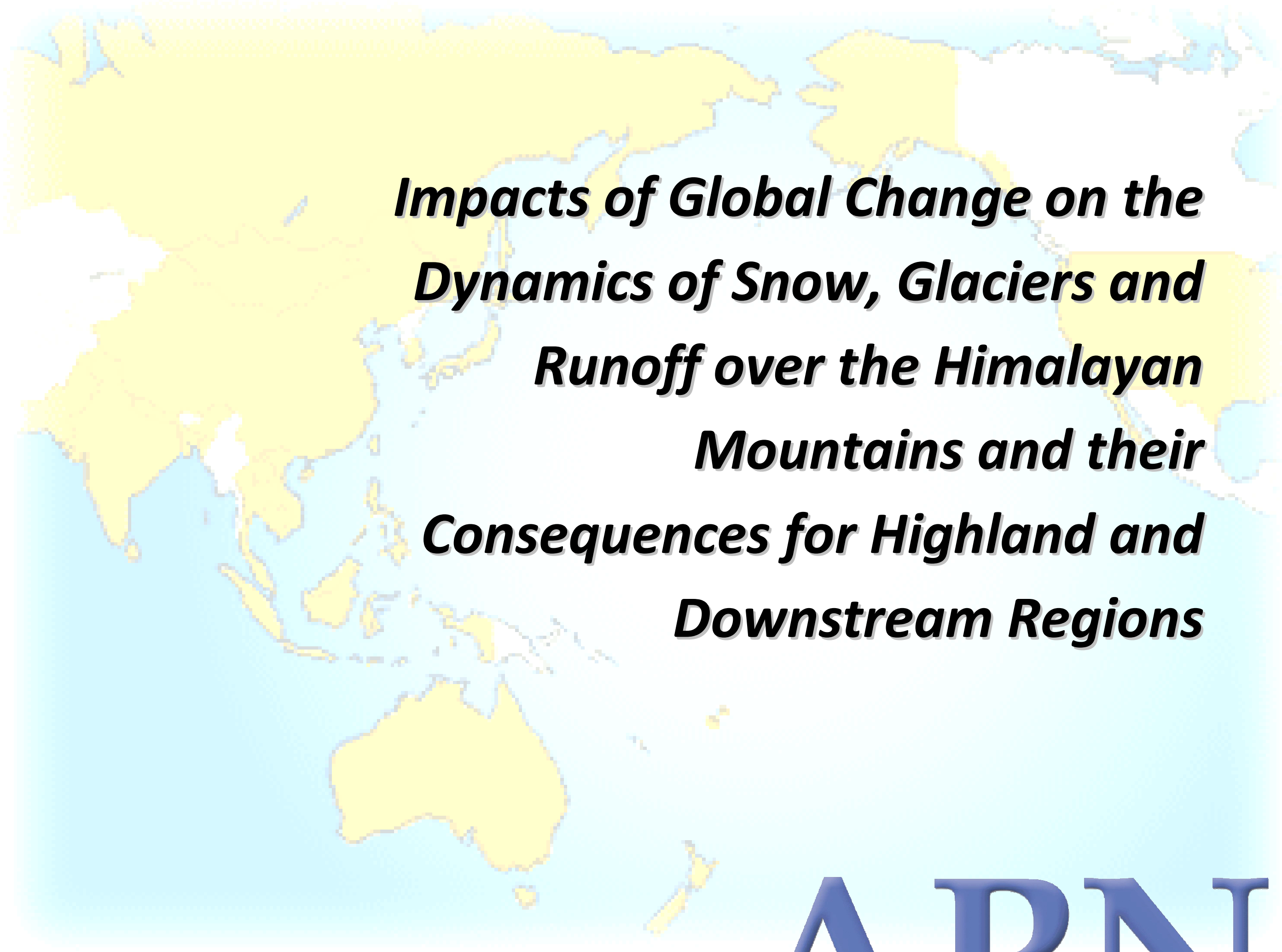
FINAL REPORT for APN PROJECT
ARCP2009-04CMY-Shrestha



Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains and their Consequences for Highland and Downstream Regions

APN
Asia-Pacific Network for Global Change Research

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OVERVIEW OF PROJECT WORK AND OUTCOMES

Non-technical summary

In the Himalaya - the water tower to millions living in and around the region - snow and glaciers and their melt rates are crucial part of the hydrological system besides monsoons and other rainfall and subsurface storage and flows. Efforts to quantify the contribution of melting snow and glacier ice to the regional hydrology are just beginning. Global change impacts on Himalayan snow, glaciers and runoff and the consequences to highland and downstream regions are the main objectives of the present study.

Although historical glacier data from the Himalaya and adjacent mountain ranges are limited mostly to terminus location measurements, more recently, measurements over larger areas are becoming available utilizing satellite remote sensing. As a result, it has now become evident that areal extent, volume and mass of glaciers in the Himalaya are indeed decreasing all along the Himalayan range and more so at the lower elevations in the eastern Himalaya, while significant spatial variations are noted in such reductions.

Along with a broad assessment based on published research studies of snow and glaciers and their melts in the Himalayan range in general and in the three major river basins namely Indus, Ganges and Brahmaputra in particular, attempts have been made through the present study to assess the global change impacts on snow, glaciers and river runoff in three selected watersheds along the Himalayan range namely Koshi basin in the east, Upper Bhagirathi basin in the middle and Hunza basin in far west, by using suitable climatological and hydrological models as well. While the contributions of snowmelt and glacialmelt in terms of percentage of total runoff in any stream/river are found to vary in the different seasons of a year, the value in percentage was also noted to reduce as one move down the streams / rivers away from the snow and glacier covered regions. As a result of climate change, significant reductions in runoff during dry periods and in the arid regions are projected in all the selected basins. As the change in water availability due to change in snowmelt and glacialmelt is found to affect the livelihood and economic activities differently to those living in the high mountains, middle mountains and downstream plane areas, apparently adaptation strategies are required to be worked out differently for the three separate altitudinal regions.

Objectives

The main objectives of the project were:

1. To assess the impacts of climate change on the dynamics of snow, glaciers and runoff over the Himalayan mountains;
2. To assess the consequences for people's livelihoods and the economies and societies in the upland and downstream regions; and
3. To provide scientific information to planners and policy makers for identifying and implementing adaptation and mitigation strategies for sustainable development of the regions.

Amount received and number years supported

The Grant awarded to this project was:
US$ 40,000 for Year1, 2008-2009:
US$ 40,000 for Year 2, 2009/2010

Activity Undertaken

Besides research activities focused primarily on attainng the project objectives through conducting concerned research studies and related model runings for the selected watersheds, severalconsultaton and dissemination workshops and seminar, as described below, were held during the project periods.

Consultations and Disseminations

A number of regional workshops involving the researchers from project partner instiyutions as well as one international workshop, two national workshops and one seminar were held at different time and places with the objectives of deliberations on specific research topics and consultations and exchange of knowledge and experience amongst the key researchers, stakeholders and project partners (Box A).

Box A

Consultative Meeting and Workshops

❖ **Initial Meeting**	**13 – 14 November 2008**
❖ **Joint Workshop**	**17 – 19 February 2010**
❖ **International Workshop**	**13 – 15 September 2010**
❖ **Scoping Workshop**	**21 – 22 February 2011**
❖ **Country Workshop-India**	**27 – 28 February 2012**
❖ **Country Workshop-Nepal**	**10 April 2012**
❖ **Seminar**	**11 November 2012**
❖ **Joint Workshop**	**29 – 30 April 2013**

