small and large dams exert adverse effects on the river's hydrology, ecology, dependent community etc. (Alley et al. 2014). Moreover, the proliferation of current and proposed dams in the basin poses foreseeable challenges regarding water availability in downstream riparian countries (China et al. 2016). Because not all of these hydropower plants are runoff-the-river projects and consist of a certain amount of pondage or damming, the impact of climate change on the hydropower can expose the region to climate-induced risks. Our study tries to create a narrative on the vulnerability of the hydropower plants, as no study has assessed the climate change impacts on the basin. Thus, we contribute valuable insights to aid in the planning and design phases of these hydroelectric projects, accounting for climate uncertainties.

In the upper reaches of the basin, particularly within the Yarlung-Tsangpo region, projections indicate either a decrease or no change in CWD in the near-future under both assessed climate scenarios. However, looking towards the far-future, this area is expected to experience a notable increase in CWD. This region, situated within the TAR, is the site of numerous existing and planned hydropower projects. The anticipated rise in CWD within this locality can be linked to the operational dynamics and power generation capacities of these hydropower facilities. The basin also observes an increase in RX1 and RX5 days, which indicates an increase in extreme flood events in the basin. Increase in SDII indicates an increase in heavy rainfall days. All the precipitation extremes agree with each other and indicate an overall wet basin with the upper reaches of the basin receiving heavy precipitation. A projected increase in future precipitation events has thus been theoretically co-related with the growing consensus on the development of hydropower plants in the basin. With the expected increase in sequential days of precipitation, it becomes imperative to assess the resilience of these hydropower projects to such hydro-meteorological changes. Typically, hydropower dams are designed to release water once it accumulates to a predefined level, a process that can lead to significant artificial flooding downstream. With the increase in RX1 and RX5 in the upper reaches of the basin, water accumulation in the catchment area of hydropower plants must be accelerated, leading to faster release of water. This uncertain release can lead to dam-induced flooding in the downstream. Figure 10 shows an overall increase in RX1 and RX5 in the far-future according to RCP 4.5 and RCP 8.5 scenarios. While these structures are reputed to be resilient to seismic activities, recent disaster events underscore the urgent need to examine their vulnerability and adaptability to the hydrological impacts within the BRB. Currently, no study has been done to understand the impacts of future climate extremes on hydropower in the basin. Construction of large water projects in the basin, especially in the TAR, Bhutan and Arunachal Pradesh (India) is taking place and without proper knowledge of climate extremes, the basin will be at a risk of disaster and economic loss.

4.6 Conclusion

The lack of comprehensive studies conducted at the basin level has significantly impeded our understanding of the complex effects of climate change in the BRB. The study efforts have highlighted the urgent need to improve our comprehension of climate projections for the future, with a special emphasis on precipitation extremes in the BRB. In the study, we have explored the future climate change projections of the basin using globally downscaled NEX-GDDP datasets against the APHRODITE observation data. The five precipitation indices (SDII, RX1, RX5, CWD and CDD) were used to understand the spatial and temporal distribution of extreme events occurring in the basin.

Findings from this study projected an increase in overall basin precipitation, showing a wet bias. An overall increase in climate extreme events was observed in near-future, as well as far-future scenario. The maximum 1-day rainfall (2.2 mm decade-1 and 4.5 mm decade-1) and the maximum 5-day rainfall (2.33 mm decade-1 and 4.9 mm decade-1) are expected to rise significantly in both RCP 4.5 and RCP 8.5 scenarios. It is anticipated that the frequency of consecutive wet days (CWD) will increase throughout the monsoon season.

With the rise in precipitation extremes, the basin is more prone to hazards such as floods, flash floods, landslides, glacial lake outburst floods etc. However, the understanding of the basin at present is either from a regional or from a global level. There is a need to understand the river from a basin level, with collaboration from all the riparian nations (China, India, Bhutan and Bangladesh), to assess the climate change anomalies.

Comprehensive basin-level studies require seamless collaboration and data exchange among the riparian nations. Unfortunately, geopolitical difficulties, varying national agendas, and limited cross-border cooperation often impeded this. Limited basin-level studies are also about the unavailability of observational data. Lack of observational data arises primarily due to a lack of meteorological stations and secondly due to a lack of open access to the data. Although meteorological data is not as securitized as hydrological data, easy access to transboundary meteorological data remains to be a constraint with such high geo-political tension prevailing in the basin. MoUs between and among the riparian nations have fostered the process for the exchange of meteorological data, however, there continues to be a void among all the four riparian nations in devising a data exchange mechanism under a common platform. Future research should focus on collaboration with the riparian nations, for seamless data access, enabling better model validation. Overcoming these challenges necessitates a concerted effort to establish diplomatic frameworks, enhance transparency, and foster mutual understanding among the nations sharing the BRB.

Lack of information on future climate conditions creates risks, especially in the context of hydropower development, where changing climate patterns can affect water availability, precipitation, and overall hydrological conditions, as indicated by this study. The construction plans for numerous hydropower dams by China, India and Bhutan on the BRB add urgency to the need to understand these impacts better. Thus, there is a need to explore how the water-infrastructure projects in the basin incorporate climate change projection scenarios in the decision making. Policies must be designed to develop adaptive strategies that enhance resilience to these climate extreme events. Investing in scientific knowledge development and necessary infrastructure must be facilitated.

4.7 Limitations of the study

One of the limitations of our study is that we did not directly use meteorological station data from all the stations of the basin-level countries. The availability of meteorological station data will lead to better calibration of the climate models, generating a more accurate result. We also did not pursue any quantitative or physical assessment for hydropower vulnerability. Hydropower data is although securitised to an extent, various parameters such as power generation, catchment area etc. can be retrieved from primary or secondary sources and considered for a vulnerability assessment. However, the researchers understand that collaboration at the basin level is required to perform such a study. The considerable elevation variations in the BRB along its course have a substantial impact on the distribution of rainfall in the area. However, we might have missed these orographic impacts by utilizing gridded datasets, which could have resulted in a less accurate depiction of precipitation patterns. Therefore, the study opens up scope for future research where incorporating regional climatic trends can precisely represent the various ways that climate change is affecting the BRB.

Chapter 5

Bridging Gaps in Hydropower Decision-Making: Embracing Open Data, Collaboration, and Climate Change Considerations in the Brahmaputra River Basin

Chapter 5

Bridging Gaps in Hydropower Decision-Making: Embracing Open Data, Collaboration, and Climate Change Considerations in the Brahmaputra River Basin

5.1 How are climate change parameters incorporated in the hydropower decision making? - *An essential introduction*

Since the basin has seen the development and planning of several hydroelectric infrastructures, sub-question three becomes increasingly crucial to answering the main issue as the susceptibility of hydropower to the effects of climate change increases. Expanding upon these discoveries, Chapter 5 investigates the vulnerability of hydropower qualitatively.

Findings from chapter 3 of the thesis provides status of scientific knowledge on climate change projections in BRB. These findings set a context to understand hydropower planning in a climate sensitive region. Findings from chapter 4 performs physical assessment of climate models and generates climate extreme scenarios. These findings further support the results from systematic mapping done and provides concern for understanding the resilience of hydropower infrastructure planning and development in the basin. The climate extreme events tend to increase in near and far future. Are the hydropower plants developed resilient to the upcoming climate uncertainties? Are the climate future climate scenarios considered while hydropower development and planning?

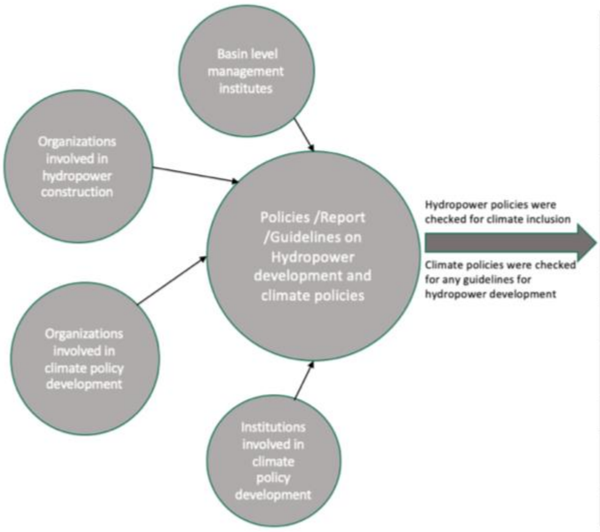
These fundamental questions were processed over and over again to develop the third sub-question of the thesis “How are the future climate projections included as a parameter in the hydropower decision making?”.

To assess this question, a qualitative survey was performed with different stakeholders to find answers and generate insights. The identification of stakeholder for interaction followed a systematic approach rather than an ad-hoc one (see Figure 5.1). To address the research objective, this chapter of the thesis explored two categories of stakeholders, a) practitioners who are involved in scientific knowledge development with respect to climate change and hydropower development, and b) practitioners who are involved in decision making of hydropower development. Following the stakeholder interaction, the data generated was qualitatively analysed using a thematic analysis method. Analysis of the data generated themes and sub-themes based on which findings were developed.

Findings from this chapter of thesis should essentially addresses the main research question of the thesis "*how hydropower projects in the Brahmaputra River Basin (BRB) incorporate scientific knowledge on future climate change?*"

5.2 Methods

5.2.1 Review of documents



Selected Policies (n=32)
Central Electricity Authority Guidelines, India, 2015
Central Water Commission Guidelines, India, 2018
International Hydropower Association, 2017
Ministry of New and Renewable Energy Guidelines, 2005 (Indian and Bhutan)
Ministry of Power, Policy on Hydropower Development 2014 (India and Bhutan)
Bhutan Sustainable Hydropower Policy, 2008
National Action Plan on Climate Change (India)
State Climate Change Action Plan (Assam & Arunachal)
Bhutan Renewable Energy Master Plan (2020)
National Policy for Hydropower Development (NHPC) (2018)
Hydropower Policy for Arunachal Pradesh (2008)

5.2.2 Stakeholder Identification and interaction

Findings of chapter 3 provides a pre-context of scientific literature on climate change projections in BRB. Firstly, to identify the knowledge developers, a systematic approach of searching the literature mapped from the findings of chapter 3 was done. Thus, practitioners who are from the basin level countries were considered relevant for the research study. Identification of second category of stakeholders followed a different approach, where first the government departments or agencies involved in hydropower development were located. Secondly, relevant knowledge developers and hydropower decision makers were identified from the literature mapped and websites of the located government departments, respectively. Thirdly, a mail was sent to each of these identified stakeholders, knowledge developers (n=12) and decision makers (n=20). If the stakeholder replied showing interest in interaction, an appointment was confirmed. If the stakeholder replied showing no interest in interaction, the subsequent stakeholder in the list was approached with a mail. If no response was received from a stakeholder, a mail was resent after a period of seven days. The procedure was repeated for two times (n<3), before terminating the loop. Once the loop of remailing was terminated, the response was considered as 'negative' and a subsequent action of mailing the next stakeholder took place until the list was complete. For all the positive responses, a meeting was held, except for Bhutan where two decision makers could not be met due to lockdown during the Covid-19 pandemic. Further communication could not be established with the decision makers as the situation in Bhutan did not stabilise until late 2022. With every meeting, a snowball approach of identification was done to identify relevant stakeholder. A backward mechanism of mailing the newly identified stakeholder was reinstated, until satisfactory number of interactions were done for the study (see Table 5.1).

