SPRINGER NATURE
Sustainable Development Goals Series

SDG: **13**
Climate Action

Kaushal Kumar Sharma
Sanjeev Sharma
Vijendra Kumar Pandey
Rupendra Singh *Editors*

Climate Change and Human Adaptation in India

Sustainability and Public Policy

Springer

Sustainable Development Goals Series

The **Sustainable Development Goals Series** is Springer Nature's inaugural cross-imprint book series that addresses and supports the United Nations' seventeen Sustainable Development Goals. The series fosters comprehensive research focused on these global targets and endeavours to address some of society's greatest grand challenges. The SDGs are inherently multidisciplinary, and they bring people working across different fields together and working towards a common goal. In this spirit, the Sustainable Development Goals series is the first at Springer Nature to publish books under both the Springer and Palgrave Macmillan imprints, bringing the strengths of our imprints together.

The Sustainable Development Goals Series is organized into eighteen subseries: one subseries based around each of the seventeen respective Sustainable Development Goals, and an eighteenth subseries, "Connecting the Goals", which serves as a home for volumes addressing multiple goals or studying the SDGs as a whole. Each subseries is guided by an expert Subseries Advisor with years or decades of experience studying and addressing core components of their respective Goal.

The SDG Series has a remit as broad as the SDGs themselves, and contributions are welcome from scientists, academics, policymakers, and researchers working in fields related to any of the seventeen goals. If you are interested in contributing a monograph or curated volume to the series, please contact the Publishers: Zachary Romano [Springer; zachary.romano@springer.com] and Rachael Ballard [Palgrave Macmillan; rachael.ballard@palgrave.com].

Kaushal Kumar Sharma
Sanjeev Sharma
Vijendra Kumar Pandey
Rupendra Singh
Editors

Climate Change and Human Adaptation in India

Sustainability and Public Policy

Springer

Editors
Kaushal Kumar Sharma
Centre for the Study of Regional
Development, SSS III
Jawaharlal Nehru University
New Delhi, India

Sanjeev Sharma
Center for the Study of Regional
Development
Jawaharlal Nehru University
New Delhi, India

Vijendra Kumar Pandey
Department of Geography
Kirori Mal College
University of Delhi
Delhi, India

Rupendra Singh
School of Social Sciences
Jawaharlal Nehru University
New Delhi, India

ISSN 2523-3084 ISSN 2523-3092 (electronic)
Sustainable Development Goals Series
ISBN 978-3-031-55820-7 ISBN 978-3-031-55821-4 (eBook)
https://doi.org/10.1007/978-3-031-55821-4

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2024

Color wheel and icons: From https://www.un.org/sustainabledevelopment
Copyright © 2020 United Nations. Used with the permission of the United Nations.

The content of this publication has not been approved by the United Nations and does not reflect the views of the United Nations or its officials or Member States.

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Paper in this product is recyclable.

Dedicated to Late Dr. Arun Kumar Tripathi (1977–2022).

This book stands as a testament to your vision, your passion, and your unwavering dedication. You may no longer walk among us, but your presence is palpable in every sentence, reminding us of your profound impact on our lives and on this world. You walked the extra mile to conduct research amongst the Himalayan villages where you left an indelible mark on the lives of the people. Your perseverance and patience as mentor are deeply remembered by the scholars as they try to follow in your footsteps to carry forward the unfinished tasks.

Though you are gone, your legacy lives on through these pages. May they serve as a beacon of inspiration to all who seek knowledge, just as you inspired us with your boundless creativity and wisdom.

In eternal gratitude and remembrance.

Preface

Climate change is a growing field, which has a crucial impact on human lives and livelihoods in the last two decades. The incidences of extreme events have increased, and there is uncertainty to predict its recurrence beyond the scientific investigation. The wrath of the climatic extremities is unbearable by the marginalized communities, particularly in the developing countries. This book is aimed to provide a comprehensive view of climate changes impact on the human lives and livelihoods, and a wider mitigation framework adopted through the indigenous knowledge and public policy. The communities have a vast amount of knowledge in the form of indigenous practices to mitigate the impact of the climatic variability and adaptation strategies through the times. The traditional knowledge can provide a breakthrough for the sustainable and effective medium of adaptations, particularly for the marginalized communities. Nevertheless, very little is known and documented in the written and other medium, which can be used by the inheritor into adaptation of extreme climatic events and long-term changes.

This book provides a framework on the understanding of climate change and its impact on human beings and environment and a policy initiative to mitigation. It requires a background knowledge of the subject in a pragmatic way to differentiate between the climatic fluctuations and a well-defined trend of climate change, which will have a severe impact. Rapid melting of glaciers, erratic precipitation pattern, heat and cold waves pose a serious challenge to survival and sustainability of human beings.

This book is divided into three parts, each covering a unique dimension of the climatic adversity with 20 chapters. The first part focusses on assessing scientific evidences of climate changes and its variability. The monitoring of cryosphere is best way to perceive even small changes in climatic variables. The changes in the atmospheric compositions, pattern and variability of precipitation were some key areas that have been covered in the first part of this book. The second part covers the topics of the climate-induced vulnerability: approaches towards sustainable livelihood. This part deals with indigenous community approaches to mitigate the impacts on the resources and their livelihood. Climatic dynamics not only affect the natural resources, it also aggravates the environment and increase frequency of natural calamities, posing severe threats to lives and livelihood sustainability. Some chapters also deal with the methods used in preserving rare floral and faunal species in the higher Himalayas. The third part of this book is dedicated to adaptation policy and governance. This part critically presents the public policy framework that has been implemented to contain the risk of climate change and enhance the capacity and resilience of communities. This part also serves as a concluding remark and presents a framework for the holistic approach of climate change adaptations.

New Delhi, India Kaushal Kumar Sharma
New Delhi, India Sanjeev Sharma
Delhi, India Vijendra Kumar Pandey
New Delhi, India Rupendra Singh

Acknowledgments

This book arose from the International Conference on “Climate Change, Natural Hazards and Sustainable Livelihoods” during March 12–13, 2022 organized by the Department of Geography, Kirori Mal College, University of Delhi, Delhi. The conference was partially funded by the ICSSR Northern Regional Centre (NRC), New Delhi (NRC-ICSSR/SEM-CONF/2021-22) and organized in collaboration with Jawaharlal Nehru University, New Delhi, India. The editors of this book would like to acknowledge all the participants, researchers, academicians, scientists and policy planners for participation and deliberation in that International Conference. The editors are highly grateful to the contributing authors of the chapters in this book along with reviewers/experts for their valuable and critical comments for improvements of the manuscripts. We are also grateful to late Dr. Arun Kumar Tripathi, Associate Professor, Kirori Mal College, University of Delhi, who kernelled the idea of this book, but unfortunately, he left us during the completion of this academic Journey. On behalf of the Editorial Team, we are grateful to Prof. Dinesh Khattar, Principal, Kirori Mal College, for his continuous support and encouragement. We would like to thank Dr. Suraj Mal for his scholarly support and guidance for preparation of the proposal. Last but not least, this project would not have been possible without the continuous support and encouragement of the Springer Nature Publishers since the inception of the development of the book proposal. The Editorial Team highly appreciates and is grateful to the Publisher Springer Nature and especially Mr Zachary Romano, Senior Publishing Editor, Geography and Sustainability Research, Springer; Mr Henry Rodger, Project Coordinator; and Ms Tina Silva, Production Editor.