The Country Workshops held in India and Nepal were attended by almost all the active key actors in the respective countries in the field of climate change impacts on Himalayan Cryosphere. Hence the Country Workshops were in particular found very helpful in updating the research strategy in the context of new research studies carried out during the gap period between the year-1 and year-2 of this two year project. Likewise the International Workshop held in Kathmandu on 13 – 15 September 2010 and organized in collaboration with a number of related institutions from abroad was participated by a number of experts from various countries. It focused in particular on the adaptaion aspect with regards to global change impacts on Third Pole cryosphere. The Scoping Workshop on the other hand dealt also on policy aspects and provided forum for discussions and dissemination amongst relevant stakeholders. The Seminar held on 11 November 2012 specifically deliberated on the role of mountains in storing and redistributing liquid precipitation in space and time as ground water and springs. While the Initial Meeting held on 13 – 14 November 2008 was dedicated to strategic planning exercise, the Joint Workshops held on 17 – 19 February 2009 and 29 – 30 April 2013 focused primarily on sharing knowledge and experience between the project researchers from the partner Institutions. The synopsis of the proceedings of the Meeting, Workshops and Seminar as well as the programme schedule and the list of participants for the indidual events are provided in Appendix A1.

Results

Some of the key results of the two year project are enumerated as follows:

I. Development of climate change scenarios and assessment of impacts on runoff corresponding to base and future climate scenarios at sub-basin scales in the selected Himalayan river basins
II. Assessment of snow and glacier melt and their contribution to total runoff
III. Techno-economic analysis of integrated water resource management in the Koshi basin in the context of global change

IV. Consequences of global change impacts on snow and glacial melt to highland and downstream regions and the necessity of different adaptation strategies at the highlamd and downstream regions to cope with the consequences

Relevance to APN's Science Agenda and objectives

The project has direct relevance to APN Science and Policy Agendas, Item 1 – Climate; Item 4 - Use of resources, such as food, water, energy, materials, and pathways for sustainable development; and Item 5 – Cross cutting and science – policy linkages.

Self evaluation

The research project delivered results and produced outcomes will hopefully be keenly considered and found useful during the formulation of the national and regional policy for the development and use of Himalayan water resource that depndens on snow and glacial melt and will also lead to awareness of the need to take the potential impacts of global change into considerations in the infrastructure development for management of this type of water resource. Monitoring of changes in snow and glaciers together with continued assessments of global chnge impact on them have been revealed to be of national and regional concern. Likewise, it will ultimately lead to enhanced national and regional focus on projections of climate change and consequent changes in snow and glacial melt components in total runoff in management and development Himalayan water resouce.

The project has however stretched longer than expected, partially due to the problems in conducting model studies and analyzing the consequqences of changes in snow and glacial melts to people's livlihood in the mountains and downstream regons. Organisation and integration of the project was sometimes difficult due to the inevitable challenge of working across countries and institutions.

Potential for further work

While Himalaya is considered as water tower to billions of people living in and around it, snow and glaciers naturally form its crucial natural water storage and redistribution system. In order to find practical strategies to adapt to global change for a sustainable development and management of the Himalayan water resources and mitigate flash flood and other flood hazards, it is essential to reduce existing scientific uncertainities in the estimations of snow and glacial melts in space and time along the Himalayan range. Further studies on global change and changes in snow, glaciers and runoff in the Himalayas using more satellite-based observations as well as ground-based observations at higher altitudes would be needed for reducing such current scientific uncertainty. Concerning their future conseqences to livilihood and development in the highlands and downstream regions, further studies would need to consider potential socio-economic changes as well. Further model exercises using various hydrological-climatological coupled models would help in reducing uncertainities in projected changes.

Recent studies have moreover revealed the important role of southern mountains in the Himalayan ranges, which are without any snow cover and glaciers, in providing valuable water supply during dry seasons through ground water, springs and perinnial rivers originating from these mountain ranges. Further studies on these matters would help more in understanding the complex hydrology of the Himalayan river systems.