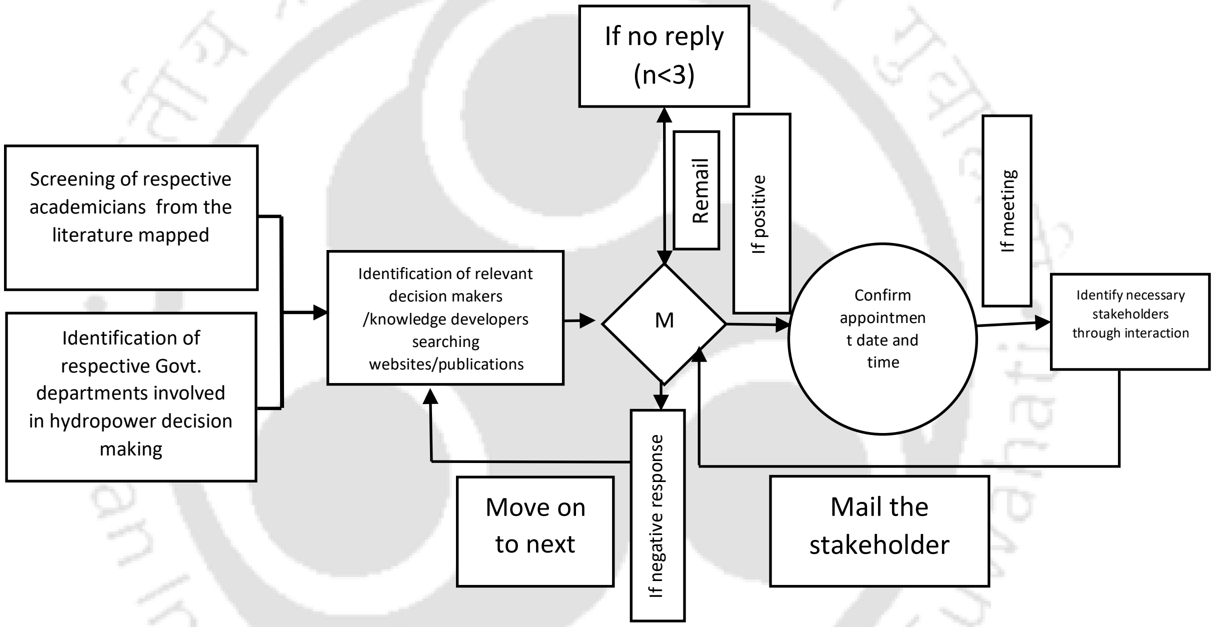


Fig: 5.1: Stakeholder identification mechanism developed for the thesis

5.2.2.1 Developing stakeholder interaction questionnaire

The stakeholders were interviewed using semi-structured questions (see Annexure II) the content of which was analysed qualitatively. The literature review and the findings from the thesis's third and fourth chapters had an impact on the design of the questions. Questions were designed to explore crucial understanding of state-of art of knowledge, science communication, and policy inclusion. Every interview question required to correspond to the thesis's third aim and third sub-question. In order to better understand how scientific knowledge about climate change forecasts on BRB is incorporated into hydropower decision making, interview questions were developed with the primary research question in consideration. Given that each group of stakeholders contributes a distinct role, distinct questionnaires were developed for each of the stakeholder categories (see Annexure II).

The interviews in Bhutan were carried out in March, 2020, in their respective offices. Interviews in India were carried out in Arunachal Pradesh between December 2022. Interactions in Assam in India were rather periodic, but followed a definite time step. Interviewees did not permit mentioning their names; hence, only the names of respective departments have been mentioned in the thesis.

Region	Knowledge developers/Scientific Community	Decision makers/Relevant government Officials
BHUTAN	College of Science and Technology, Phuentsholing (2)	Department of Hydropower (2)
		Department of Renewable Energy (1)
		National Environment Commission (2)
		National Centre for Hydrometeorology (1)
India (Arunachal Pradesh)	NERIST, Nirjuli (2)	Department of Hydropower (2)
		Department of Water Resources (1)
		Arunachal Pradesh Energy Development Agency (1)
		State Disaster Management Authority (1)
		Climate Change Cell (1)
		NEEPCO (1)
India (Assam)	Indian Institute of Technology Guwahati (2)	Assam Climate Change Society (1)
		Brahmaputra Board (1)
		Assam Water Research and Management Institute (1)

Table 5.1: Stakeholders identified using the stakeholder identification mechanism

5.2.3 Data collection and storage

The main method of gathering data was audio recording with an electronic recorder (ZOOM HN41). To protect privacy, several stakeholders, however, disallowed any form of audio-visual recording. In these situations, thorough notes were made on a notepad and then expanded upon. The gathered data were immediately transcribed into a Microsoft Word document and stored in Google Drive for further analysis.

5.2.4 Qualitative analysis of data

Thematic analysis is a common form of qualitative data analysis. Thematic analysis is extremely versatile, adaptive, and compatible with a broad range of approaches (Braun and Clarke, 2006). The purpose of strictly following a "Thematic" method in qualitative analysis was to understand the perspectives of knowledge providers and decision makers, and to classify each idea as it was understood into unique themes. In the thesis' methodology chapter, the choice of an inductive thematic analysis over other qualitative analysis methods has been justified (Chapter 2).

Braun and Clarke's thematic analysis method is an iterative process consisting of six steps: (1) becoming familiar with the data, (2) generating initial codes, (3) searching themes, (4) reviewing themes, (5) defining and naming themes, and (6) producing report. To address the larger purpose of creating themes from the data generated, iterative cycles of reading and re-thinking was done to get familiarised with the data. Secondly, codes were generated for as many topics as possible and applying the code to a contextual segment using NVivo software. Using NVivo enables quick reform and reorganization of the code and node structure, which makes the process of data analysis more accurate and transparent (Ella and Alistair, 2006; Hamed, Saleh and Alabri, 2013; Zamawe, 2015) . The codes generated were aggregated into tables for sorting and grouping in order to produce the themes and sub-themes. The themes and sub-themes were further investigated for relevance and sense-making. Data codes were also revisited during this stage of analysis to see if there was enough data to justify the theme. This has led to omission or renaming of the theme. Finally, the themes were described to produce a report.

5.3 Results and Discussion

Three primary themes emerged from the thematic analysis of the data produced via stakeholder interaction: a) *Data availability and accessibility, b) Collaboration for joint research* and *c) Climate Change and hydropower planning*. These themes were arranged into a hierarchical system of themes, sub-themes, and codes, which is shown in Table 5.3.

Main themes	Sub-themes	Codes	Examples ad verbatim
Data availability and accessibility	*Data gaps*	funding, role of academia in data management, data access, data generation, policy implications for data generation	*"When a design on basin is planned, you need data from the entire basin. Having data just from certain points is not enough."*

	Lack of interdepartmental co-ordination	communication, data challenges	*"Due to lack of integrated approach, there is no coordination within the department."*
Collaboration for joint research		government-academia relationship, status of academic collaboration, role of government bodies and academic institutions in knowledge development and decision making	*"No primary data is collected from academicians to run any kind of analysis hence, no relation with academicians with respect to data collection or data curation."* *"The flow of scientific knowledge from academicians to Government is less and has to be broadened."*
Climate Change and hydropower planning	*Climate change in hydropower*	Climate change research, hydropower planning and development, science communication, science-policy interface	*"Sceptical about future sustainability of Hydropower due to climate change hence an alternative measure must be thought of"-Official from Department of renewable energy* *"Climate change is effecting the discharge of river which is having impact on hydropower generation and hence alternatives must be explored*
	Climate change adaptation	Solutions to adapt, funding for alternatives, renewable energy	*"Renewable Energy (RE) is an adaptation to climate change"* *"The state has enormous potential for micro and small hydropower development."*

			"Wind feasibility mapping going on with the help of Wind Energy Institute, Chennai and MNRE."

Table 5.3: Organization of the Thematic Map with description of codes

5.3.1 *Data availability and accessibility*

Within this theme, we grouped the answers associated with the institutional and geographical data challenges. All the knowledge developers and decision makers reported challenges in accessing data and its availability.

This theme was further divided into two sub-themes a) *data gaps* and b) *lack of interdepartmental co-ordination.* Under the sub-theme data gaps, answers associated with funding, role of academia in data management, data access, data generation and policy implications for data generation were emphasized. Under the sub-theme lack of interdepartmental co-ordination, data challenges within departments and academia has been highlighted along with lack of communication.

"When a design on basin is planned, you need data from the entire basin. Having data just from certain points is not enough."

Brahmaputra basin lacks data with respect to the basin which is the primary reason for the lack of development of scientific knowledge within the basin. For any climate or river knowledge you need data, data which is upto date. According to NHP (National Hydro Project) one of the mandates was to digitize all the data (erosion, sedimentation, siltation, hydrometeorology etc.) however, the creation of database is still under pipeline. There exists a huge data gap especially in case of climate data. Data which exists are available only on certain points and not the entire basin.

"Due to lack of integrated approach, there is no coordination within the department."

Data which used to be available is no more readily available with all the departments. For instance, during the 1980s Water Resources Department used to be an integrated department, and under one umbrella all the relevant line departments such as Department of Irrigation, Department of Soil Conservation etc. used to be present. Any data developed existed within one banner enabling smooth coordination and communication within the departments. Post 1980s all the government departments of Assam underwent restructuring and formation of new departments was observed. Currently Water Resources Department focuses only on its mandates and the data developed aren't easily communicated. Earlier Water Resources Department used to maintain the hydrological data, currently it is data is maintained by Central Water Commission.

"Lack of gauge stations in different locations ... especially areas with high elevation is missing." "All data generated and maintained by NCHM are open access"-Official from NCHM

Since Bhutan is a mountainous country with different elevations, presence of limited meteorological stations adds to the data bias. Accessibility being another factor for installation and fetching data, the collection becomes a challenge. NCHM an autonomous body (not under any ministry and takes its own decision) under GOB is the nodal point for World Meteorological Organization and IPCC, generating and maintaining all kind of hydrological and meteorological data (historical and future). They work in close consultation with other departments to provide technical backstopping. To analyze the unpredictable rainfall over Bhutan, TRMM (Tropical Rainfall Measuring Mission) data was also checked but due to data deficiency validation could not the carried out. All data reports generated by NCHM are open access and maintained in their website. Data developed can be accessed by the line departments for their respective analysis. Some precautionary measures to combat adverse effects of changing climate such as GLOF and Flood are also among the mandates by NCHM.