About the Editors

Kaushal Kumar Sharma is Professor of Geography in the Centre for the Study of Regional Development and the Dean of the School of Social Sciences at Jawaharlal Nehru University, New Delhi. His areas of specialization include regional development planning, water resources management, disaster risk reduction, landslides and applied physical geography. Previously, he served as Associate Professor in the Department of Geography at Kirori Mal College, University of Delhi, Delhi. With over four decades of teaching experience at the undergraduate, postgraduate, and research levels, he has led numerous research projects funded by the Department of Science and Technology, Ministry of Science and Technology, Government of India; Planning Commission; University Grant Commission; and THDC-SEVA.

His primary research focuses on landslide hazard and risk assessment, the impact of climate change on communities, water resource management and rural development. Dr. Sharma has successfully implemented several action-based research projects for rural transformation in the Himalayas, funded by SEVA-THDC. This project stands as an exemplary effort by an academician to improve the lives of communities residing in remote areas. He has authored numerous books, research papers in leading journals and book chapters.

Sanjeev Sharma is currently working as Associate Professor in the Centre for Study of Regional Development, School of Social Science, Jawaharlal Nehru University New Delhi, India, since 2017. Over the past one and half decades, he has worked in different academic and research institute in India, viz. Dr. Ambedkar International Centre, MoSJE, Govt. of India, Dr. H.S. Gour Central University of Sagar (M.P.), IISER, Mohali, WWF-India and G. B. Pant National Institute of Himalayan Environment (NIHE). He has been worked in the higher altitude region of western Himalaya on various society-nature and environmental issues. He has developed many conservations model for resource management and sustainability for natural resource conservation and socio-economic transformation in the western Himalaya. His work is extensively focused on field-based applied research with local community to know the grassroot-level issues and develop model other related stakeholders. He has more than 50 international and national research publications to his credit in journals, book chapters, proceedings, popular articles, etc. He has completed and currently working on Research Project funding from ICSSR, ONGC, THDC and Dept. of Wildlife Protection, Jammu and Kashmir, etc.

Vijendra Kumar Pandey is currently serving as Assistant Professor in the Department of Geography at Kirori Mal College, University of Delhi, Delhi. He holds a Master's and Ph.D. in Geography from the Centre for the Study of Regional Development, Jawaharlal Nehru University, New Delhi. His areas of specialization encompass geomorphology, landslide modeling, geo-chronology, climatic variability and adaptations, natural hazards, remote sensing and physical geography. Dr. Pandey is actively involved in a research project focused on climate change adaptations in the central Himalayan region, exploring indigenous approaches to climatic resilience. He has authored more than 15 research papers in leading journals and contributed 9 chapters to edited books, covering topics such as landslide susceptibility and risk assessment, climate change adaptations and governance.

Rupendra Singh is working at the School of Social Sciences, Jawaharlal Nehru University, New Delhi. He has completed his Master's from the Department of Geography, University of Allahabad, Prayagraj, UP, and Ph.D. in Environmental Science from the Department of Environmental Science, School of Basic Sciences and Research, Sharda University, Greater Noida, UP. His field of specialization is geomorphology, natural hazards, Himalayan glaciers, remote sensing and physical geography. He has published 13 research papers in the prestigious, high-impact, Scopus-indexed international journals and co-authored a book published by Space Application Centre, Indian Space Research Organisation (SAC-ISRO) Ahmedabad, Gujarat, India and 1 chapter in the edited books.

Contents

Part I Proxy Evidences of Climate Change

Part II Climate-Induced Vulnerability: Approaches Towards Sustainable Livelihood

Part III Policy and Governance

Part I

Proxy Evidences of Climate Change

Glaciological Study and Climate Change in Indian Perspective

Promila Bhardwaj, Rupendra Singh,
and Syed Umer Latief

1 Introduction

The description of glaciers can be traced back to the eleventh-century literature of Iceland. It was before 500 years that Scheuchzer in 1723 (Hutter & Gross, 2019) put forward the theory of glacier movement, according to which water enters the crevasses and freezes, which causes the ice to move down the hill. By the mid-1700s, gravity was recognized as the cause of motion which can be seen in the work of Altman in 1751 (Singh, 2020). The idea that ice cover had been more extensive came first in 1815 in the writings of Swiss guide Perraudin and later by a Swiss engineer J. Vinetz 1829 (Singh, 2020) who also opined that glaciers had once been more extensive than what they were during his lifetime. His observations inspired Jean de Charpenlier to begin a field study on glaciers. In 1841 Jean de Charpenlier presented his results to the Swiss Naturalist Louis Agassiz (considered to be the father of glaciology) who developed the first comprehensive theory of glaciations based on the Principle of Uniformitarianism. The term ice age was coined by Schimper in 1837 (Fairbridge, 1987).

Glacial studies in the Himalayas started in the late nineteenth century with the snout measurement of a few glaciers. Geologists and naturalists in British India took interest in the glacial theory as proposed by Agassiz. As a consequence, many papers describing the glacier geology and geomorphology were published. The modern scientific study of Himalayan glaciers started in 1810 when Raper and Webb, went to locate the Bhagirathi River Valley, and marked the position of the snout of Gangotri Glacier. A glacier was discovered in Kumoun Himalayas by Madden in 1847 which was named Pindari by the explorer. Subsequently, the geologists of the Geological Survey of India reported various glaciers from the Hindukush – Himalayan region. Blanford published his notes and observations on the Himalayas during the years 1873, 1877, and 1891. The other earlier notable studies on Himalayan glaciers in the nineteenth century were done by Cunninham (1848). The fluctuation records of Himalayan and Trans-Himalayan Glaciers date back to about 200 years. The movement of the glacier termini of Chong Kumdan was studied in 1812 (Vigne, 1842; Ullah, 1843). The fluctuation of 34 glaciers of Trans-Himalayas was documented by Mason (1930) using historical records, notes, and photographs. Out of these

P. Bhardwaj
Department of Commerce, Dyal Singh Evening College, Delhi University, New Delhi, India

R. Singh (✉)
School of Social Sciences, Jawaharlal Nehru University, New Delhi, India

S. U. Latief
Department of Geography, Government Degree College Magam, Budgam, Jammu Kashmir (UT), India

K. K. Sharma et al. (eds.), *Climate Change and Human Adaptation in India*, Sustainable Development Goals Series, https://doi.org/10.1007/978-3-031-55821-4_1

34 glaciers, the records of 21 glaciers were summarized by him and noted that distinguishable variations were displayed in their fluctuations in several records. Their study also indicated that during the period from 1900 to 1910, most of the glaciers, for which records were available, showed advancement, whereas during the period from 1910 to 1920 the majority were retreating. Tewari (1971), while studying the Himalayan and Trans-Himalayan glaciers tabulated the fluctuation records of 17 glaciers and concluded that glaciers in the Himalayas were retreating in general, while in Trans-Himalayas some glaciers showed unexplained cyclic fluctuations.

The earliest record in 1780 AD, observations of glaciers in the Himalayas documented significant events, such as floods caused by the Kumdan glaciers in Ladakh's upper Shyok valley. The mid-nineteenth century saw the publication of sketches of glacier fronts, including the Rimo glacier, Kumdan Glaciers, and Sonamarg Glacier in Jammu-Kashmir. Additionally, a photograph of the Gangotri Glacier's snout, known as 'Cow's mouth' (Gaumukh), was featured. The Geological Survey of India recorded a detailed report on the Machoi Glacier in Jammu and Kashmir in 1895, marking one of the earliest publications on Indian glaciers. Over the past 150 years, glacier studies in the Himalayas have evolved from simple front monitoring to more comprehensive and advanced approaches, reflecting a holistic understanding of these natural phenomena for the glaciological studies, and the Indian Government is supporting through the research grants.