Publications

Shrestha, K. L., 2013. *Investigating Impacts of Global Change on The Dynamics Of Snow, Glaciers and Run-Off over The Himalayan Mountains,* Proceedings of GBPIHED organized Workshop on 27 – 28 February 2012 in Almora, India, to be published by Springer-Verlag and Society of Earth Scientists (SES), India (in press)

Shrestha, K. L., 2012. *Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains and Their Consequences for Highland and Downstream Regions,* Asia Pacific Network for Global Change Research (APN) Newsletter, Volume 18, Issue 3, September 2012, p. 20-25

Shrestha, K. L., 2009. *Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains and their Consequences for Highland and Downstream Regions,* Mountain Research Initiative (MRI) Newsletter, Vol. 2, No. 3, p. 6-9.

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Acknowledgments

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TECHNICAL REPORT

Preface

Himalaya, the abode of snow, has the third largest reservoir of snow and ice after Arctic/Greenland and Antarctic regions and is the source of all the major perennial rivers in Asia and provides fresh water to billions of people living in the mountains and the downstream regions. As a modest initiative, this Two Year Project on *"Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains and Their Consequences for Highland and Downstream Regions"* was initiated with research grant from the Asia Pacific Network on Global Change Research (APN) in the year 2008 (ARCP2008-16NMY-Shrestha and ARCP2009-04Cmy-Shrestha) with a focus primarily on the Himalayan range covered within countries of the participating institutions.

Attempts are made to overview the characterization of glaciers and snow in the three major river basins in the Himalaya namely Indus, Ganges, and Brahmaputra basins and assess objectively the available evidence of the impacts of climate change on glaciers and snow as well as the runoff in the Himalayan region. The work carried out in the three selected river basins in the countries of the participating institutions with objectives to observe the impact trends and consequences at the meso scale are also presented here.

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1.0 Introduction

Soon after the International Panel on Climate Change (IPCC) released its Fourth Assessment Report (AR4) in 2007 (IPCC, 2007), two statements therein, namely *(a) the high mountains of Asia till then remained a "white spot" and (b) all glaciers in the Himalayas could disappear by 2035*, drew the attention of all concerned and subsequently there seemed to be a sudden rise in the studies and research activities on the dynamics of snow and glacier in the Himalayas as well as on their potential impacts on the runoff of the Himalayan perennial rivers. Meanwhile, the second statement after considerable discourse was altered into a new statement (IPCC, 2010).

Himalaya, the abode of snow, has the third largest reservoir of snow and ice after Arctic/Greenland and Antarctic regions and is the source of all the major perennial rivers in Asia and thus provides fresh water to billions of people living in mountains, valleys, hills and plains in the region. Figure 1 presents a panoramic view of the Himalayan range with its associated glaciers and snow cover.

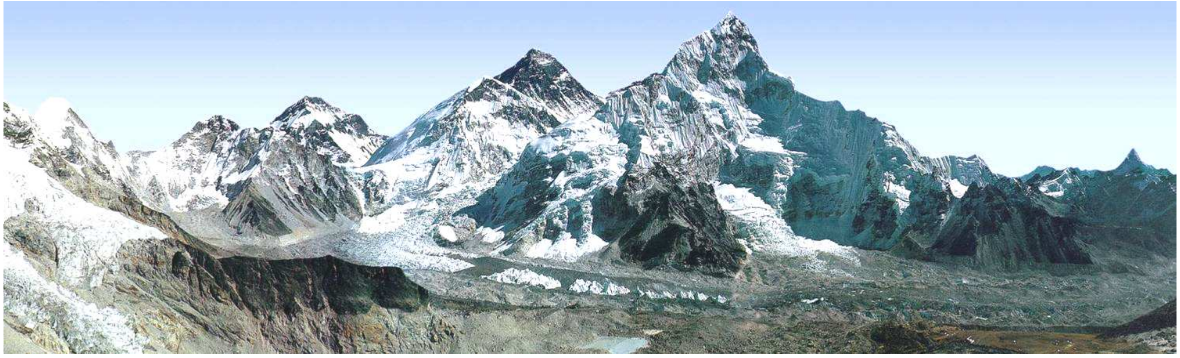


Fig. 1. A panoromic view of the Himalayan range with its associated glaciers and snow cover