"We do not generate any kind of meteorological or climate data and are dependent on NCHM for the same". "So far meteorological parameters like precipitation and temperature are used only for hydrological analysis but not future climate analysis".

Department of Hydropower (DOH) receives all kind of meteorological data from NCHM, which may or may not be used for any decision making. It is primarily the discharge data which are collected by the Hydropower department from each hydels a glimpse of which can be observed in the quarterly reports of National Statistics Bureau, Bhutan. The data collected are vaguely used for hydropower demand forecast, other than hydrological modeling. No incorporation of future climate data has been observed in the decision-making process as of now.

Data sharing, one of the key cause of interaction with India, follows all necessary guidelines and norms. For internal rivers, the decisions taken do not require permission from India, but for transboundary rivers Bhutan has to. NCHM led JET (Joint Expert Team) for transboundary river management, mainly Assam/WB and Bhutan. Sub-hourly basis data is shared with CWC, India, but not sure how data is moved from Centre to local bodies. During winter, Bhutan imports power from India. During energy shortage, Energy banking from India is done. On conversing with the government officials, it was identified that lack of funds have been one of the major reasons for the existing data deficit system, followed by the geography of the region. Similar perspective was also observed among the academicians who pointed towards the poor data management and limited access to a data repository. Also highlighted was unavailability of a data repository (particularly hydrological and meteorological) maintained exclusively by the academicians of Bhutan.

"Even if we get all the climate data will there be any mechanism to facilitate it?"

There is no common platform for data sharing interstate as well as inter country. There are also no proper data sharing platforms within the districts of the state. There exists certain department with data relevant to climate and water, however, status of the data is not available in the public domain.

Findings from this theme and sub-themes demonstrate that both knowledge developers and decision makers emphasized on geographical challenges of data generation and lack of funding for generating data. Knowledge developers highlighted the role of academia in storing data and revealed that academia is not the custodian in storing datasets. They further emphasised on the challenges in retrieving data from government bodies. Data produced is redundant within government bodies with one department being unaware of the data produced in other. This disintegration among line departments leads to limited sharing of inter-departmental data.

"DONER, NEC, NERIWALM are also not equipped to provide a decision on the entire basin"

Inter-state disputes can affect the mechanism of data sharing and smooth management of the river. Majoritarism can also play a role in dominating the water related decisions. For instance, Arunachal Pradesh holds major part of the river in India, thus even though there is a committee with members from other riparian states sharing the basin, decisions will be enforced by the majoritarian. Political instability between the upper riparian Arunachal Pradesh and lower riparian Assam may also effect the mechanism. In such cases one single unbiased regulating authority is necessary where the authority can veto over the federal river and state cannot over power on certain issues. E.g., Tennese Valley Authority. NEWMA (North East Water Management Authority) is planned which can bring the matter of water under one single umbrella. The recent NEWMA bill passed in the parliament brings hopes for enhanced integrated mechanism atleast within North East India.

5.3.2 *Collaboration for joint research*

Within this theme, we grouped the answers associated with the government-academia collaboration, status of academic collaboration, role of government bodies and academic institutions in knowledge development and decision making.

"Incorporating academicians in recent hydropower projects as a technical advisor is a recent phenomenon and is in its initial stage."

"No primary data is collected from academicians to run any kind of analysis hence, no relation with academicians with respect to data collection or data curation."

Academicians also point the challenges in easy access of data as one has undergo to several procedures and permissions in availing them. The difficulties in access might also be due to the sensitivity of the data. NCHM, the sole authority for any kind of meteorological data generation, storage and maintenance in Bhutan has collaboration with Sherubtse college, College of Science and Technology, Phuentshoeling and Jigme Namgayal College for technical advice. The colleges have however been actively involved in scientific and technological implementations to combat the impacts of climate change depicting current climate change adaptation strategies. For instance, the establishment of GLOF early warning systems by CST over various parts of Bhutan, modelling of Bhutan Power Grid, installation of Solar lights in CST campus etc. are some of the effective technological measures taken by the academic community of GOB to combat climate change. It was also noted that most projects in Bhutan are dependent on donor organization for funding and the respective donor may use its own expertise to get the work done, not necessarily including the native academicians in the project. However, when it comes to decision making itself, the inclusion of academicians directly have been observed to be very low. As of now very few native academicians have been involved in developing policies and the process is in its initial stage. Government of Bhutan, indeed has collaboration with academicians and scientific bodies outside Bhutan to advise them with developing their hydropower projects, however the mode of hydropower development has so far been conventional with little or no suggestions of climate change be included as a parameter in the decision making itself.

"The flow of scientific knowledge from academicians to Government is less and has to be broadened."

The resource institutes do not have the budget to work on the dissemination of the scientific knowledge to common people. State Govt's approach on the other hand has been to directly connect with the beneficiaries, which is the citizens. Any kind of indirect connection like Research and Development funding has been very weak within the state Government. Data based driven planning is the need of the hour and any planning without the climate data is not a good planning. The approach should be reduction of carbon emission and climate mitigation.

"There has been lack of collaboration observed inter-state and intra-state. Boundaries are not well defined. Develop the hydropower potential in Arunachal Pradesh which is untapped as of now."

"R&D is necessary without that the exact use of climatic parameters cannot be said... better if academicians do the R&D work"-Officials from Department of Hydropower

Although, it was well established that the officials mainly involved with the hydropower decision making were technically aware about the changing climate dynamics of the region, their engagement in activities related to Research and Development (R&D) have been substantially difficult due to the commitment towards official 'pen and paper' work. Thus, the thought that if any kind of R&D work could be carried out by the academicians in incorporating climate change into the decision making algorithm in this case, it might provide a way forward to further climate resilient model and was endorsed by both government officials as well as academicians.

"I always had a problem with academicians, why complicate things?"

There is some academic/scientific data available but there is no blending. There has been emphasis by the government officials to take accountability of disseminating the work. Indian Meteorological Department, Pune provides all kinds of weather and climate data, however the data available in public domain is complex and usually not simplified for general audience. As community is the client of the climate data, it has to be reached to people in simplified way.

Findings from this theme demonstrate that both knowledge developers and decision makers emphasized on insufficient incorporation of academia insights in decision making. Lack of collaboration within basin level institutions, academia and policy makers has been demonstrated. This finding supports the finding from chapter 3, where systematic literature mapping did not find any publication with collaboration among basin level countries to assess the future climate change projection on the basin. Academic practitioners or knowledge developers do get involved in government projects for certain research and development activities. However, their involvement in direct decision making process was not observed. Knowledge developers expressed willingness to collaborate in Govt. projects and be a part of the decision-making process so as to incorporate technical suggestions. In a special case of India, where the river travels from a higher altitude in Arunachal Pradesh to the low-lying flood-plains of Assam, lack of collaboration among inter-state departments to develop any water infrastructure plan has been exhibited.

5.3.3 *Climate change and hydropower planning*

In this theme, we included those answers that emphasised on climate change on BRB, hydropower development in BRB and communication of scientific knowledge on climate change. This theme was further divided into two sub-themes a) *climate change in hydropower* and b) *climate change adaptation*. Under these sub-themes, the thesis included answers that reflect research on climate change and hydropower, climate vulnerability in the basin and use of existing scientific knowledge on climate change.

"All hydropower in Bhutan are Run of River with a very few having a pondage area … the infrastructure is designed to be resilient to PMF and GLOF"- Official from department of hydropower

"Stakeholder interaction and public consultations are done before the construction of Hydropower"

"NEC checks the hydropower project for environmental clearance" "Environmental restoration is done as per policy. Compensatory afforestation, financial compensation to the land holders …. are provided."- Official from Department of Hydropower

Bhutan, the only country in the world with Gross National Happiness (GNH) index has one of its mandate towards the protection of environment. Hence, any kind of developmental activities taking place in Bhutan must be pursued without having negative impact on the environment of Bhutan. To monitor this, an autonomous body under the Government of Bhutan was established named National Environment Commission (NEC). NEC takes lead in developing, evaluating and reviewing policies and plans including water and climate policies. Different adaptation plans like NAPA III have been developed by NEC in collaboration with GNH. To look into matters at local level, different implementation agencies like District Environment Committee have also been created by NEC. NEC is also working with several international agencies like UNDP, UNEP, WWF, ADB, WB, ICIMOD, IGES etc. who provide support both financially and technically for materializing a plan into action. Hence, in the process, many experts are recruited for evaluation from different organizations and institutions. NEC has started to focus on long term strategy for development of climate resilient infrastructures but doesn't get involved in any kind of primary Research and Development (R&D).

The department of hydropower with a mandate to formulate, supervise and implement the hydropower policies in Bhutan, claims the hydropower infrastructure within Bhutan to be resilient to the changes of climate. The environmental impacts are asserted to be minimum as all the hydropower projects in Bhutan are run of the river projects and are pursued with consideration to public opinion. However, when enquired regarding the incorporation of future climate projections into the policies for future climate preparedness, no such evidences of inclusion were noted. Established in 2011 with a mandate to provide alternative source of energy, department of renewable energy looks into developing policy, plan and implementation of renewable sources such as bioenergy, solar energy, wind energy and small-hydropower. The implementation of the projects is carried at sites which do not fall under the National Protected Areas as per the rules laid by NEC. Certain funding from the external agencies is also observed for the development of renewable energy sources for instance funding from ADB for the construction of Wind Mill project in Bhutan. All micro and mini hydropower were funded by donor organizations as well. Although the department has been trying to excel in the implementation of renewable energy by formulating 'Alternative Energy Policy and Renewable Energy Master Plan', no research related activities were reported so far. The R&D cell within the department has been focused on calculating the energy efficiency rather than the research, and thus, the department has plans to rename it into Energy Efficiency Cell. Although, a significant amount of policy attention has been focused upon developing stronger regulatory systems and establishing socio-environmental safeguards for managing the impacts from hydropower projects, diminutive work has been focused on understanding the impact of future climate changes on the hydropower of Bhutan with little or no focus of incorporating the future climate scenario into the hydropower decision making.

"No snowfall in Thimpu was observed this year and it is already March"-Official from Department of Hydropower

"Flash flood do not help in hydropower generation, which is happening due to erratic rainfall"

"During winter, hydropower generation is dependent on glacial water flow … in winter small hydropower plants dry up"

" Areas with higher elevation with colder climatic condition are able to grow certain crops nowadays which were earlier grown only in areas with lower elevation"-Official from Department of Renewable Energy

The interview carried out started with understanding the perspective of climate change of both the groups of people. With interaction, a clarity of perception of current climate change, vulnerabilities due to climate change and future climate uncertainties was observed. Certain evidences such as sudden absence of snowfall in Thimpu, shifting of monsoon pattern, decrease in generation of hydroflow, decrease in individual hydropower generation since the past 6-7 years, erratic rain during summer etc. were well justified with individual experiences of the stakeholders. It is also to be noted that the officials and academicians chosen for the interview had expertise in their subject with in depth understanding of climate dynamics. This provided a base for continuing the interview to understand the incorporation of climate change in the decision-making level.