2 Latest Technology in Glaciological Studies

The remote sensing technique has found well-established applications in glacier studies, particularly in glacier mapping, as extensively discussed by Della Ventura et al. in 1987. One effective method involves creating a false colour composite (FCC) from three bands in the visible and near-infrared regions. This approach has proven successful in mapping various glacier features, including glacier boundaries, snow/equilibrium lines, accumulation, and ablation areas, as detailed by Ostrem in 1975. The ability to map these areas on satellite images is facilitated by the substantial differences in spectral reflectance between glacier and non-glacier regions. Spectral reflectance values obtained from both field and satellite observations indicate that the accumulation area, covered by a snowpack, exhibits high reflectance in bands 2, 3, and 4 in Landsat-Thematic Mapper (TM) and Indian Remote Sensing Satellite (IRS), resulting in a white appearance in the FCC. Conversely, in the ablation area where ice is exposed on the surface, reflectance in bands 2 and 3 is higher than non-glacial features but lower than vegetation in band 4. This distinction imparts a blue-green tone to the FCC, as highlighted by studies such as Hall et al. in 1988 and Dozier in 1984. The unique spectral characteristics observed in these different areas make it feasible to effectively differentiate between glacial and non-glacial features using remote sensing techniques.

The studies mentioned provide valuable insights into glacier dynamics and the impact of climate change on glacier systems:

Wangensteen et al. (2005) demonstrated the calculation of "glacier velocities" on Svalbard using Digital Elevation Models (DEMs) and height-differentiated tandem Interferometric Synthetic Aperture Radar (InSAR) data. Their approach involved the utilization of modules within ESRI's ArcGIS software. They developed a semi-automatic algorithm to calculate glacier velocities in the flow direction, resulting in maps that illustrate the velocity fields for the glaciers. Khalsa et al. (2004) investigated space-based observations of glacier parameters in conjunction with historical glaciological data to predict changes in ice extent and volume for the Ak-Shirak Range in the interior Tien Shan of Central Asia. They employed ASTER data and traditional glaciological measurements to estimate the response of glacier systems to changes in climate, particularly expressed in the equilibrium line altitude.

Kaser et al. (2004) introduced a novel concept for studying the retreat of Kilimanjaro's glaciers based on the physical understanding of glacier-climate interactions. They proposed that a significant drop in humidity at the end of the nineteenth century, leading to a less humid atmosphere, could be a probable factor contributing to the glacial retreat on Kilimanjaro.

Paul (2002) conducted an analysis of the trend in area change for 235 glaciers in Tyrol, Austria, between 1969, 1985, and 1992. Utilizing Landsat Thematic Mapper (TM) imagery and data from the Austrian glacier inventory, he observed a significant shrinkage of glaciers with areas less than 1 km^2, amounting to approximately −35% during the period 1969–1992. The total glacial area loss was about 43 km^2, representing approximately −18.6% of the total area (230.5 km^2). Notably, smaller glaciers (less than 1 km^2) contributed 59% to the overall loss in glacial area.

These studies collectively contribute to our understanding of glacier dynamics, climate change impacts on glaciers, and the importance of combining traditional glaciological methods with advanced remote sensing technologies.

Carrara and Rampini (2002) described a systematic study of thematic maps for change detection in glacier dynamic studies. Schaper and Seidel (2000) presented runoff simulations (SRM + G model) for snow and ice melt with the help of multispectral remote sensing data. He also presented climate change simulations for the scenarios 2030 and 2100. Oerlemans et al. (1998) developed dynamic ice flow models using various climate change scenarios. He didn't find any good relationship with the glacier size and fractional volume change under any climatic scenarios.

Application of satellite optical remote sensing in the mapping of snow and ice surface on the earth has recently been attempted by numerous workers. The striking contrast of snow and ice with surrounding features enables their study in the visible spectrum. Operational testing of the data for snowmelt run-off predictions has been made by Ostrem. Ødegard et al. (1980) in their studies in Norway have used the digital analysis of multispectral Landsat data for inference of snow water equivalent information. The glacier inventory data thus derived from optical remote sensing has been used for stream flow run-off modelling, and a number of runoff models have been developed to assess stream flow runoff for the river basin based on meteorological parameter and snow cover characteristics. Similarly the glacier inventory data from the Himalayan region has been used to estimate the number of glaciers and corresponding ice volumes (Bolch et al., 2012).

Radar interferometry has been used for glacial studies. Glacial topography and movement have been estimated using SIR-C and ERS-1 data (Goldstein & Healy, 1995). In addition, Digital Elevation Modal derived from SPOT stereo imagery has been utilized in conjunction with geological, meteorological, and hydrological data to identify suitable sites for hydro-electric power generation. Remote sensing methods in conjunction with GIS have been used for estimation of glacial mass balance (Bindschadler, 1998). This is also useful to estimate the contribution of glacial melt into the sea-level rise.

The frequent obscuration of snow-covered areas by clouds hinders the optical remote sensing experiments, and hence, microwave remote sensing data has been used because it's all-weather day and night data acquiring capability. Chang et al. (1976) have reported promising attempts to calculate snow and water equivalent and depth.

3 Glacier Inventory

Water, as a crucial component of life, led to the initiation of guidelines for completing glacier inventory data by the International Commission on Snow and Ice (ICSI) in 1970. The United Nations Educational, Scientific and Cultural Organization (UNESCO), the International Association of Hydrological Sciences (IAHS), and the International Union of Geodesy and Geophysics (IUGG) collaborated in this effort, establishing the Temporary Technical Secretariat (TTS) at the Swiss Federal Institute of Technology (ETH) in Zurich. The World Glacier Inventory, registering all perennial snow and ice masses, was executed under this program. The TTS Computer system recorded various glacier parameters related to identification, areal extent, and elevation. The World Glacier Inventory's comprehensive status in 1988 was published in 1989, but it lacked detailed glaciological information according to the World Glacier Monitoring Service (WGMS, 1989). Subsequently, significant changes occurred to standardize the preparation of the glacial inventory following WGMS guidelines, as indicated by Barry in 2006 and Kaser et al. in 2006. Recognizing the need for an updated global glacier database, the strategy of the Global Terrestrial Network for Glaciers (GTN-G) emphasized this urgency (Haeberli et al., 2007). The United Nations Environmental Program, Regional Resource Centre for Asia and the Pacific (UNEP/RRC-AP), in collaboration with Mountain Environment Regional Information Systems (MENRIS) of the International Centre for Integrated Mountain Development (ICIMOD), further reinforced efforts to create a comprehensive inventory and GIS database of glaciers and glacial lakes in Nepal and Bhutan. Detailed glacier parameters, including area, length, elevation, hypsography, and ice volume, are particularly needed for glacierized regions in the Himalayas, Arctic, and Patagonia. These regions are currently lacking from global mass balance records, with only preliminary data available (Braithwaite & Raper, 2002; Dyurgerov & Meier, 2000). Glacier inventory in India is being conducted by Geological Survey of India under the guidelines given by TTS (Vohra, 1980). This inventory was conducted using Survey of India, topographical maps in conjunction with limited ground truth and aerial photographs. This has suggested approximately 5000 glaciers in India (Vohra, 1980). However, many limitations of this technique can reduce the usefulness of the updated glacier inventory data of GSI which indicates that there are 9875 glaciers in the Himalaya, and updated glacier inventory of the Chenab basin prepared by SAC would be of immense help in the present investigation.