While the hydrological cycle of the region is dominated by the Asian monsoons, accumulation and melting of glaciers and snow in the Himalaya contribute important components of flows during the dry periods of a year and in the years of poor monsoon and reducing inter-annual and inter-seasonal variability during the lean summer and post monsoon months.

The Himalayan ranges are the regions of the globe where recent climate change is most evident, consistent with the notion that high-elevation mountain ranges that extend into the mid- to near the top of troposphere will experience greater warming. Global warming is severely impacting the amount of snow and ice and resultant downstream water availability in both the short and long term. As surface air temperatures rise in the high mountains and the mountain basins, changes in accumulation and melting of snow and glaciers in the Himalaya is likely to alter these flow patterns with significant impacts on the economy in terms of water availability, food security and hydropower generation. Changes in precipitation are ambiguous with both increasing and decreasing trends in different parts of the region. The most serious changes are probably those related to the frequency and magnitude of extreme weather events, such as high intense rainfalls leading to flash floods, landslides and debris flows. Most studies have excluded the Himalayan region because of its extreme and complex topography and the lack of adequate hydro-meteorological and other relevant field data. In addition, rising population and increasing pace of economic development in the region will raise demands for fresh water in the scenario of changed availability of this resource. Hence understanding the impacts of global change on snow and ice dynamics in the Himalayas and their hydrological consequences has become urgent and important in view of its scientific significance as well as its primary socio-economic relevance for the region.

As a modest initiative, this Two Year Project on *"Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains and Their Consequences for Highland and Downstream Regions"* (ARCP2008-16NMY-Shrestha) was initiated in the year 2008 with research grant from the Asia Pacific Network on Global Change Research (APN) with the following objectives (with their relevance to APN science agenda in the paranthesis):

- To assess the dynamics of snow and glacier of the Himalayan region in response to the climate change (APN science agenda, Item 1 - climate)
- To assess the resulting impacts on flow regime of major river system of the region through relevant hydrological models with snow and glacier melt component.
- To assess the consequences of the projected hydrological regimes on the people's livelihood both in highland and lowland and their implications on the highland lowland linkages and transboundary cooperation for sustainable development (APN science agenda, Item 4 - use of resources and pathways for sustainable development).
- To provide science based information for determining adaptation and mitigation strategies for dealing with the impacts and consequences of climate change on the Himalayan ecosystem services in terms of water resource (APN science agenda, Item 5 - cross cutting and science- policy linkages).

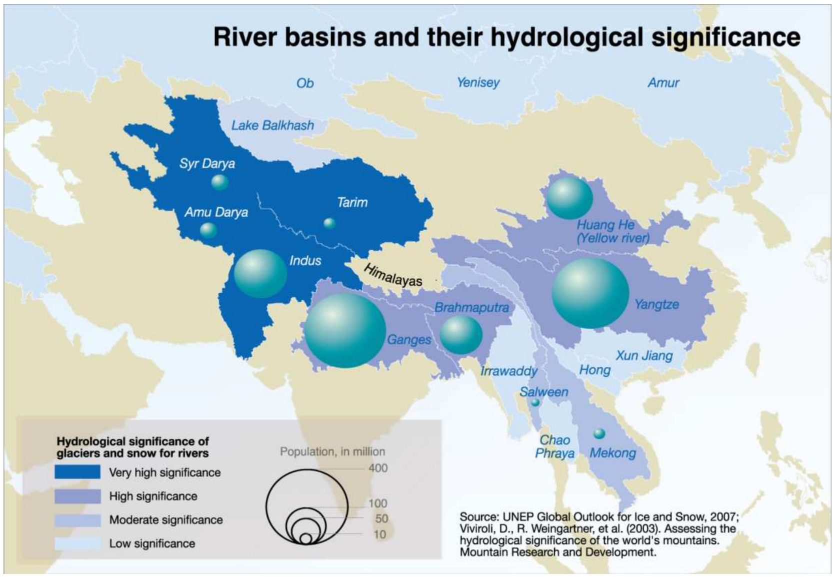
In order to elucidate a coherent and physically plausible picture of water storage properties and 'melt-water' resouces of snow and glaciers in the three major Himalayan river basins in the context of global change, so that they would in turn help to serve as guidelines for assessing the future dynamics and role of melt water resource in various aspects of regional water cycle and water availability in the region, a comprehensive review and careful sysnthesis of all currently available scientific knowledge on glacier systems and seasonal snow cover in the Himalayas together with the recent (last 50 years) changes in them are presented first.