"I also believe that any impact on the upstream of the river will have some impact on the downstream".

It is confirmed that extreme events are increasing due to climate change. However, the annual discharge yield remains same. The impacts of climate change have been acknowledged by the government officials and academicians.

"Renewable Energy (RE) is an adaptation to climate change"

"Feed in tariff is required. More funding is necessary to boost the use of renewable energy as the energy produced from hydropower is cheaper as compared to that produced by Renewable Energy sources"-Official from Department of Renewable Energy

As the newly formed Department of Renewable Energy, its prime mandate has been to explore and assess the potential of the country for the development of alternate source of energy. In the era of climate change it was understood that there could be a need to adapt to the future uncertainties and hence an alternative to hydropower was necessary. However, since its inception very little has been implemented than the expected. Multiple reasons account for the slow-paced growth of renewable energy development in Bhutan of which the cost intensive installation has been a hindrance. Primarily, solar and wind are the two identified potential alternatives of which the former has been successfully generating energy but at an unaffordable cost. 17Nu/Unit (inclusive of all taxes) for the energy produced by wind power plants versus 5.5 Nu/Unit for the energy produced by hydropower creates a huge difference in itself. At a public purview, it becomes impossible for government to offer energy at different price rates to match the market viability. To subsidize the rate of the energy produced by any other renewable sources shall also put an economic burden on GOB. Thus, making return on investment relatively lower when compared to hydropower. Limited funding from external agencies to promote renewable energy being another reason for the rough functioning of renewable sources of energy.

"Sceptical about future sustainability of Hydropower due to climate change hence an alternative measure must be thought of"-Official from Department of renewable energy

"Climate change is effecting the discharge of river which is having impact on hydropower generation and hence alternatives must be explored"-College of Science and Technology, Phuentsholing

While interacting with the government officials as well as academicians it was understood that preference for small hydropower was opted by the academicians over larger reservoir type hydropower megastructure. With a strong technical opposition to reservoirs, academicians cited that the mountains of Bhutan are very young and instable with tremendous seismic activity observed. On the contrary, the government officials did suggest certain measures to create pondage to store the flowing water to combat the energy crisis during non-monsoon lean season. Having a pondage was also considered useful in case of peak hours (rain load time). Glacial water which is usually seen going unutilized was recommended to be tapped by the officials.

In addition to all the technical measures, awareness of climate change at the local level was another input provided by both academicians as well as government officials. It is evident that Bhutan with its pillars being 'sustainable development' and 'conservation of natural resources' under the Gross National Happiness index, always had the idea of prioritizing the environment. However, climate change being a dynamic and relatively recent phenomenon, also needs to be reached to the local level. The need for a ‘Hydromet Act’ which is so far absent in Bhutan was also put forward by government officials as well as academicians. The Act which if comes to action can formalize the data sharing guidelines within Bhutan as well as with its neighbouring countries.

“The state has enormous potential for micro and small hydropower development.”
“Wind feasibility mapping going on with the help of Wind Energy Institute, Chennai and MNRE.”

Atleast 100 micro hydro projects are being planned on Arunachal Pradesh. As of now 100KW of the total microhydropower potential has been utilised. However, micro hydels do not have enough fundings to step up the development process. No external fundings are provided for the development of micro hydel projects unlike large hydropower dams. Wind Energy is another source of energy for Arunachal Pradesh with estimated potential of 9GW. Solar Energy has a minimal potential of 5MW.

Findings from this theme established the perception and level of understanding of the impacts of climate change on hydropower by the stakeholders from both the categories. Both the categories of stakeholders agreed on the impact of climate change on hydropower on BRB. The knowledge developers emphasised on lack of research on impacts of climate change on hydropower. For government bodies, more emphasis is given to action oriented work like construction, planning, operations, management and testing rather than research.
Interactions around climate communication and incorporation of climate knowledge on the basin with stakeholders revealed that there has been no direct inclusion of climate change as a parameter in the decision making of hydropower. This is the most significant finding from the thesis chapter as it addresses the third objective of thesis as well as the larger research question. Hydropower projects are considered to be stable, however the process of its development is conventional. Climate change being a comparatively recent phenomenon has never been addressed as a parameter while the development of hydropower. Although other environmental parameters such as e-flow, hydrological flow are forecasted, considering climate change uncertainties in the basin has not been found during the course of this research.

5.4 Key Insights

Availability and accessibility of data remain as one of the primary challenges in research. Thus, emphasis on the need for open access data is encouraged. Efforts should be put towards fostering a landscape where data is not just available in a platform, but also accessible to a researcher. This recognition of open access of data will promote transparency and facilitate collaboration.

Considering that climate change is impacting globally, collaboration at multiple levels is crucial to address the cross-cutting impacts of climate anomalies. Adaptation to the uncertainties imposed by climate change demands multidisciplinary collaborations and involvement of stakeholders, so as to develop strategies. For a region like BRB which is geographically and politically complex, understanding the impacts of climate change will require collaborations at multiple level from all the countries sharing the basin.

Although the impact of climate change on hydropower is acknowledged and understood, there exists a lacuna in its incorporation in the policy level. There is an urgent need to integrate the climate change parameters into hydropower decision making framework. There has been a pro-active shift towards clean and green energy in BRB and development of large hydropower plants are already in process. This necessitates a comprehensive exploration and prioritization of addressing the climate uncertainties to infrastructure planning in the basin to ensure a sustainable development. Expanding energy portfolio by exploring alternate sources of energy like micro and mini hydropower plants, solar energy, wind energy and bioenergy can ensure the energy security and ecological sustainability of BRB.

Chapter 6

Conclusion and Future perspectives

Chapter 6

Conclusion and Future perspectives

6.1.Conclusion

Over the past few decades, a global rise in energy demand has been observed. Hydropower considered a prominent renewable energy option, offers a reliable and environmentally friendly solution to meet the escalating energy demand, unlike non-renewable energy sources, such as fossil fuel-based energy sources, which lead to high carbon emissions. Transboundary rivers stand as a pivotal resource in meeting the global energy demand, with enormous potential for hydropower generation. This thesis explores the intricate relationship between transboundary waters and hydropower development in the context of climate change. As demonstrated, there are gaps in the application of reliable science regarding climate change to hydropower development.

Considering this, the thesis explores the nexus among climate studies, science communication and hydropower development in BRB. Based on the evidence presented in the empirical chapters that comprise this thesis, the idea that hydropower development initiatives, regardless of their size, are resilient to climate change is challenged. By establishing state-of-the-art knowledge on climate change in the basin, the thesis indicates the uncertainties of future climate scenarios. Through interaction with the knowledge developers (academic/scientific practitioners) and decision makers (government officials), this thesis has explored the relationship between science and policy in hydropower development.

To gain an understanding of the hydropower development initiatives are resilient to climate change, the central research question that guided this research was formulated as follows:

"How do hydropower projects in the Brahmaputra River Basin (BRB) incorporate scientific knowledge on future climate change?"

Three sub-questions were developed to address this larger question with respective three objectives. The sub-questions were explored across three chapters, following an analytical logic that first frames the phenomenon of climate change projections on BRB and then explores if the science developed on climate change is incorporated during hydropower development. The findings of this thesis demonstrate the status of knowledge on future climate change in the basin and that these scientific studies on climate projections need to be directly incorporated into the policies for hydropower development.

In this concluding chapter, the thesis argues how a lack of incorporation of scientific knowledge on future climate scenarios can lead to hydropower vulnerability in the basin. First, the overview and findings from empirical chapters of the thesis are presented followed by a reflection on the contribution to addressing the sub-questions and main question. Secondly, the thesis provides conclusory remarks and explains the study's limitations. Thirdly, the chapter concludes by providing future perspectives of research.

6.2 Overview of the thesis and its key findings

To assess the first objective, the thesis questions *"How has the status of scientific knowledge on climate change scenarios evolved in the last three decades in BRB?"* Chapter 3 of the thesis answers this question in which existing literature on climate change projections on the basin is reviewed using a systematic literature mapping technique 'ROSES'. It quantifies publications and evaluates collaborations, sectoral priorities, and scientific characteristics such as emission scenarios. In addition, this chapter identifies research gaps and publishing quality, which will help shape future research questions.

Findings from this chapter show an overall growth in the number of publications in the past thirty years. The chapter indicates that several studies underscored the future climate scenario in the basin. However, studies with a focus specifically on the basin have been scarce. It is prominent from the mapping that sound science on climate projections has been done on the regional level, especially in the Chinese and Indian parts of the basin. However, understanding climate change scenarios on the basin level has mostly been sporadic. Studies to understand the climate change in the Bhutanese part of the basin have been the lowest. Lack of collaboration among basin-level countries has been one of the significant observations from this mapping-based analysis. No research hasn't been done with collaborations from all the four riparian nations sharing the basin. The lack of studies focusing on climate extremes raises concern for the climate preparedness of the basin. Thus, chapter 3 motivates the thesis's second sub-question to investigate the basin's precipitation extremes. The findings of this chapter also establish the context for chapter 5 of the thesis, where the thesis explores the inclusion of scientific knowledge within a science-policy interface for hydropower development.

To assess the second objective, the thesis questions "*How can the future climate scenario for entire BRB be assessed physically?*" This is addressed in Chapter 4 of the thesis, where physical climate model analysis uses a globally downscaled dataset. Chapter 4 addresses the second sub-question by examining future climatic scenarios for the whole BRB. Using the NEX-GDDP global climate dataset entails creating climate forecasts for the near (2050s) and far (2070s) future, emphasising precipitation extremes. The chapter emphasises the viability of basin-wide climate change estimates and how they relate to hydropower vulnerability.
Findings from this thesis demonstrate the exponential rise in precipitation in BRB during peak monsoon season when the basin receives the maximum amount of rainfall. Evaluating the precipitation extreme events of the basin projected high uncertainties in both near and far future scenarios. Increased precipitation over BRB is continuously indicated by the expected intensification of RX1DAY and RX5DAY over the twenty-first century. In the RCP 8.5 scenario, precipitation for RX1DAY and RX5DAY shows a sharp rise, which could lead to heavy rainfall in the BRB region. Both in the near and long future, there are discernible differences in CWDs between the RCP 8.5 and RCP 4.5 scenarios, with a larger geographical gradient in the far future. Compared to the southern portion of the basin, primarily a plain with lower elevation, the northern portion, which is primarily hilly, is likely to see more wet days. Rising CWD increases concerns about natural dangers, particularly in an area where landslides and flash floods are already common. This chapter's findings also indicate that shorter dry spells may occur in the future, especially under the RCP 8.5 scenario, as indicated by the decline in CDD. A rise in CDD is seen in the lower portion of the basin, particularly in the floodplains of Bangladesh and Assam. Both the rise in CWDs and the decline in CDDs point to increased total precipitation, fewer instances of drought, and longer wet period durations over BRB. Findings further establish the hydropower vulnerability of the basin to future precipitation extremes.