Department of Space, Govt. of India, has also undertaken a program to study glaciers through a project to map glaciers in the Indian Himalaya by using remote sensing techniques. In this project, remote sensing technique has been successfully used for glacier mapping on 1:250,000 scale in the Indian Himalaya. A total of 39 maps showing various glacier features such as glacier boundary, ice divide, snow/equilibrium line, ablation area, accumulation area, and glacier dammed lakes were prepared. It covers the entire Indian Himalaya between Jammu-Kashmir and Arunachal Pradesh. The glaciers were numbered by using a method suggested by UNESCO-TTS and their areal extent estimated using an electronic planimeter. The total number of the glacier of size greater than 0.56 km^2 mapped in the Indian Himalaya is 1702 having an areal extent of about 23,315 km^2. (Kulkarni & Buch, 1991). The volumes of individual glaciers were estimated by using Muller's method and compiled for major river basins (Müller et al., 1977). The total volume was estimated to be approximately 2337 km^3 and snow water equivalent of glacier ice as 2033 km^3.

Glacier inventory carried out in the Chenab basin by GSI shows that there are 989 glaciers covering an area of 2280 km^2, which is 7.97% of the total Chenab basin area. The recent study carried out by Space Applications Centre, Ahmadabad, in collaboration with H.P. Remote Sensing Centre, Shimla, using Remote Sensing satellite data suggests that presence of 454 glaciers in Chenab (5Q 212) basin covering as a glaciated area of 1174.5km^2 distributed in 55 sub-basin of the estimated stored water budget of 93.03 km^3. Most of the glaciers in the mountainous region such as the Himalaya have receded substantially during last centuries due to global warming (Kulkarni et al., 2002, 2005, 2006).

The information generated in the glacier inventory project is being used successfully for the estimation of water availability based on the potential of snow and glaciated streams in the Himalaya. This, in turn, helps the hydropower stations manage their production and plan for the new hydropower installations. Space Applications Centre has also carried out a detailed inventory of the Himalayan glaciers covering Indus, Ganga, and Brahmaputra basin on 1:50,000 scale, monitored the retreat/advance of glaciers over a period of 2004–2008 and studied the mass balance of glaciers distributed all over Himalaya. Snow Cover Mapping using NDSI Algorithm in 10 days duration in the entire Himalaya was another important objective of the study and concluded that there are 32,392 glaciers in the Indus, Ganga, and Brahmaputra basins feeding into India. Based on the temperature data analysis of upper Indus basin for seasonal and annual trends over the period 1961–2000, a fall of 1 °C has been observed in mean summer temperature since 1961 and a decrease of 20% in summer runoff in the rivers Hunza and Shyok (Fowler & Archer, 2006). The observed trend in summer temperature and runoff is consistent with the observed thickening and surging of few glaciers in the Karakoram while there are a widespread decay and retreat of glaciers in the eastern Himalaya.

4 Geomorphological Mapping

The geomorphological sketches of the fore-field of glaciers in Indian Himalaya were started by Geological Survey of India (records of the Geological Survey of India, 1907). Sketches of snouts were prepared and cairns were made to analyse the retreat in snout position of glaciers.

In the year of 1906 (August-September), a primary survey of main glaciers, located in the Kumaon, Lahaul, and Kashmir Himalaya, was initiated by the Geological Survey of India. Twelve glaciers were examined and photographed. Plane-table sketches were drawn, depicting the exact position of the ice caves with reference to fixed points in the valleys and to the prominent and nearby peaks. The glaciers monitored at that time are discussed below.

Kashmir Himalaya: The Barche and Hinarche Glaciers of Bagrot valley, the Minapin, Hispar and Yengutsa Glaciers of Nagir state, and The Hassanabad glacier of Hunza valley were surveyed and investigated by Mr. H.H. Hayden.

Lahaul Himalaya: The Bara Shigri and Sonapani Glaciers were mapped and investigated by Messrs. H. Walker and E.H. Pascoe.

Kumaon Himalaya: The Pindari, Milam, Shunkulpa, and Poting Glaciers were mapped and examined by Messrs. G.deP. Cotter and J.C. Brown.

This was found that glaciers of the Hunza valley and the Karakoram Range are normally located at lower altitudes as compared to those in Lahaul and Kumaon regions. It was also reported that old moraines (sometimes covered with grasses) at lower altitudes in the valleys were taken as a proxy to retreating of glaciers. The valleys downstream of the snouts are generally covered by moraines and talus from the hills. Furthermore, below the snout of the Sonapani Glaciers, there was a large and dry lake-basin (length ~ 2.4 km and width ~ 1.6 km) that was desiccated due to breach in the terminal moraine (records of the Geological Survey of India, 1907).

The new trends in sketching of snouts and other geomorphic features were introduced by Auden (1937). He used a plane table and prismatic compass for detailed mapping of the geomorphic features near the Gangotri snout at 1:9600 scale. Srikantia and Padhi (1964) used theodolite to map the geomorphic features (1:3000 scale) and prepared contours lines to estimate ELA of Bara Shigri Glacier (Himachal Pradesh). For the first time, Owen et al. (1996) used global positioning system (GPS) in the geomorphological mapping of glaciers (1:10,000 and 1:1000 scales) in Lahul Himalaya. The modern-day mapping trend in the geomorphic mapping of glaciers in Himalaya has been started by Dortch et al. (2010). They prepared topography (base) map using ASTER and SRTM DEMs and updated geomorphic features on this base map through detailed field works in Nubra and Syok confluence area at 15 m resolution. The combined effort of GSI-ISRO (GSI and NRSC) prepared geomorphological map of India at 1:50000 scale using LISS-III satellite images through visual interpretation, but only the second level classification of geomorphic units is freely available through Bhuvan, Indian Geospatial platform of IRSO (GSI and NRSC 2012). Since the resolution of the LISS-III image is 23.5 m, many glacial features cannot be mapped with ease if their extent is less than the spatial resolution of LISS-III. Furthermore, Saha et al. (2016) used high-resolution Cartosat DEM (2.5 m spatial resolution) along with Google Earth and IRS-LISS-III images to map geomorphic features of Chandra Tal and upper Spiti valley of Himachal Pradesh. The detailed glacio-geomorphic maps have been prepared to show the stages of glaciations in Himalaya with the help of relative (number of vascular plant species, plant cover, and number of lichen species and their diameter, boulder varnish and strength) and absolute dating techniques such as optically stimulated luminance (OSL) and cosmogenic radio nuclide (CRN) that were applied on sediments of lateral and end moraines (e.g. Owen et al., 1996; Bali et al., 2013; Ali & Juyal, 2013). Some of the studies on glacio-geomorphic mapping in Himalaya are as follows. In 1937 Auden studied Gangotri glacier using plane table and prismatic compass survey methods and mapped Gangotri Glacier snout, moraines, sand flats, gully talus, Bhagirathi River, moraine hillock, and boulders; in 1956 Jangpangi (1958) and his team from Geological survey of India (GSI) mapped old (grass covered) moraines, freshly exposed lateral moraines, palaeo channel, active channel, sandy flats, end moraine, snout, and gully talus for Gangotri, Satopanth, Bhagirathi Kharak, and Arwa Valley Glaciers; in 1971 – again GSI team mapped freshly exposed lateral moraines, Old bank of Bhagirathi River, Talus cones, and snout positions of the year for Gangotri Glacier; in 1957 Dutta and Ahmed studied Bara Shigri glacier; in 1964 Srikantia and Padhi – surveyed and mapped medial and lateral moraines, ice caves and snout, and channel bars of Shigri river, transverse, longitudinal, and marginal crevasses, ice cave and snout, and equilibrium line at an altitude of 4267 m. retreat in snout position was also reported; in 1996 and 1998 Owen and Sharma in Upper Bhagirathi, Upper Kedar Ganga, Rudugaira, Kalapani, Sian, Lamkhaga, and Jaonli valleys (Owen and Sharma, 1998), mapping and reconstruction of the geomorphological features Lateral Moraines, paraglacial fans, Hanging Glaciers, Glacial stages, Lateral terraces, Unsorted stone stripes, exposed bedrock, hummocky landforms, gradient in degrees, Glaciofluvial Outwash Plain and Ablation valley, Debris flow, Palaeo channels, Flutes, Terminal Moraines, and Tabular Ground; in 1995 and 1996 Lewis Owen in Upper and Lower Kulti valley, Milang valley, Mulkila valley, Upper Chandra Tal valley, Batal glaciers of Lahul Himalaya, Northern India, mapped streams, concave break in slopes, cliffs, well-defined Moraine ridges, edge of degraded moraine ridges, paleochannels, debris flow channels, debris flow/solifluction lobes, scree, paraglacial fans, river terraces, Floodplains, Bedrocks, snow and ice avalanches, spot height (in m), slope angle, glacial eroded surfaces, delta striations, Supraglacial debris, Glaciofluvial outwash plains, Glaciolacustrine sediments, and landslide; and in 1974 Ahmad and Hashimi mapped lake, cirque, hanging valleys, waterfalls, subglacial, and end moraines of Kolahoi glacier which extended up to Pahalgam town in Liddar valley.

