Introduction

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Abstract The Himalayan region harbors plenty of water resources exploited by the populace of mountainous and downstream areas for domestic uses and other purposes. This region, source of supply to almost 80 % of the water resources and major rivers of North India, has profound influence on the climate and environmental front of this region. Indus and Ganges are the two major rivers in Western Himalayan region which directly impact the lives of a large population living in northern part of India, and even beyond the national boundaries. The Himalayas contain over half the permanent snow and ice-fields outside the polar regions. Because of the potential impacts of climate change on ecology and environment, the Himalayan region is considered as one of the most sensitive regions to global warming as change in climate has marked effect on water resources. Considering the importance of this "Water Tower" of South Asia, study of its water resources becomes imperative in context of changing climate. In the present book, attempts have been made to analyze the dynamics of climate change and water of the Northwestern Himalayan (NWH) region. In this publication various aspects related to dynamics of climate change and water resources including seasonal snow cover, glacier, melt runoff, rainfall, GLOFs, climate change, aerosols, atmospheric CO_2 level in glaciated catchment, hydrology of glacial and non-glacial river systems and springs, glacier retreat and mass balance, chemical characterization of glacier melt water, and socio-economic dimension of snow and glacier melt have been covered. The present book, an outcome of the deliberations held during

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the workshop organized by GBPIHED, also attempts to understand and estimate impacts of climate change on the dynamics of snow, glaciers, and runoff over the Himalayan Mountains and their consequences, both for the upland and downstream regions. The contents of the book have been summarized in the three sections (i) Dynamics of Snow in North–West Himalaya, (ii) Assessment of Climate Change Patterns, and (iii) Consequences of Changes and Flow Regime.

Keywords Climate change · Water resources · Snow cover · Glacier · GLOF · Aerosol · Hydrology · Springs · Northwestern Himalaya

Himalayan ranges, the source of fresh water supply and a perennial store house of ice, snow and permafrost as well as a vast repository of rich biodiversity, have always evoked profound interest in the global scientific community. In recent times, climate change has fuelled major research agenda to understand the processes and interactions operative in the region in order to approximate possible impacts. The Himalayan ranges house numerous glaciers and hundreds of small and big lakes, many of which are considered sacred. As per the inventory, there are 9,575 glaciers in the Indian part of Himalaya, out of which the Indus basin houses 7,997 and the Ganga Basin (including the Brahmaputra basin) has 1,578 glaciers located across five states of India, namely Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh. Himalayan rivers yield almost double the amount of water as compared to peninsular river. This is because glaciers and snow contribute important components of flow in these rivers (i) in years of deprived monsoon, (ii) during the lean summer and post-monsoon months; both of these factors help to reduce inter annual and inter seasonal variability, sustain water availability, hydropower generation, and agricultural production. Change trends in temperature and snow precipitation are bound to impact the hydrological cycle causing altered volume and timing of river runoff. At the global level there seems to be no homogeneous trend relating stream flows to temperature or precipitation changes. In fact it is also felt that water resource issues have not been adequately investigated in the climate change analyses and climate policy formulations.

The effects of climate change on stream flow and related variables are crucial for the planning of water resources and their management in time and space. Snow and glacier melt plays a crucial role, both in upstream as well as downstream areas. The downstream effects of changing water flow regimes in the large Himalayan rivers are largely, unknown. It is likely that these changes will have major impacts on downstream societies. IPCC in its fourth assessment report (AR4) has estimated that warming of the earth-atmosphere system is likely to change temperature and precipitation which may affect both the quantity and the quality of freshwater resources and various sectors (such as tourism, agriculture, forests, human health, industry, etc.) across the world. Furthermore, rising population and ever increasing pace of economic development will additionally enhance demands for fresh water in the changing scenario of reduced availability of resource. Therefore, quantitative estimates of the effects of climate on hydrology are essential for understanding, planning and management of water resource systems in the future.