To evaluate the third objective, the thesis questions *"How are the future climate projections included as a parameter in the hydropower decision making process?"* This is addressed in Chapter 5 of the thesis, which explores the connection between scientific or academic knowledge of climate science and policies for hydropower development. With several hydropower infrastructures developed and planned on the basin, sub-question three becomes of utmost importance in addressing the larger question, as the hydropower vulnerability due to climate change impacts rises. Building on these findings, Chapter 5 examines hydropower vulnerability from a policy standpoint. Content search, stakeholder engagement, and qualitative analysis are used to investigate the third sub-question of the thesis, which reveals that decision-making processes related to hydropower do not take climate change into account. Engaging with academic practitioners and government officials in Bhutan and India shed additional light on this disparity. In this chapter, the identified gap in directly incorporating academic knowledge on climate change in hydropower decision-making points to a disconnect between scientific findings and policy implementation. The absence of meteorological department involvement in hydropower policy development indicates a potential oversight in incorporating expert opinions crucial for climate resilience. This chapter's findings are crucial as they demonstrate the gap in the science-policy interface. The main research question is addressed in this chapter, where the inclusion of scientific knowledge on climate projects in hydropower development is assessed qualitatively.

6.3 Conclusory remarks

The need for more articles to comprehend the future climate scenario of the entire Brahmaputra basin reveals a potential disconnect in prioritizing comprehensive basin-level research. The absence of collaborative efforts among researchers from all basin-level countries (CIBB) underscores potential political and institutional barriers hindering a collective understanding of the BRB's future climate dynamics. This may indicate a lack of shared interests or cooperative frameworks at the regional level. Collaborative research is imperative for Brahmaputra as four growing economies share the river with diverse national interests, and the solutions for basin-level development need to be looked at from a basin scale. Collaboration also has the potential to drive the transboundary governance for the co-management of the basin and for a river like Brahmaputra, which is amongst the context of geo-political debates, must be considered even by international funding organisations to foster growth and development and resolve conflicts. Collaborative research for generating the future climate projection is necessary to provide a way forward to the decision makers for making climate-informed decisions, which is essential for the sustainable development of the basin. If the current state of solitary research mindset within the basin-level countries prevails, growth and development within the basin will be limited to the current necessity of individual countries. Action for the ongoing climate change over the BRB will be justified only when basin-level countries, such as China, India, Bhutan, and Bangladesh (CIBB), cooperate in addressing the basin holistically.

Executing basin-wide research poses a formidable task due to the geopolitical complexities inherent in the BRB. The lack of comprehensive basin-level studies has significantly hindered our understanding of the intricate impacts of climate change within the BRB. Comprehensive basin-level studies require seamless collaboration and data exchange among the riparian nations. Unfortunately, geopolitical difficulties, varying national agendas, and limited cross-border cooperation often impeded this. Limited basin-level studies also pertain to the unavailability of observational data. Lack of observational data arises primarily due to a lack of meteorological stations and secondly due to a lack of open access to the data. Although, meteorological data is less securitised than hydrological data, easy access to transboundary meteorological data remains a constraint with such high geo-political tension prevailing on the basin. MoUs between and among the riparian nations have fostered the process for the exchange of meteorological data. However, there continues to be a void among all the four riparian nations (CIBB) in devising a data exchange mechanism under a common platform.

The thesis has shed light on the critical need to deepen our understanding of future climate projections, particularly focusing on precipitation extremes within the BRB. Lack of information on future climate conditions creates risks, especially in the context of hydropower development, where changing climate patterns can affect water availability, precipitation, and overall hydrological conditions, as indicated in this thesis. The acknowledgement that RCP4.5 and RCP8.5 scenarios project significant changes in the future climate of the basin, marked by an increase in climate extremes, highlights the vulnerability of the BRB. The existence of multiple hydropower projects and plans to create more hydropower exposes the basin to heightened risks associated with climate uncertainties, suggesting potential conflicts between economic development goals and environmental considerations. The construction plans for numerous hydropower dams by China and India on the BRB add urgency to the need to understand these impacts better.

In conclusion, our research underscores the significance of bridging the gap between scientific knowledge and policy action to safeguard the Brahmaputra River Basin's ecological integrity and socio-economic well-being. Overcoming these challenges necessitates a concerted effort to establish diplomatic frameworks, enhance transparency, and foster mutual understanding among the nations sharing the Brahmaputra River Basin.

6.4 Limitations of the thesis

One of the limitations of this thesis is that meteorological station data from all the stations of the basin-level countries was not used. The availability of meteorological station data will lead to better calibration of the climate models, generating a more accurate result. The thesis did not pursue any quantitative or physical assessment of hydropower vulnerability. Hydropower data is, although securitised to an extent, various parameters such as power generation, catchment area, etc., can be retrieved from primary or secondary sources and considered for a vulnerability assessment.

6.5 Future perspectives of research

In addition to our primary research on the above discussed topics, the thesis suggests that systematic reviews of grey literature, including policy and project reports, would allow key questions to be asked concerning the future climate scenario of the basin. The thesis has explored the perceptions of stakeholders only from India and Bhutan. Interacting with Chinese practitioners will provide further insights into hydropower development at the basin's upper reaches. It is crucial to address the fact that China, a hydro-hegemon with most of the river under its governance, will have more control of the basin's water resources. Understanding the Chinese perspective will provide a holistic view of hydropower vulnerability. The perspective of the lower riparian nation Bangladesh should be explored to understand their interest in basin-level collaboration in assessing the impacts of climate change.

A test of the research hypothesis considering one of the hydroelectric power projects will further validate the findings from this thesis. The thesis also opens the door to re-thinking a multi-dimensional model incorporating future extreme climate events, hydrological data of the river, hydropower operations, etc., to assess downstream impact.

Chapter 7

Bibliography

Chapter 7

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7. Bibliography

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ANNEXURE I

Region specific studies									
China									
Title	**Year**	**Journal Name**	**Correspondence Author Affiliation**	**Collaboration**	**Models/Dataset Used**	**Climate Scenarios**	**Location/ Geographical Area of Research**	**Focus of Study**	**Focus on Extreme Events**
The impact of climate change on runoff in the southeastern Tibetan Plateau	2013	Journal of Hydrology	Australia	Australia	20 GCMs (1 MPI-ECHAM5 2 GISS-ER 3 IPSL 4 IAP 5 CSIRO-MK3.0 6 INGV 7 CSIRO-MK3.5 8 CCCMA-T63 9 CCCMA-T47 10 BCCR-BCM 11 MIUB 12 GISS-AOM 13 NCAR-PCM 14 CNRM 15 GFDL 2.1 16 MRI 17 INMCM 18 MIROC-M 19 GFDL 2.0 20 MIROC-H)	A1B	YZBR	Climatology + Hydrology	No
The impact of climate change on runoff in the	2014	Stochastic Environment Research	China	Australia	RegCM3	A1B	YZBR	Climatology + Hydrology	No

Yarlung Tsangpo River basin in the Tibetan Plateau		and Risk Assessment							
Impacts of climate change on hydrological processes in the Tibetan Plateau: a case study in the Lhasa River basin	2015	Stochastic Environment Research and Risk Assessment	Switzerland and China	Switzerland	Echam5 and Miroc3.2_Medres	A1B, A2 and B1	Lhasa	Climatology + Hydrology	No
Projected changes of temperature extremes over nine major basins in China based on the CMIP5 multimodel ensembles	2018	Stochastic Environment Research and Risk Assessment	China	No	27 GCMs (ACCESS1.0 ACCESS1.3 BCC-CSM1.1 BCC-CSM1.1-M BNU-ESM CanESM2 CCSM4 CMCC-CM CMCC-CMS CNRM-CM5 CSIRO-Mk3.6.0 FGOALS-g2 FGOALS-s2 GFDL-ESM2G GFDL- ESM2 M HadGEM2-CC HadGEM2- ES INMCM4 IPSL-CM5A-LR IPSL-CM5B-	RCP 4.5 and RCP 8.5	9 River basins in China	Climatology	Yes (Temperature)

					LR MIROC5 MIROC-ESM MIROC-ESM-CHEM MPI-ESM-LR MPI-ESM- MR MRI-CGCM3 NorESM1-M)				
Responses of hydrological processes to climate change in the Yarlung Zangbo River basin	2019	Hydrological Sciences Journal	China	Switzerland	CMIP5 (MIROC5)	RCP 2.6, RCP 4.5, RCP 8.5	YZRB	Climatology + Hydrology	No
Downscaling of daily extreme temperatures in the Yarlung Zangbo River Basin using machine learning techniques	2019	Theoretical and Applied Climatology	China	No	MPI-ESM-LR	RCP 2.6, RCP 8.5	YZRB	Climatology	Yes (Temperature)
A preliminary investigation on the climate-discharge relationship in the upper region of the Yarlung Zangbo River basin	2021	Journal of Hydrology	China	No	CMIP6 (BCC-CSM2-MR)	SSP1-2.6, SSP-4.5, SSP3-7.0, SSP5-8.5	YZRB	Climatology+Hydrology+ Glaciology	No
Variation of Runoff and Runoff Components of the Lhasa River	2022	Atmosphere (MDPI)	China	No	CanESM5	SSP1-2.6, SSP-4.5	Lhasa	Climatology+Hydrology+ Glaciology	No

Basin in the Qinghai-Tibet Plateau under Climate Change									
Changes in the Suitable Habitats of Three Endemic Fishes to Climate Change in Tibet	2022	Biology (MDPI)	China	No	CMIP5 (ACCESS-ESM1-5 and FIO-ESM-2-0)	RCP 2.6, RCP 8.5	YZRB	Climatology + Fishery	No
Investigating Extreme Snowfall Changes in China Based on an Ensemble of High-Resolution Regional Climate Models	2023	Sustainability (MDPI)	China	Canada	CORDEX (CNRM-CERFACS-CNRM-CM5, HadGEM2-ES, MPI-M-MPI-ESM-LR, ICHEC-EC-EARTH, HadGEM2-ES)	RCP 4.5 and RCP 8.5	Tibet (With little emphasis on Brahmaputra)	Climatology + Glaciology	No
Impact of climate change on the long-term water balance in the Yarlung Zangbo basin	2023	Frontiers in Earth Science	China	No	CMIP5 and CMIP6 (GFDL-ESM3M IPSL-CM5A-LR MIROC5 NorESM1-MM HadGEM2-ES)	SSP1-2.6, SSP2-4.5, SSP5-8.5	YZRB (Lazi (LZ) in the upper reaches, Nugesha (NGS), Rikaze (RKZ), Yangcun (YC), and Lhasa (LS) in the middle reaches, and Nuxia (NX) and Gengzhang (GZ))	Climatology+Hydrology+ Glaciology	No