The applications of unmanned aerial vehicle (UAV), Terrestrial Light Detection and Ranging (TLiDAR), and Light Detection and Ranging (LiDAR) are new techniques available for geomorphic and topography surveys in the inaccessible areas at a very high resolution, but these techniques are not in use to map the Himalayan glaciers located in Indian territory due to security restrictions (Damm, 2006).

5 Climate Glacier Relationship Studies

The study of the climate-glacier relation is relatively young. About 60 years ago the scientists of Scandinavian school applied micrometeorology to the study of glacier surface when the first theories of ice flow were tested. The development of glacial meteorology has been reviewed by Hoinkes (1968, 1970) and a comprehensive list of energy and mass budget studies up to 1966 compiled by Paterson (1994) and Meier (1965).

They summarized the chain of processes that combined the climatic and the dynamic responses of morphological evidence of past variations.

Climate change influence is evidently reflected in changing mass and volume of glaciers. Because of this interrelationship, the snow and glacial measurements are the key parameters for understanding the climate system (Haeberli et al., 1988). The snow and glacial changes with the changing climate is one of the visible signals of global warming and being used as a proxy in climate change studies (Haeberli et al., 1988). There are widespread consequences of mountain glacier recession during the last century. According to Meier et al. (2007), 15–20% of the current rise in ecstatic sea level is because of the enhanced glacier melting on the globe. It also plays a significant role in terms of the amount of runoff and its timing that, in turn, affects water resources for agriculture consumption and hydropower. It also has a huge impact on tourism and the disappearing of the glaciers will, in turn, affect the economy of alpine countries/regions (Barry, 2006).

The Trans-Himalayan glaciers are the centre of attraction since the middle of nineteenth century. Looking into the importance of glaciers, there are many glaciological studies in place and getting supported by national and international funding agencies. The different types of glaciers were analysed in Himalayan and Trans-Himalayan glaciers since 1812 by Mayewski and Jeschke (1979), and they concluded that the fluctuation histories vary among different types of glaciers, and since approximately 1850, longitudinal glaciers have generally been in a state of retreat. However, between 1900 and 1930, advancement or standstill condition of glaciers was dominant. On the other hand, transverse glaciers, in general, retreated from 1850 to 1870, while combined advance and stand still dominated from 1870–1910 and 1920–1930. They also suggested that the complex records displayed by transverse glaciers, in general, may be due to shorter in size, perpendicular flow to the incoming atmospheric circulation pattern and having a very sheer slope. They also concluded that there is also a difference in fluctuation records of Himalayan and Trans-Himalayan glaciers. They found that most of the glaciers of the Himalayas, in general, are in the state of retreat since 1850 and those of Trans-Himalayan glaciers (southern side of Karakoram) were either advancing or retreating from 1850 to 1880. They reflected nearly equivalent influences of retreat and standstill from 1880 to 1940, and however, advance regime from 1880 to 1940 has been reported again in the state of retreat since 1940. Same conclusions were derived by Tewari (1971) in his report on Himalayan Glaciers.

But in 2010 Government of India took it as its mission, and National Mission for Sustaining the Himalayan Eco-System under National Action Plan on Climate Change took place because main resources of snow and its glaciers exist in Himalayas and it is the biggest source of mineral and clean water for the incessant rivers like the Ganga, the Indus, and the Brahmaputra. The core objective of the mission was to cultivate a continuous assessment on health status of the Himalayan Ecosystem. This assessment helps the policy makers and the States in drafting policies and their implementation for sustainable development in the Indian Himalayan Region. The mission also observed that scientific valuation of susceptibility of the Himalayan eco system changes in the weather and climate effects in all its dimensions of physical, biological, and social-cultural aspects (Government of India, NMSHE Mission Document, 2010). Government of India launched a budget outlay of ₹550 crores in 2010 which increased to ₹9,52,60,980 in 2021.

Government of India has not only realized the effect of climate change on declining of glaciers but the World realized the melting of glaciers. Figure 1 clearly shows that due to snowballing, change in mass balance of a set of “reference glaciers” has started worldwide in 1956. The blue line in the first part of the given Fig. 1 denotes the average of all McCall Glaciers, Alaska. Net loss of snow and ice is compared with the base year, that is, 1956, and it is shown by negative values. The average thickness of a glacier is measured in meters of water equivalent. Second part of the Fig. 1 demonstrates the number of glaciers measured every year.