Next, the research studies on impacts of global change on the dynamics of snow, glaciers and runoff over three selected river basins in the Himalayan Mountains by using various tools and technics are presented in brief. The details on used tools, technics and results are annexed as supplementary materials separately on the three selected basins.

Finally, the consequences of global change impacts on the dynamics of snow, glaciers and runoff over the Himalayan Mountains for highland and downstream regions are considered and their policy implcations discussed.

2.0 Snow, Glaciers and Melt Water Runoff in the Himalayas

The Himalayas play a prominent role in the precipitation and spatial and temporal distribution of runoff through their orographic effect and water storage in the form of seasonal snow and glacier systems as well as ground water systems. Nine major river systems in Asia originates from the Himalaya provides fresh water to almost one fifth of world population. The hydrological significnce of river basins in Asia is well depicted in Fig. 2.1.



Source: UNEP Global Outlook for Ice and Snow, 2007; Viviroli, D., R. Weingartner, et al. (2003). Assessing the hydrological significance of the world's mountains. Mountain Research and Development.

Fig. 2.1 Asian River basins and their Hydrological Significane

The Indus, Ganges and Brahmaputra are the three major Himalayan river basins (Fig. 2.2) and are the source of fresh water to almost a billion people living in the northern part of South Asia. In terms of inhabitants, the Ganges river basin (inhabiting 454 million people) and the Indus river basin (inhabiting 212 million people) are the two largest basins. The general characteristics of all the three basins are given in Table 2.1.

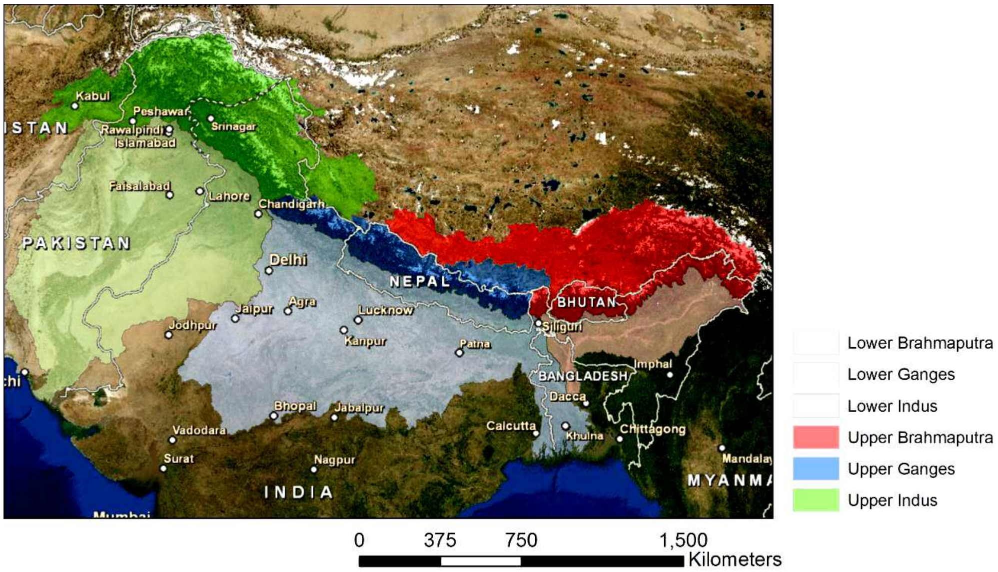


Fig. 2.2 The three major Himalayan river basins with highlighted upper regions of the basins