Projection and Uncertainty Analysis of Future Temperature Change over the Yarlung Tsangpo-Brahmaputra River Basin Based on CMIP6	2023	Water (MDPI)	China	No	CMIP6 (ACCESS-ESM1-5 BCC-CSM2-MR CanESM5 CMCC-CM2-SR5 EC-Earth3-Veg GFDL-ESM4 IPSL-CM6A-LR MIROC6 MRI-ESM2-0)	SSP1-2.6, SSP-4.5, SSP3-7.0, SSP5-8.5	YZRB	Climatology	No
Impact of Climate Change on the Hydrological Regimes of the Midstream Section of the Yarlung Tsangpo River Basin Based on SWAT Model	2023	Water (MDPI)	China	No	22 GCMs (ACCESS-CM2 ACCESS-ESM1-5 AWI-CM-1-1-MR BCC-CSM2-MR CanESM5-CanOE CAMS-CSM1-0 CESM2 CESM2-WACCM CNRM-CM6-1 FGOALS-f3-L FIO-ESM-2-0 GFDL-ESM4 GISS-E2-1-G HadGEM3.GC31.LL HadGEM3.GC31.MM IPSL.CM6A.LR KACE.1.0.G MIROC-ES2L MPI-ESM1-2-HR MRI-ESM2-0	SSP1- 2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5	YZRB	Climatology+Hydrology+Glaciology	No

					NESM3 NorESM2.LM)				
Flood Increase and Drought Mitigation Under a Warming Climate in the Southern Tibetan Plateau	2023	JGR Atmospheres	China	No	28 GCMs	RCP 4.5 and RCP 8.5	YZRB (Nugexia, Nuxia, Lhasa, Rikaze)	Climatology+Hydrology+ Glaciology	No
Snowmelt Runoff in the Yarlung Zangbo River Basin and Runoff Change in the Future	2023	Remote Sensing	China	No	CMIP6 (BCBCC-CCS-MC2S-MR2, FGOALS-g3, MIROC6, NorESM2-LM, NorESM2-MM, CMNCoCrE-ESSM2, MPI-ESM1-2-HR, MPI-ESM1-2-LR, TaiESM1)	SSP1-2.6, SSP-4.5, SSP5-8.5	YZRB	Climatology+Hydrology+ Glaciology	No
					India				
Title	**Year**	**Journal Name**	**Correspondence Author Affiliation**	**Collaboration**	**Models/Dataset Used**	**Climate Scenarios**	**Location/ Geographical Area of Research**	**Focus of Study**	**Focus on Extreme Events**
Impact of climate change on flood characteristicsin Brahmaputra basin using a macro-scaledistributed hydrological model	2012	Journal of Earth System Science	India	No	PRECIS (RCM)	A2	Brahmaputra Basin Subansiri, Dibang, Siang, Jia Bhorali, Kopili, Noa Dehing, Lohit, Sankosh,	Climatology+Hydrology+ Flood	No

							Manas, Dhansiri		
Impact of climate change on floods in the Brahmaputra basin using CMIP5 decadal predictions	2015	Journal of Hydrology	India	Australia	CMIP5 (F-GOALS-g2, BCC-CSM1-1, IPSL-CM5A, CanCM4 and MRI-CGCM3)	**NA**	Kulsi, Kameng, Subansiri, Dihing and Siang	Climate+Flood	No
Analysis and trends of precipitation lapse rate and extreme indices overnorth Sikkim eastern Himalayas under CMIP5ESM-2M RCPs experiments	2015	Atmospheric Research	India	No	CMIP5 (ESM2M)	RCP 2.6, RCP 4.5, RCP 8.5	Teesta River Catchment	Climatology	Yes (Precipitation)
Changes in climate extremes by the use of CMIP5 coupled climatemodels over eastern Himalayas	2016	Environmental Earth Sciences	India	No	CMIP5 (CM2P1 and CM3ESM2M)	RCP 2.6, RCP 4.5, RCP 8.5	Teesta River Catchment	Climatology	Yes (Precipitation and Temperature)
Spatio-temporal heterogeneity and changes in extremeprecipitation over eastern Himalayan catchments India	2016	Stochastic Environmental Research and Risk Assessment	India	No	CMIP5 (ESM-2M)	RCP 2.6, RCP 4.5, RCP 8.5	Teesta	Climatology	Yes (Precipitation)
Analysis of the change in temperature trends in	2017	Theoretical and Applied Climatology	India	No	CMIP5 ESM2G	RCP2.6, RCP6.0, and RCP8.5	Subansiri	Climatology	No

Subansiri River basin for RCP scenarios using CMIP5 datasets									
Unsteady High Velocity Flood Flows and theDevelopment of Rating Curves in a HimalayanBasin under Climate Change Scenarios	2017	Journal of Hydrologic Engineering	India	No	CMIP5 (CM3)	RCP 2.6, RCP 4.5, RCP 8.5	Teesta	Climatology+Hydrology	No
Spatiotemporal and joint probability behavior of temperatureextremes over the Himalayan region under changing climate	2017	Theoretical and Applied Climatology	India	No	CMIP5 (ESM2G, CM3, ESM2M)	RCP 2.6, RCP 4.5, RCP 8.5	Teesta	Climatology	Yes (Temperature)
Future climate change impact evaluation on hydrologic processes in the Bharalu and Basistha basins using SWAT model	2018	Natural Hazards	India	No	GFDL-ESM2M	RCP 2.6 and RCP 8.5	Bharalu and Baisistha	Climatology+Hydrology	No
Index-based study of future precipitation changes over subansiri river	2019	Journal of Environmental Informatics	India	No	ESM2G, ESM2M, GFDL-2M3	RCP; 2.6, 4.5, 6.0, 8.5	Subansiri	Climatology	No

catchment under changing climate									
Projection of hydro-climatological changes over eastern Himalayan catchment by the evaluation of RegCM4 RCM and CMIP5 GCM models	2019	Hydrology Research	India	No	Reg CM4, ESM-2M, CM3, CM2P1	RCP 4.5 & RCP 8.5	Teesta	Climatology+Hydrology	No
ANN-SCS-based hybrid model in conjunction with GCM to evaluate the impact of climate change on the flow scenario of the river subansiri	2020	Journal of Water and Climate Change	India	No	HadCM3	A2	Subansiri	Climatology+Hydrology	No
Assessment of the changes in precipitation and temperature in Teesta River basin in Indian Himalayan Region under climate change	2020	Atmospheric Research	India	No	CNRM-CM5, CSIRO-BOM-ACCESS1-3, GFDL-CM3, GFDL-ESM2M, GFDL-2G (GOLD) [CMIP5]	RCP4.5 and RCP8.5	Teesta	Climatology+Hydrology	Yes (Precipitation and Temperature)
Assessment of Hydroclimatological Changes in Eastern Himalayan River Catchment of Northeast India	2021	Journal of Hydrologic Engineering	India	No	GFDL-ESM2G, GFDL-ESM2M, and GFDL-CM3	RCP2.6, RCP6.0, and RCP8.5	Subansiri	Climatology+Hydrology	No

Spatial prediction of landslide susceptibility using projected storm rainfall and land use in Himalayan region	2021	Bulletin of Engineering Geology and the Environment	India	No	CSIRO-MK3.6.0 and MIROC5	RCP; 2.6, 4.5, 6.0, 8.5	Upper Rangit River (Teesta Basin)	Climatology	No
Historical and projected precipitation extremes over Pare watershed in Arunachal Pradesh, India	2021	Applied Water Science	India	No	CORDEX RegCM4-4	RCP 4.5 & RCP 8.5	Pare watershed (River)	Climatology	Yes (Precipitation)
Sensitivity assessment of hydrologic processes in an eastern Himalayan watershed to potential climate change using RHESSYS	2023	Sustainable Water Resources Management	India	No	CMIP5 (CORDEX) ACCESS 1.0, CCSM 4, CNRM-CM5, MPI-ESM-LR, NorESMI-M	RCP 4.5 & RCP 8.5	Nuranang Watershed	Climatology+Hydrology	No
Analysis of non-parametric trend and climatic parameter homogeneity tests in a data-scarce region: a spatio-temporal perspective in the Tawang River basin, Eastern Himalayas	2023	Theoretical and Applied Climatology	India	No	11 GCM (NEX-GDDP) ACCESS1, BNU-ESM, CCSM4, CESM1-BGC, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, IPSL-	RCP 4.5 & RCP 8.5	Tawang Chu basin	Climatology	No

					CM5A-LR, IPSL-CM5A-LR				
Projected Discharge of Dudhnai River: A Tributary of the Brahmaputra River	2023	Journal of the Indian Society of Remote Sensing	India	No	CCSM4, CNRM-CM5, MPI-ESM-LR, and NorESM1-M (NEX-GDDP)	RCP 4.5 & RCP 8.5	Dudhnai River	Climatology+Hydrology	No
Trends in Temperature, Precipitation, Potential Evapotranspiration, and Water Availability across the Teesta River Basin under 1.5 and 2 °C Temperature Rise Scenarios of CMIP6, Atmosphere, 10.3390/atmos13060941, **13**, 6, (941), (2022).	2022	Atmosphere (India)	India	No	CMIP6 (CanESM, GFDL-ESM4, IPSL, CM6A-LR, MIROC6, MRI-ESM2.0)	SSP1-1.9 and SSP1-2.6	Teesta	Climatology	No
Copula-based probabilistic characterization of precipitation extremes over North Sikkim Himalaya	2018	Atmospheric Research	India	No	ESM2G, ESM2M and CM3	RCP2.6, RCP4.5 and RCP8.5	Teesta	Climatology	Yes (Precipitation)
					Bangladesh				
Title	**Year**	**Journal Name**	**Correspondence Author Affiliation**	**Collaboration**	**Models/Dataset Used**	**Climate Scenarios**	**Location/ Geographical Area of Research**	**Focus of Study**	**Focus on Extreme Events**