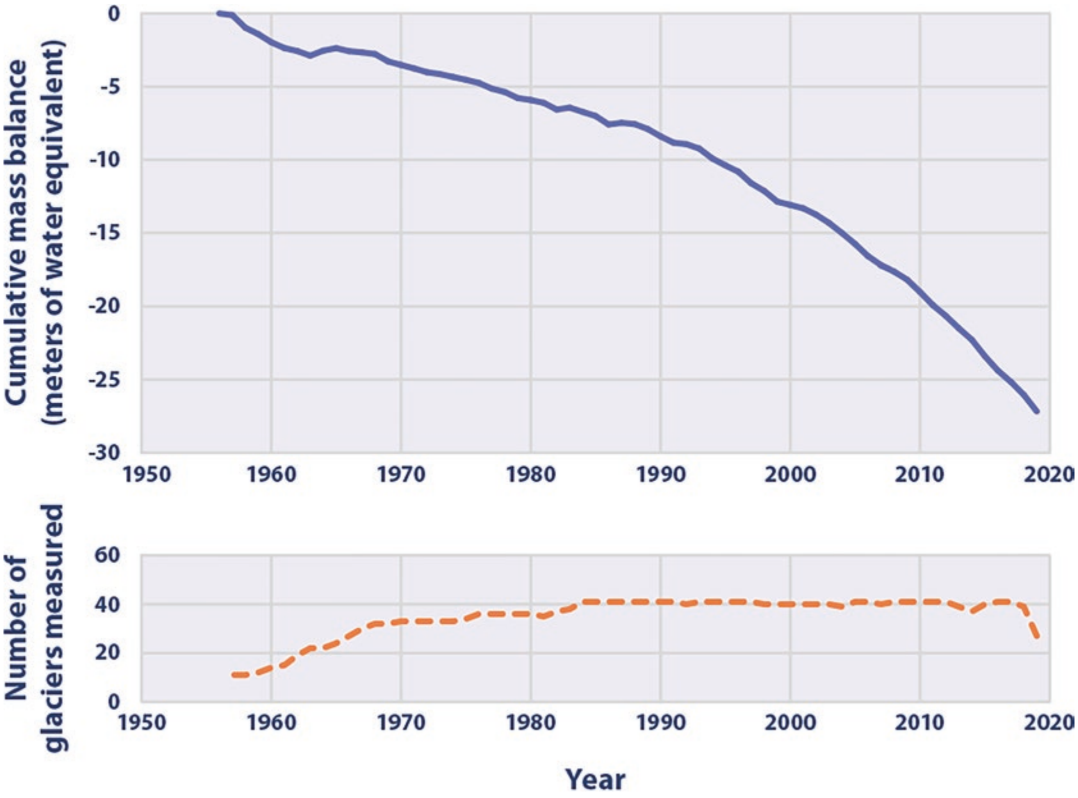

Fig. 1 Average cumulative mass balance of "Reference" Glaciers Worldwide, 1956–2019. (Data source: WGMS (World Glacier Monitoring Service) (2020). For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators)

Now, every year a Climate Change Performance Index (CCPI) is maintained. The CCPI is a ranking system designed by German watch (the German Environmental and Development Organisation). CCPI compares the climate protection performance of 60 countries with European Union which are jointly responsible for more than 92% of Green House Gas emissions (Rachel, 2022). India is at eighth position in CCPI in 2023 with a score of 67.35%, whereas Denmark is at the fourth position with 79.61% and scored the highest because first three positions remain vacant. India scores best among the G20 countries in CCPI 2023 because India is continuously working regarding climate change which improves its score from tenth position in CCPI 2022 to eighth position in CCPI 2023.

References

Ali, S. N., & Juyal, N. (2013). Chronology of late quaternary glaciations in Indian Himalaya: A critical review. *Journal of Geological Society of India, 82*(6), 628–638.

Auden, J. B. (1937). Snout of the Gangotri Glacier, Tehri Garhwal. *Records of the Geological Survey of India, 72*, 135–140.

Bali, R., Ali, S. N., Agarwal, K. K., Rastogi, S. K., Krishna, K., & Srivastava, P. (2013). Chronology of late Quaternary glaciation in the Pindar valley, Alaknanda basin, Central Himalaya (India). *Journal of Asian Earth Science, 66*, 224–233.

Barry, R. G. (2006). The status of research on glaciers and global glacier recession: A review. *Physical Geography, 30*(3), 285–306.

Bindschadler, R. (1998). GEOSCIENCE: Future of the West Antarctic Ice Sheet. *Science, 282*, 428–429.

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., & Stoffel, M. (2012). The state and fate of Himalayan glaciers. *Science, 336*, 310–314.

Braithwaite, R. J., & Raper, S. C. B. (2002). Glaciers and their contribution to sea level change. *Physics and Chemistry of the Earth, 27*, 1445–1454.

Carrara, P., & Rampini, A. (2002). An event-based archive of soft maps for temporal analysis and visualisation of glacier changes. *Environmental Impact Assessment Review, 22*(5), 463–474. https://doi.org/10.1016/S0195-9255(02)00022-7. ISSN 0195-9255.

Chang, A. T. C., Gloersen, P., Schmugge, T. J., Wilheit, T., & Zwally, H. J. (1976). Microwave emission from snow and glacier ice. *Journal of Glaciology, 16*(74), 23–39.

Cunninham. (1848). Note on the motion of the glacier of the Pindur in Kumaon. *The Journal of the Asiatic Society of Bengal, 17*, 203–205. Or (1849). *The Edinburgh New Philosophical Journal, 45*, 258–262.

Damm, B. (2006). Late Quaternary glacier advances in the upper catchment area of the Indus River (Ladakh and Western Tibet). *Quaternary International, 154–155*, 87–99. [Google Scholar].

de Charpenlier, J. (1841). *Essaisurles glaciers*. Duclou.

Della Ventura, A., Rampini, A., Rabagliati, R., & Barbero, R. S. (1987). Development of a satellite remote sensing technique for the study ofalpine glaciers. *International Journal of Remote Sensing, 8*, 203–215. (22) (PDF) Glacier mapping in high mountains using DEMs, Landsat and ASTER data. Available from: https://www.researchgate.net/publication/318266298_Glacier_mapping_in_high_mountains_using_DEMs_Landsat_and_ASTER_data. Accessed November 24, 2023.

Dortch, J. M., Owen, L. A., & Caffee, M. W. (2010). Quaternary glaciation in the Nubra and Shyok valley confluence, northernmost Ladakh, India. *Quaternary Research, 74*, 132–144.

Dozier, J. (1984). Snow reflectance from Landsat Thematic Mapper. *IEEE Transactions on Geoscience and Remote Sensing, 22*(3), 323–328.

Dyurgerov, M. B., & Meier, M. F. (2000). Twentieth century climate change: Evidence from small glaciers. *Proceedings of the National Academy of Sciences, 97*(4), 1406–1411.

Fairbridge, R. W. (1987). Ice age theory. In *Climatology. Encyclopedia of earth science*. Springer. https://doi.org/10.1007/0-387-30749-4_91

Fowler, H. J., & Archer, D. (2006). Conflicting signals of climatic change in the Upper Indus Basin. *Journal of Climate, 19*, 4276–4293.

Geological Survey of India. (1907). *Records of the Geological Survey of India*. Messrs. K. Paul, Trench, & Co., London, and Geological Survey Office, Calcutta.

Goldstein, H., & Healy, M. J. R. (1995). The graphical presentation of a collection of means. *Journal of the Royal Statistical Society. Series A (Statistics in Society), 158*(1), 175–177. https://doi.org/10.2307/2983411

Government of India, NMSHE Mission Document. (2010). *National Mission for Sustaining the Himalayan Eco-System under National Action Plan on Climate Change*. https://dst.gov.in/sites/default/files/NMSHE_Mission_document.pdf

GSI-ISRO, Geosciences Division (2012) MANUAL FOR GEOMORPHOLOGY AND LINEAMENT MAPPING (WEB VERSION). National geomorphological and lineament mapping on 1:50,000 scale using Resourcesat-1 LISS-III data (ISRO - GSI collaboration under Standing Committee on Geology), Document Number NRSC-RSAA-ERG-G&GD-SEP' 12-TR-445

Haeberli, W., Bosch, H., Scherler, K., Ostrem, G., & Wallen, C. C. (1988). World Glacier Inventory, World Glacier Monitoring Services, Global Environmental Monitoring Service and International Hydrological Programme, pp. 1–458. Accessed and download in April 2019.

Haeberli, W., Hoelzle, M., Paul, F., & Zemp, M. (2007). Integrated monitoring of mountain glaciers as key indicator of global climate change: The European Alps. *Annals of Glaciology, 46*, 150–160.

Hall, D. K., Chang, A. T. C., & Siddalingaiah, H. (1988). Reflectances of glaciers as calculated using Landsat-5 Thematic Mapper data. *Remote Sensing of Environment, 25*, 311–321.