In the above context, a 2 days national workshop on "Impacts of global change on the dynamics of snow, glaciers and runoff over the Himalayan Mountains, with particular reference to Uttarakhand" was organized by GBPIHED, Almora during 27–28 February, 2012. The aim of the workshop was to bring together leading experts working in the subject area to deliberate on issues related to alterations in the dynamics of Himalayan snow, glaciers and runoff vis-a-vis climate change so as to provide much needed science based information for identifying and implementing adaptation and mitigation strategies for sustainable development of the region. The present book, an outcome of the deliberations held during the workshop, attempts to understand and estimate impacts of climate change on the dynamics of snow, glaciers and runoff over the Himalayan mountains and their consequences, both for the upland and downstream regions. The contents of the book have been summarized in the following three parts.

1 Part I: Dynamics of Snow and in North–West Himalaya

The first chapter in this part presents an assessment of the variations in snow cover over space and time in the upper part of Bhagirathi river basin, Uttarakhand Himalaya. MODIS data have been used which provide repetitive coverage, and thus enable monitoring of snow variations at small time intervals. The use of MODIS data is one of the first attempts at snow cover monitoring in the study basin. This chapter narrates the importance of the work undertaken in monitoring of snow cover variations in the Bhagirathi river basin, and also highlights the details of MODIS satellite and the frequency of data that have been used in the work presented. The authors have also digitized the contours, at 40 m interval, in a GIS environment for preparing the digital elevation model and the altitudinal snow cover variations. They have attempted to assess the snow cover variations in different altitudinal zones across seasons, and have discussed seasonal and decadal variations.

The second chapter presents an approach for melt-runoff modeling which is quite meaningful for the prediction of meteorological and run-off parameters. Author has used different existing models using the data already generated, to predict the future meteorological and discharge scenarios, particularly in the Koshi basin (Nepal) and partly in the Hunza basin (Pakistan). The author has derived interesting future scenarios for Koshi basin that can lead to meaningful outcomes for studies in glacierized areas. The adopted approach and the methodology open new avenues of research and future activities in the high altitude glacierized basins of the Himalaya. The third chapter in this part, entitled "Identification of Glacial lake and the potentially dangerous glacial lake in the Himalaya basin", discusses the generic methodology used to identify the Glacial lakes. It is an important aspect under the climate change conditions that may give rise to the formation of large number of glacial lakes and GLOFs causing huge destruction. The authors have made mention of the identification of glacial lakes in the Himalayan basins. The next chapter on “Assessment and simulation of glacial lake outburst floods for a basin in Himalayan region” deals with the methodology of assessment of GLOF. A case study has been taken up to illustrate the methodology employed by using the MIKE 11 model. It has been argued that the mathematical models can indeed be very useful for this purpose; however, these require accurate longitudinal and cross-sectional data on the drainage systems using advanced technologies such as LIDAR scanning. The last chapter on “A model study of Dokriani glacier, Garhwal Himalaya, India” deals with one dimensional flow line model to simulate the glaciation process as well as the future behaviour of the glaciers. The model has been used on the Dokriani glacier and found to be satisfactory for predicting the observed changes in the glacier.

2 Part II: Assessment of Climate Change Patterns

Chapters under this theme cover different aspects of climate change patterns in the Northwestern Himalaya. The sparse data coverage and very few stations with significantly long term climatological observations are obvious limiting factors for conclusive research to arrive at a convincing picture of changing climate. However, authors tried to highlight diverse aspects of climate change issues using the data available at selected stations to draw conclusions about temporal change of local climate in the Himalaya. Low density of rain gauge stations especially in mountainous area, extreme variation in altitudes and large size of these basins forces adaptation of remote sensed data for estimation of average annual precipitation. Further, it has also been highlighted that recent augmentation of ground observations, supplemented by remotely sensed data can bring out the changes in the last few decades, with better spatial resolution.

First chapter in this part presents varying nature of average annual precipitation in three major river basins of India including the Indus, the Ganges and the Brahmaputra which constitute more than 50 % of the river discharge of India. Authors have used 11 years (2000–2010) Tropical Rain Measurement Mission (TRMM) generated radar precipitation raw data for estimation of the annual precipitation for the Indus, the Ganges and the Brahmaputra basins. The contoured distribution of precipitation indicates the orographic control as the primary factor on the summer monsoon precipitation in the Ganges and the Brahmaputra basins.