Risk-based evaluation for meeting future water demand of the Brahmaputra floodplain within Bangladesh	2010	Water Resources Management	Bangladesh	No	CCCma	A2 and B2	Jamuna	Climatology+water demand analysis	No
Multi-factor impact analysis of agricultural production in Bangladesh with climate change	2013	Global Environmental Change	USA	Bangladesh and Thailand	16 GCMs	A2 and B1	Lower Brahmaputra (GBM)	Climatology +Hydrology	No
A first look at the influence of anthropogenic climate change on the future delivery of fluvial sediment to the Ganges-Brahmaputra-Meghna delta	2015	Environmental Sciences: Processes and Impacts	UK	Bangladesh	HadRM3P	A1B	Lower Brahmaputra (GBM)	Climatology +Hydrology	No
Downscaling river discharge to assess the effects of climate change on cholera outbreaks in the Bengal Delta	2015	Climate Research	USA	Bangladesh and USA	HadCM3, GFDL, and ECHAM5	A1B and A2	Lower Brahmaputra (GBM)	Climatology +Hydrology+Public Health	No
Hydroclimatic sustainability assessment of changing climate on cholera in the Ganges-	2017	Advances in Water Resources	USA	No	HADCM3, ECHAM5, and GFDL	A1B and A2	Lower Brahmaputra (Ganga-Brahmaputra)	Climatology+Public Health	No

Brahmaputra basin									
South Asian river basins in a 1.5 °C warmer world	2019	Regional Environmental Change	Netherlands	Netherlands, Bangladesh and Nepal	8 GCMs (CMIP5)	RCP 4.5 and RCP 8.5	BRB (Indus, Ganges and Brahmaputra)	Climatology	Yes (Precipitation)
Application of Regional Climate Model Simulation and Flow Data for Assessing Future Water Availability in the River Jamuna	2011	INTERNATIONAL JOURNAL OF ENVIRONMENTAL SCIENCES	Bangladesh	Canada	PRECIS	A1B	Jamuna	Climatology +Hydrology	No
Impact of climate change on the stream flow of the lower Brahmaputra: trends in high and low flows based on discharge-weighted ensemble modelling	2011	Hydrology and Earth System Sciences Discussions	Netherlands	Italy and Netherlands	12 GCMs	A1B and A2	Lower Brahmaputra	Climatology +Hydrology	No
Impact of climate change on rainfall in NorthwesternBangladesh using multi-GCM ensembles	2013	International Journal of Climatology	India	No	15 GCMs	A1B,A2 and B1	Jamuneswari River (Part of Teesta Basin)	Climatology	No
A dynamic assessment of water scarcity	2014	Ecological Indicators	Italy	No	ECHAM5 and HadGEM	A1B	Lower Brahmaputra	Climatology+Water demand analysis	No

risk in the LowerBrahmaputra River Basin: An integrated approach									
Thresholds of hydrologic flow regime of a river and investigation of climate change impact – the case of the Lower Brahmaputra river Basin	2013	Climatic Change	Italy	Italy and Germany	MICRO, GFDL, GISS, CCCMA, CGCM, BCCR, HADGEM, NCAR, ECHAM, CSIRO, ECHO, and IPSL	A1B and A2	Lower Brahmaputra	Climatology+Hydrology	No
Bhutan									
Title	**Year**	**Journal Name**	**Correspondence Author Affiliation**	**Collaboration**	**Models/Dataset Used**	**Climate Scenarios**	**Location/ Geographical Area of Research**	**Focus of Study**	**Focus on Extreme Events**
Water Resources Under Climate Change in HimalayanBasins	2015	Water Resources Management	Norway	Norway, India	RCM (RCA4 and REMO)	RCP2.6, RCP4.5 and RCP8.5	Chamkhar Chu	Climate, Glaciology and Hydrology	No
Assessment of climate change impact on hydrology of a transboundary river of Bhutan and India	2021	Journal of Water and Climate Change	Thailand	Bhutan	ACCESS, CNRM-CM5 and MPI-ESM-LR	RCP 4.5 and RCP 8.5	Raidak River	Climatology + Hydrology	Yes (Precipitation and Temperature)
Comparative Studies									
Title	**Year**	**Journal Name**	**Correspondence Author Affiliation**	**Collaboration**	**Models/Dataset Used**	**Climate Scenarios**	**Location/ Geographical Area of Research**	**Focus of Study**	**Focus on Extreme Events**

On the Suitability of GCM Runoff Fields for River Discharge Modeling:A Case Study Using Model Output from HadGEM2 and ECHAM5	2011	Journal of Hydrometeo rology	The Netherland s	No	HadGEM2 and ECHAM5	NA	Amazon,Bra hmaputra, Lena, Mississippi, Rhine, and Zambezi	Climatology+Hydrology	No
Regional climate projections in two alpine river basins:Upper Danube and Upper Brahmaputra	2011	Advances in Science and Research	Germany	Germany , China, India, Austria	RCM (COSMO-CLM)	A1B, B1 and A2	Upper Danube and Upper Brahmaputra	Climatology	Yes (Precipit ation and Tempera ture)
Global river discharge and water temperature under climate change	2012	Global Environmen t Change	The Netherland s	Netherla nds, USA, Norway, Australia	CNCM3, ECHAM, IPSL	A2, B1	25 rivers (Includes Ganges-Brahmaputra)	Climatology+Hydrology	No
Regional projections of North Indian climate for adaptation studies	2012	Science of the Total Environmen t	U.K.	UK, Japan, Netherla nds, Switzerla nd, Germany	HighNoon Project [2 GCMs (HadCM3 & ECHAM5) and (REMO & HadRM3)]	A1B	Ganges-Brahmaputra	Climatology	No
Future water resources for food production infive South Asian river basinsandpotenti al for	2013	Science of the Total Environmen t	The Netherland s	Netherla nds, UK, Germany , Austria	HadRM3 and REMO	A1B	Indus, Ganges, Brahmaputra , Godavari and Krishna	Climatology+Adaptation for Food Production	No

adaptation—A modeling study									
Hydrological cycle over South and Southeast Asian river basins as simulated by PCMDI/CMIP3 experiments	2013	Earth System Dynamics	Germany	Germany and UK	PCMDI/CMIP3 (13 GCMs)	A1B	Indus, Ganges, Brahmaputra and Mekong	Climatology+Hydrology	No
Projections of the Ganges–Brahmaputra precipitation—Downscaledfrom GCM predictors	2014	Journal of Hydrology	USA	No	CMIP3 (CGCM3.1)	A1B and A2	Ganges-Brahmaputra	Climatology	No
Seasonality of the hydrological cycle in major South and Southeast Asian river basins as simulated by PCMDI/CMIP3 experiments	2014	Earth System Dynamics	Germany	Germany and UK	PCMDI/CMIP3 (13 GCMs)	A1B	Indus, Ganges, Brahmaputra and Mekong	Climatology+Hydrology	No
Selecting representative climate models for climate changeimpact studies: an advanced envelope-based selection approach	2015	International Journal of Climatology	The Netherlands	The Netherlands and Nepal	CMIP5 (14 GCMs)	RCP 4.5 and RCP 8.5	Indus, Ganges and Brahmaputra	Climatology	Yes (Precipitation and Temperature)
South Asia river-flow projections and their	2015	Hydrology and Earth	UK	No	HighNoon Project [2 GCMs	A1B	8 Rivers of South Asia (Includes	Climatology	No

implicationsfor water resources		System Sciences			(HadCM3 & ECHAM5) and 1 RCM (HadRM3)]		Brahmaputra)		
Future changes in hydro-climatic extremes in the Upper Indus, Ganges, and Brahmaputra River basins	2017	PLOS ONE	The Netherland s	The Netherla nds and Nepal	8 GCMs	RCP 4.5 and RCP 8.5	Indus, Ganges and Brahmaputra	Climatology	Yes (Precipit ation)
Climate change vs. socio-economic development: understanding the future South Asian water gap	2018	Hydrology and Earth System Sciences	The Netherland s	The Netherla nds and Nepal	8 GCMs	RCP SSP1-4.5 and RCP SSP3-8.5	Indus, Ganges, and Brahmaputra	Climatology+Socioecono mic study	No
A framework estimating cumulative impact of damming on downstream water availability	2019	Journal of Hydrology	China	China, Australia and Austria	CMIP5 (28-29 GCMs)	RCP 4.5 and RCP 8.5	BRB	Climatology+Glaciology+ Hydrology+Dam Analysis	No
Modelling climate change impacts on the Brahmaputra streamflow resulting from changes in snowpack attributes	2021	Journal of Hydrology	Australia	No	CMIP5 (4 GCMs) and CORDEX (3 RCMs)	RCP 8.5	YZBR, Yangtze and Yellow	Climatology+Glaciology+ Hydrology	No
Climate Change Impacts on the Hydrology of the	2023	Climate (MDPI)	Nepal and Australia	Canada, Nepal, Australia and	GISS-E2-R, IPSL-CM5A-LR-, IPSL-CM5A-LR-,	RCP 4.5 and RCP 8.5	BRB	Climatology+Hydrology	No

Brahmaputra River Basin				Bangladesh	CanESM2, GFDL-ESM2G, IPSL-CM5A-LR, CSIRO-Mk3-6-0, CanESM2				
Climate change impact assessment of water resources of India	2011	Current Science	India	No	RCM PRECIS	A1B	26 river basins of India (includes Brahmaputra)	Climatology+Hydrology	No
Hydrological response to future climate changes for the major upstream river basins in the Tibetan Plateau	2016	Global and Planetary Change	China	China, Sweden and South Korea	CMIP5 (20 GCMs)	RCP 2.6, RCP 4.5, RCP 8.5	Upstream of Yellow, Yangtze, Mekong, Salween, Brahmaputra and Indus	Climatology+Hydrology+ Glaciology	No
Assessing responses of hydrological processes to climate change over the southeastern Tibetan Plateau based on resampling of future climate scenarios	2019	Science of the Total Environment	China	No	CMIP5 (18 GCMs)	RCP 2.6, RCP 8.5	UYZBR and upper Lancang River	Climatology + Hydrology	No
Projecting climate change impacts on hydrological processes on the Tibetan Plateau	2019	Journal of Hydrology	China	No	CMIP5(1. CSIRO-MK3.6.0 2 HadGEM2-ES 3 MIROC5	RCP 2.6, RCP 4.5	Yellow, Yangtze, Mekong, Salween, and	Climatology+Hydrology+ Glaciology	No

with model calibration against the glacier inventory data and observed streamflow					4 MIROC-ESM 5 MIROC-ESM-CHEM)		Brahmaputra rivers		
Impact of Climate Change on Runoff of the Major River Basins of India Using Global Circulation Model (HadCM3) Projected Data	2011	Journal of the Indian Society of Remote Sensing	India	No	HadCM3	A2	17 Indian river basins (includes Brahmaputra)	Climatology + Hydrology	No
The impact of climate change on global river flow in HadGEM1 simulations	2006	Atmospheric Science Letters	United Kingdom	No	HadGEM1	A1B and A2	10 rivers (Includes Brahmaputra)	Climatology +Hydrology	No
Impacts of climate change and socio-economic scenarios on flow and water quality of the Ganges, Brahmaputra and Meghna (GBM) river systems: Low flow and flood statistics	2015	Environmental Science: Processes and Impacts	UK	UK, India, USA and Bangladesh	HadCM3	A1B	Brahmaputra (GBM)	Climatology +Hydrology+Socioeconomic Model	No
Impacts on river systems under 2 °C warming:	2017	Climate Services	Bangladesh	No	RCM (SMHI and CNRM)	RCP 8.5	Brahmaputra (GBM)	Climatology +Hydrology	No