Hoinkes, H. (1968). Presidential address: glaciology in the International Hydrological Decade. (General Assembly of Bern, 25 September to 7 October 1967 – Commission of Snow and Ice, Reports and Discussions) *International Association of Hydrological Sciences (IAHS) Publication, 79*, 7–16.

Hoinkes, H. (1970). Methoden und Möglichkeiten von Massen-Haushaltsstudien auf Gletschern: Ergebnisse der Messreihe Hintereisferner (Ötztaler Alpen) 1953–1968. *Zeitschrift für Gletscherkunde und Glazialgeologie VI*, 1–2, 37–89.

Hutter, K., & Gross, D. (2019). Brief historical tour of glacier ice on earth and its role in climate dynamics. *Journal of Earth and Environmental Sciences, 7*, 174. https://doi.org/10.29011/2577-0640.100174

Jangpangi, B. S. (1958). Report on the survey and glaciological study of the Gangotri glacier, Tehri Garhwal District: Glacier No. 3, Arwa Valley: Satopanth and Bhagirath Kharak Glaciers, Garhwal District, Uttar Pradesh. Memoirs of the Geological Survey of India, 18.

Kaser, G., Hardy, D. R., Mölg, T., Bradley, R. S., & Hyera, T. M. (2004). Modern glacier retreat on Kilimanjaro as evidence of climate change: Observations and facts. *International Journal of Climatology: A Journal of the Royal Meteorological Society, 24*(3), 329–339.

Kaser, G., Cogley, J. G., Dyurgerov, M. B., Meier, M. F., & Ohmura, A. (2006). Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004. *Geophysical Research Letters, 33*, 5.

Khalsa, S. J. S., Dyurgerov, M. B., Khromova, T., Raup, B. H., & Barry, R. G. (2004). Space-based mapping of glacier changes using ASTER and GIS tools. *IEEE Transactions on Geoscience and Remote Sensing, 42*(10), 2177–2183. https://doi.org/10.1109/TGRS.2004.834636

Kulkarni, A. V., & Buch, A. M. (1991). *Glacier atlas of Indian Himalaya*. Space Application Centre (ISRO).

Kulkarni, A. V., Mathur, P., Rathore, B. P., Alex, S., Thakur, N., & Kumar, M. (2002). Effect of global warming on snow ablation pattern in the Himalaya. *Current Science, 83*(2), 120–123.

Kulkarni, A. V., Rathore, B. P., Mahajan, S., & Mathur, P. (2005). Alarming retreat of Parbati glacier, Beas basin, Himachal Pradesh. *Current Science, 88*(11), 1844–1850.

Kulkarni, A. V., Dhar, S., Rathore, B. P., & Kalia, R. (2006). Recession of Samudra Tapu glacier, Chandra river basin, Himachal Pradesh. *Journal of the Indian Society of Remote Sensing, 34*(1), 39–46.

Mason, K. (1930) Indus foods and Shyok glaciers. *Himalayan Journal, 1*, 10–29.

Mayewski, P. A., & Jeschke, P. A. (1979). Himalayan and Trans-Himalayan glacier fluctuations since AD 1812. *Arctic and Alpine Research, 11*(3), 267–287. Retrieved from http://www.jstor.org/stable/1550417

Meier, M. F. (1965). Glaciers and Climate. In: The Quaternary of the United States. (Wright, H. E. and D. G. Frey , eds.), Princeton University Press: 795–805

Meier, M. F., Dyurgerov, M. B., Rick, U. K., O'Neel, S., Pfeffer, W. T., Anderson, R. S., Anderson, S. P., & Glazovsky, A. F. (2007). Glaciers dominate eustatic sea-level rise in the 21st century. *Science, 317*(5841), 1064–1067. https://doi.org/10.1126/science.1143906. Epub 2007 Jul 19. PMID: 17641167.

Müller, F., Caflisch, T., & Müller, G. (1977). *Instructions for the compilation and assemblage of data for a World Glacier Inventory*. Zürich, Swiss Federal Institute of Technology, Temporary Technical Secretariat for World Glacier Inventory, International Commission on Snow and Ice, 28 p.

Oerlemans, J., Anderson, B., & Hubbard, A. (1998). Modelling the response of glaciers to climate warming. *Climate Dynamics, 14*, 267–274. https://doi.org/10.1007/s003820050222

Ødegaard, H. A., Andersen, T., and Østerm, G. (1980). Application of Satellite Data for Snow Mapping in Norway. Part of NASA Conference Publication 2116: Operational Applications of Satellite Snowcover Observations. Avalable at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19800017251.pdf [last accessed May 2019].

Østrem, G. (1975). ERTS data in glaciology–an effort to monitor glacier mass balance from satellite imagery. *Journal of Glaciology, 15*, 403–415.

Owen, L. A., & Sharma, M. C. (1998). Rates and magnitudes of paraglacial fan formation in the Garhwal Himalaya: Implications for landscape evolution. *Geomorphology, 26*, 171–184.

Owen, L. A., Benn, D. I., Derbyshire, E., Evans, D. J. A., Mitchell, W. A., & Richardson, S. (1996). The Quaternary glacial history of the Lahul Himalaya, northern India. *Journal of Quaternary Science, 11*, 25–42.

Paterson, W. S. B. (1994). The Physics of Glaciers (3rd edition). Elsevier Science, Amsterdam, 480 pp.

Paul, F. (2002). Changes in glacier area in Tyrol, Austria, between 1969 and 1992 derived from Landsat 5 Thematic Mapper and Austrian Glacier Inventory data. *International Journal of Remote Sensing, 23*(4), 787–799. https://doi.org/10.1080/01431160110070708

Rachel, H. (2022). "U.S. Lags in Latest Climate Protection Rankings". Developed by Germanwatch, NewClimate Institute and the Climate Action Network, the CCPI is an independent monitoring tool for tracking countries' climate protection performance.

Saha, S., Sharma, M. C., Murari, M. K., Owen, L. A., & Caffee, M. W. (2016). Geomorphology, sedimentology and minimum exposure ages of streamlined subglacial landforms in the NW Himalaya, India. *Boreas, 45*(2), 284–303. https://doi.org/10.1111/bor.12153

Schaper, J., & Seidel, K. (2000). Modelling daily runoff from snow and glacier melt using remote sensing data. In *Proceedings of the 2nd EARSel workshop – Special interest group land ice and snow* (pp. 308–316).

Singh, R. (2020). *Glacier Dynamics of Karakoram Himalaya, using Remote Sensing and GIS*, PhD Thesis.

Srikantia, S. V., & Padhi, R. N. (1964). Report on the Bara- Shigri Glacier, Lahaul-Spiti district, Punjab. Report of Geological Survey of India, Lucknow, Uttar Pradesh, India, p. 23. Available at: http://www.portal.gsi.gov.in/gsiDoc/fspReports/NRO/19601965/NRO_20088_1962_1963_REPORT_1.pdf

Tewari, A. P. (1971). A short report on glacier studies in the Himalaya Mountains by the Geological Survey of India. *Studia Geomorphologica Carpatho-Balcanica, 5*, 173–181.

Ullah, M. I. (1843). Travels beyond the Himalaya. *Journal of the Royal Asiatic Society of Great Britainand Ireland, 7*(2), 283–342. https://doi.org/10.1017/S0035869X00155947

Vigne, G. T. (1842). *Travels in Kashmir, Ladak, Iskardo, the countries adjoining the mountain-course of the Indus, and the Himalaya North of the Panjab*. Henry Colburn.