Next three chapters in this part deal with analyses and/or observations of climatologically important parameters, such as temperature, rainfall, CO_2 levels, and aerosols in the atmosphere and their optical properties. Contents of these chapters will be useful for the readers as they summarize some of the climate change related conclusions in the Himalayan region. The chapter on “Climate Change in the northwestern Himalaya” is a comprehensive review of the science of climate change in the northwest Himalaya. The author has used long term

(1866–2006) climatological data of three stations in the region and provided details of the recent data network with reasonably good spatial distribution. The chapter further describes the general climatology of the region. The next chapter on Aerosols presents details of the measurements at an important location in Himachal Pradesh in Northwestern Himalaya. The last chapter that describes the atmospheric CO_2 levels at Dokriani Bamak glacier is both unique and interesting, and deals with a comparative estimate of annual mean CO_2 concentration in Dokriani Bamak of Garhwal Himalaya, along with the global average values. The patterns in respect of diurnal variations of CO_2 levels across different months are reflective of combined effects of biogenic and meteorological factors. The authors have tried to explain the possible cause of high CO_2 levels in the relatively cleaner areas, such as glaciers of the Himalayan region.

3 Part III: Consequences of Changes and Flow Regime

The first chapter in this part investigates the specific features of hydrological behaviour of glacial and non-glacial river systems. For a case study, authors have taken one glacial basin (the Gangotri glacier-one of the largest glaciers in Garhwal region of Indian Himalaya) and a non-glacial basin (the upper Kosi basin in Kumaun region of Indian Himalaya) of Uttarakhand state in India. Glacial basins are characterized as high energy landforms with less biotic activities, whereas the non-glacial basins have gentle slopes and are subjected to more intense biotic activities. Hydrological responses of the studied basins confirm the role of these characteristics.

The glaciers are fragile and dynamic in nature and influence the climate system (e.g. albedo feedback) and hence are key indicator of climate change. The reduction in mass, volume, area and length of glaciers are considered as clear signals of a warmer climate. The second chapter deals with variable response of glaciers to climate change in Uttarakhand Himalaya, India. In this chapter, the authors have presented the results of a detailed mapping campaign and ground-based measurements for terminus retreat, area vacated and mass/volume change carried out on few glaciers for the period 1962–2010. The study shows continuous negative mass balance on Tipra, Dunagiri, Dokriani and Chorabari glaciers during last three decades. The study shows that the glaciers of Uttarakhand Himalaya are under substantial thinning (mass loss) and reduction of length and area in the present climate conditions.

The third chapter on “Declining changes in spring hydrology of non-glacial river basins in Himalaya” deals with a very important aspect of natural springs in the Himalayan areas, which are a major source of water for the local communities. This chapter, through a case study of Dabka catchment in Kumaun region of Uttarakhand, has tried to establish that springs which exist along the thrust/fault planes and fluvial deposit areas are perennial, and most of those that exist along fracture/joints and shear zones are non-perennial. The authors have tried to establish a relationship on springs’ yield and geology based of the case study presented.

The next chapter of the part presents an analysis of chemical characterization of glacier melt water vis-à-vis western Himalayan meltwater streams. As a case study, snow samples of late winter season from Rathong Glacier and its pro-glacial stream Rathong Chhu were analyzed to study the chemical composition, weathering, and geochemical processes in ice and meltwater at high altitudes. Analyses shows that enrichment of samples with NO_3^- and NH_4^+ suggests scavenging of HNO_3 present in the atmosphere is a major contributor for these ions. Lastly the chapter six of this part deals with the socio-economic dimension of snow and glacier melt in the Nepal Himalaya. The author has investigated possible impacts of change in the runoff due to changed climate, and has discussed the resulting consequences in the downstream areas of Koshi river basin in Nepal.

The melting of snow and glaciers and subsequent changes in water regime have multi-facet impacts on society and economy because of direct linkage of water with people, ecosystem, economy and society. It is therefore, concluded that the impacts of climate change on runoff regime and other water resources would widen the gaps between water supply and demand disproportionately on marginalized and subsistent communities and the economic units which are directly dependent on natural system.

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