Bangladesh Case Study									
Future floods in Bangladesh under 1.5°C, 2°C, and 4°C global warming scenarios	2018	Journal of Hydrologic Engineering	Banglades h	Banglade sh and Italy	EC-Earth3-HR and HadGEM3	Specific Warming Levels 1.5°C, 2°C, and 4°C	Brahmaputra (GBM)	Climatology +Hydrology+Flood Forecasting	No
Enhanced flood risk with 1.5 °c global warming in the Ganges-Brahmaputra-Meghna basin	2019	Environmen tal Research Letters	Banglades h	Banglade sh and UK	8 GCMs	Specific Warming Levels 1.5°C	Brahmaputra (GBM)	Climatology +Hydrology+Flood Forecasting	Yes (Precipit ation)
Climate impact emergence and flood peak synchronization projections in the Ganges, Brahmaputra and Meghna basins under CMIP5 and CMIP6 scenarios	2022	Environmen tal Research Letters	Germany	Germany ,UK and Banglade sh	CMIP5 and CMIP6	RCP 2.6 and RCP 8.5	Brahmaputra (GBM)	Climatology +Hydrology	No
Climate change and global water resources	1999	Global Environmen tal Change	UK	No	HadCM2 and HadCM3	IS92a and SA90	42 rivers (includes BRB)	Climatology+Hydrology	No
Impact of climate change on water resources in India	2018	Journal of Environmen tal En-gineering	India	India and USA	ESM2M	RCP 8.5	Narmada and Teesta	Climatology+Hydrology	No
Model study of the impacts of future climate change on the hydrology of Ganges–	2015	Hydrol. Earth Syst. Sci.	Japan	Japan and Singapor e	MRI-AGCM3.2S, MIROC5, MIROC-ESM, MRI-CGCM3, HadGEM2-ES	A1B (MRI-AGCM3.2 S) and RCP 8.5 (MIROC5,	GBM (Includes lower Brahmaputra)	Climatology+Hydrology	No

Brahmaputra–Meghna basin Hydrol. Earth Syst. Sci. 19 747–70						MIROC-ESM, MRI-CGCM3, HadGEM2-ES)			
Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation	2014	Nature Climate Change	The Netherlands	The Netherlands and Nepal	RCP 4.5 (GISS-E2-R IPSL-CM5A-LR CCSM4 CanESM2) and RCP 8.5 (GFDL-ESM2G IPSL-CM5A-LR CSIRO-Mk3-6-0 CanESM2)	RCP 4.5 and RCP 8.5	upper Ganges, upper Brahmaputra, upper Salween, upper Mekong and upper Indus	Climatology + Hydrology + Glaciology	No
Basin level studies									
Title	**Year**	**Journal Name**	**Correspondence Author Affiliation**	**Collaboration**	**Models/Dataset Used**	**Climate Scenarios**	**Location/ Geographical Area of Research**	**Focus of Study**	**Focus on Extreme Events**
Historical trends and future predictions of climate variability in the Brahmaputra basin	2008	International Journal of Climatology	The Netherlands	The Netherlands	6 GCMs (CCSR, CGCM2, CSIRO-Mk2, ECHAM4/OPYC3, GFDL-R30, HADCM3)	A2 and B2	BRB	Climatology	No
Climate change over the Yarlung Zangbo-Brahmaputra River Basin in the 21st century as simulated by a high resolution	2011	Quarternary International	China	China and Italy	RCM (RegCM3) and GCM(MIROC3.2_hires)	A1B	BRB	Climatology	No

regional climate model									
Assessing the impacts of climate and land use and land cover change on the freshwater availability in the Brahmaputra River basin	2014	Journal of Hydrology: Regional Studies	USA	USA	CMIP5 (CGCM3.1)	A1B and A2	BRB	Climatology+Hydrology	No
Assessment of Future Water Scarcity at Different Spatialand Temporal Scales of the Brahmaputra River Basin	2014	Water Resource Managemen t	Italy	Italy and Netherla nds	3 GCMs (ECHAM5, HadGEM1, HadGEM2)	A1B and A2	BRB (BRB and Lower BRB)	Climatology + Water demand analysis	No
Future Streamflow of Brahmaputra River Basin underSynthetic Climate Change Scenarios	2016	Journal of Hydrologic Engineering	Canada	Banglade sh and Canada	9 GCMs	RCP 2.6, RCP 4.5, RCP 6, RCP 8.5	BRB	Climatology+Hydrology	No
The future nexus of the Brahmaputra River Basin: Climate, water, energy and food trajectories	2016	Global Environmen tal Change	USA	No	37 GCMs	RCP 2.6, RCP4.5, RCP 6.0 and RCP 8.5	BRB	Climatology+Hydrology+ Socioeconomic Study	No
Extreme flows and water availability of the Brahmaputra	2017	Climatic Change	Banglades h	Banglade sh and Italy	CORDEX-SA (11 Projections)	RCP 8.5	BRB	Climatology +Hydrology+Flood Forecasting	Yes (Precipit ation)

River under 1.5 and 2 °C global warming scenarios									
Impact of high-end climate change on floods and low flows of the brahmaputra river	2017	Journal of Hydrologic Engineering	Bangladesh	Bangladesh and Italy	CORDEX-SA (11 Projections)	RCP 8.5	BRB	Climatology +Hydrology+Flood Forecasting	No
Hydrological response to climate change of the brahmaputra basin using CMIP5 general circulation model ensemble	2017	Journal of Water and Climate Change	Bangladesh	No	11 RCMs CORDEX-SA	RCP 8.5	BRB	Climatology +Hydrology	No
Projected climate change impacts on future streamflow of the Yarlung Tsangpo-Brahmaputra River	2019	Global and Planetary Change	China	China and Saudi Arabia	CORDEX (HadGEM3-RA (RCM1) RegCM (RCM2) SNU-MM5 (RCM3) SNU-WRF (RCM4) YSU-RSM (RCM5))	RCP 4.5 and RCP 8.5	BRB	Climatology + Hydrology	No
Changes in flow and sediment load of poorly gauged Brahmaputra river basin under an extreme climate scenario	2021	Journal of Water and Climate Change	Bangladesh	Bangladesh	CORDEX-SA	RCP 8.5	BRB	Climatology +Hydrology	No

Multi-model ensemble projection of mean and extreme streamflow of brahmaputra river basin under the impact of climate change	2021	Journal of Water and Climate Change	Bangladesh	USA, Bangladesh and Canada	BCC-CSM1.1, BCC-CSM1.1(m), GISS-E2-H, GISS-E2-R, HadGEM2-ES, MIROC-ESM, MIROC-ESM-CHEM, and MRI-CGCM3.	RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5	BRB	Climatology +Hydrology	Yes (Precipitation)
Future climate and its impact on streamflow: a case study of the Brahmaputra river basin	2021	Modelling Earth Systems and Environment	India	No	CMIP5 (GFDL-ESM2M, HadGEM2-CC, and IPSL-CM5-1R)	RCP 4.5 and RCP 8.5	BRB	Climatology + Hydrology	No

Annexure I Table 1: List of publications on climate change projections over BRB with their corresponding details

Annexure II Questionnaires for stakeholder interaction (Objective 3)

Questionnaires for Decision makers

1. What is your perception of Climate Change?
2. Do you think it is important to include climate change scenarios in the hydropower decision-making process? If yes, how do you want to include these CC projections? (there are questions of data availability)
3. Climate change is an unpredictable subject, how resilient are the existing hydropower dams to the impacts of climate change?
4. Are there concerns if extreme variation of precipitation and temperature is realized in the upstream of the reservoir?
5. Do you foresee any downstream impacts (be it social or ecological) if there is a variation in precipitation upstream to the hydropower reservoir?
6. Do you think there is enough scientific knowledge for the Brahmaputra basin to understand climate change?
7. How are the academic/scientific knowledge on climate change incorporated in the hydropower decision making process?
8. How important is it to develop a hydropower project with the consent from its neighbouring countries?

Questionnaires for Academicians/Scientists

1. How and What kind of communication takes place between the academicians and hydropower decision makers?
2. Do you think there is enough basin level scientific knowledge for the understanding of climate change?
3. How do you think are the academic/scientific knowledge on climate change incorporated in the hydropower decision making process?
4. What could be the impacts (be it social or ecological or with respect to power generation) if there is a variation in precipitation and temperature upstream to the hydropower reservoir?
5. Since Brahmaputra is a transboundary river, how necessary is it for all the countries sharing the basin to academically collaborate for a better understanding of the basin?
6. Do you think there is an existing data gap among the riparian countries sharing BRB? If yes, does it affect the hydropower development?

List of publications

Conference proceedings

1. Investigating climate change on Brahmaputra river basin using downscaled global model data. International Conference on Climate Change, Biodiversity and Sustainable Agriculture (ICCBSA-2018)- (Rupam Bhaduri, Koteshwar Rao Kundenti, Vinodh Buri, Sudhir Sabade)

2. Climate Change uncertainties over Brahmaputra River Basin: A way forward to decision making. 1st International Conference on Sustainable Water Management under National Hydrology Project (NHP)-2018 (Rupam Bhaduri, Anamika Barua)

3. Understanding the inclusion of climate change as a parameter in the hydropower decision making over Brahmaputra River Basin WATER 2020 (Rupam Bhaduri, Vinodh Buri Anamika Barua, Koteshwar Rao Kundenti, Sudhir Sabade, Arup Kumar Sarma)

Journal proceedings

1. Ignorance is not a bliss? A systematic mapping of climate change scenarios for the Brahmaputra Basin (Under peer review)- (Rupam Bhaduri, Sumit Vij, Anamika Barua, Arup Kumar Sarma) *Climate and Development (Taylor & Francis)* Submission ID 242512834

2. Understanding future climate extremes over Brahmaputra basin using Globally downscaled NEX-GDDP model (Published)- (Rupam Bhaduri, Vinodh Buri Anamika Barua, Koteshwar Rao Kundenti, Sudhir Sabade, Arup Kumar Sarma) (Received revisions and accepted by two reviewers)- *Water Conservation, Science and Engineering (Springer*) Submission ID d35579f2-3ed4-40fb-b6be-df7f617f628c

3. Bridging Gaps in Hydropower Decision-Making: Embracing Open Data, Collaboration, and Climate Change Considerations in the Brahmaputra River Basin (Manuscript under preparation)- *International Journal of Water Resources Development (Taylor & Francis)*