Vohra, C. P. (1980). Some problems of glacier inventory in the Himalayas. *IAHS Publication, 126*, 67–74.

Wangensteen, B., Weydahl, D. J., & Hagen, J. O. (2005). Mapping glacier velocities on Svalbard using ERS tandem DInSAR data. *Norsk Geografisk Tidsskrift – Norwegian Journal of Geography, 59*(4), 276–285. https://doi.org/10.1080/00291950500375500

WGMS (World Glacier Monitoring Service). (2020). Global glacier change bulletin no. 3 (2016–2017). In M. Zemp, I. Gärtner-Roer, S. U. Nussbaumer, F. Hüsler, H. Machguth, N. Mölg, F. Paul, & M. Hoelzle (Eds.), *ICSU (WDS)/IUGG (IACS)/UNEP/UNESCO/WMO*. World Glacier Monitoring Service. https://doi.org/10.5904/wgms-fog-2019-12

WGMS (1989). World glacier inventory – Status 1988. Haeberli, W., Bösch, H., Scherler, K., Østrem, G. and Wallén, C. C. (eds.), IAHS (ICSI) / UNEP / UNESCO, World Glacier Monitoring Service, Zurich, Switzerland: 458 pp

Climate Change Impact on Hydrogeochemical Characteristics of Himalayan Glacier Meltwater

Ramesh Kumar, Rajesh Kumar, Atar Singh,
Prity Singh Pippal, Pankaj Kumar, Payal Sharma,
Tanuja, Abhilasha Sharma, and Jagvir Singh

1 Introduction

The Himalayan glaciers serve as natural reservoirs, accumulating snow and ice during the winter and melting during the warmer months, thereby feeding rivers and providing a continuous supply of water to the downstream population (Kumar et al., 2018a, b; Immerzeel et al., 2020; Kumar et al., 2022a, b). Water plays a vital role in the ecosystems, agriculture, hydropower generation, and drinking water supply for mountain and downstream populations (Singh et al., 2016; Kumar et al., 2016). The Indian Himalayan Region is home to diverse ecosystems, including forests, alpine meadows, wetlands, and glaciers, which provide numerous ecosystem services (Kumar et al., 2023). These services include the provision of freshwater, regulation of climate, support for agriculture, habitat for biodiversity, and cultural and recreational values. In mountain glacier regions, the residents encounter potential contamination risks due to the glaciation processes and the high necessity of meltwater as a valuable resource (Singh et al., 2018a; Biemans et al., 2019; Rowan et al., 2021; Kumar et al., 2021; Singh et al., 2022). However, the rapid population growth, increased water demand, and the impacts of climate change create a compounding effect on water scarcity. This challenge poses significant implications for sustainable development, food security, ecosystems, and human well-being (Blunden et al., 2020). Climate change is one of the foremost global challenges we face today. It poses a threat to the natural

---

R. Kumar
Department of Environmental Science, School of Earth Sciences, Central University of Rajasthan, Ajmer, Rajasthan, India

Department of Environmental Science, Parul Institute of Applied Sciences, Parul University, Vadodara, Gujarat, India

R. Kumar (✉) · P. S. Pippal · P. Sharma · Tanuja
Department of Environmental Science, School of Earth Sciences, Central University of Rajasthan, Ajmer, Rajasthan, India
e-mail: rajesh.kumar@curaj.ac.in

A. Singh
Department of Environmental Science, School of Earth Sciences, Central University of Rajasthan, Ajmer, Rajasthan, India

Centre for Cryosphere and Climate Change Studies, National Institute of Hydrology, Roorkee, India

P. Kumar
Department of Environmental Science, Parul Institute of Applied Sciences, Parul University, Vadodara, Gujarat, India

A. Sharma
SUDIKSHA, Ajmer, Rajasthan, India

J. Singh
Ministry of Earth Sciences, Government of India, Prithvi Bhawan, New Delhi, India

K. K. Sharma et al. (eds.), *Climate Change and Human Adaptation in India*, Sustainable Development Goals Series, https://doi.org/10.1007/978-3-031-55821-4_2

environment and human societies around the world, including India. As one of the countries highly susceptible to changing climate, India has already witnessed the tangible impacts of this global phenomenon on its environment, agricultural sector, and water resources. The region's ecosystems and the communities that rely on them face significant challenges from rising temperatures, shifting precipitation patterns, and melting glaciers. Changes in temperature and precipitation can impact water availability, alter water quality, and increase the risk of natural hazards (Moomaw et al., 2020). Climate change affects different facets of the water cycle, influencing aspects like rainfall patterns, evapotranspiration rates, and extreme weather events. These changes have significant implications for the availability and distribution of water resources and quality.

Furthermore, climate change impacts water quality due to rising temperatures, which can increase water temperatures, and changes in rainfall patterns can also affect water quality (Eekhout & de Vente, 2022). Intense rainfall events can lead to the runoff of pollutants from the land, such as sediments, nutrients, and chemicals, into rivers and lakes, degrading water quality (Ryberg & Chanat, 2022). Nonetheless, there is typically a notable increase in runoff and the amount of newly pulverised rock dust within glaciated catchments at higher altitudes. This can be attributed to the rapid flow of water over finely textured surfaces composed of recently crushed and reactive minerals. This phenomenon leads to the optimisation of chemical erosion and weathering rates. Consequently, glaciers demonstrate a heightened capacity to efficiently enhance the solubilisation of trace-reactive and chemical constituents in bedrock, including sulphides and carbonates, into the glacier meltwater (Tranter, 2003). Moreover, the chemical concentration in the glacial meltwater of this region remains unaffected by the limited organic matter content in the underdeveloped soil (Binda et al., 2020). Mountain regions do not act as direct sources of elements. The introduction of anthropogenic sources to this region can be attributed to atmospheric contributions and long-distance transport (Shah et al., 2012).

Despite being a crucial freshwater resource, the Himalayan region lacks comprehensive research data on geochemical properties (Kumar et al., 2018a, b, Kumar N et al., 2019, Kumar R et al., 2019). Thus, quantifying the impact of climate change and human activities on water quality is significant for achieving global long-term and complex water quality safety goals (UN, 2018). The escalating climate variability is also responsible for changing water quality and needs long-term strategies to safeguard environmental services and public health. The significance of the Himalayan water resources in quantity and quality has been crucial for the economy, human health, and biodiversity conservation (Khanday et al., 2021). Addressing variations in water quality concerning climate change poses more significant challenges than managing changes in water quantity for three primary reasons. Firstly, data are scarce on water quality, chemical concentrations, and chemical fluxes, with shorter time series and a higher number of parameters when compared to conventional hydrologic measurements of flux and storage. Secondly, our understanding of the intricate feedback mechanisms between climatic variability and water quality remains limited, in contrast to the better-established understanding of feedback between climate and hydrology through global and regional hydrologic modelling. Thirdly, disentangling the overlapping consequences of climatic variabilities on water quality due to anthropogenic activities presents a significant challenge, making it arduous to discern the actual impact of climate change alone.

To address the existing research gap, this study aims to enhance our understanding of the consequences of climatic variabilities on water quality. We primarily emphasise reviewing peer-reviewed literature to identify the impact of climate change on glacier meltwater quality. This research provides a perspective on these impacts by examining observed and projected changes in glacier meltwater quality across various regions of the Himalayan glacier. Initially, a concise review is presented on the effects of extreme climatic events on water quality. Subsequently, detailed illustrations are provided regarding changes in the water quality of different glaciers in response to long-