Table 2.1 General Characteristics of the three Himalayan River basins

Characteristics	Himalayan Main River Basins		
	Indus	**Ganges**	**Brahmaputra**
Annual Average Precipitation	700-2,000 mm	3,500 mm	up to 10,000 mm
Drainage Area	1,263,000 km^2	1,075,000 km^2	940,000 km^2
Length	3,200 km	2,510 km	2,900 km
Average Annual Runoff	208 km^3	494 km^3	510 km^3
Specific Runoff	3.05	13.95	21.28
Minimum Water Supply per Person (1995) (m3/person/year)	-	1,700	1,700
Maximum Water Supply per Person (1995) (m3/person/year)	830	4,000	4,000
Average Population Density (people per sq. km.)	165 (186)	401 (443)	182
Cropland (Percent of Basin)	30	72.4	29.4
Irrigated Cropland (Percent of Basin)	24.1	22.7	3.7

Source: Bajrachrya and Shrestha, 2011

The aim of this part is to review and synthesize currently available scientific knowledge on glacier systems and seasonal snow cover in the Himalayas together with the recent (last 50 years) changes in them. Cosiderable research studies in Himalayan glacier system exist that deal with the glacail systems in the Hindukush-Karakorum-Himalaya (HKH) region (Scheel et al., 2011; Miller et al., 2010; Bhambri et al., 2009, ICIMOD, 2007). However in order to focus on the impacts of global change on the water storage properties and 'melt-water' resouces of the Himalayan cryosphere, characterization of glacier systems and seasonal snow cover in the three major Himalayan river basins are considered here. Various earlier attempts to assess the impacts of climate change on the water storage properties and 'melt-water' resouces in the regions are examined with an objective of development towards a coherent and physically plausible picture of the evolution of meltwater from seasonal snow and glacier system in the basins, so that they would in turn help to serve as guidelines for future projection of various aspects of regional water cycle and seasonal water availability in the study basins.

The general trend of climate change impacts on snow and glaciers in the region are considered including the one as obtained by focusing first on seasonal snow cover and glaciers for the study basins in the 30-year baseline interval of 1961-1990 and next on the first decade of the new millennium 2001-2010 and then by comparing the changes in them during the two periods (Savoskul et al., 2013a). Next, melt water from the sessonal snow and glaciers and their role in the total runoff of the three major rivers are presented (Savoskul et al., 2013a) and impacts of climate change on them are discussed.

2.1 Seasonal Snow Cover and Snow Melt in the Himalayas

Seasonal snow in the Himalayan Mountains is an important component of the regional water cycle and the study of its trends is essential for understanding regional climate change and managing water resources. It has a high water storage capacity due to its large areal extent, significantly exceeding that of glaciers. Contrary to glaciers, seasonal snow accumulates and discharges water mainly within one annual cycle. Detailed knowledge about snow cover in space and time is important for assessing water discharge, understanding and mitigating snow disasters, and analysing climate change. ICIMOD (Gurung et al., 2011) has recently analysed the snow cover in the HKH region and the ten major river basins originating from the HKH range by using the decadal (2000-2010) 8-day snow products recorded by the moderate resolution imaging spectroradiometer (MODIS). The thus determined average annual snow cover area over the period 2002 – 2010 for the three Himalayan river basins are given in Table 2.2.

Table 2.2 Average Annual Snow Cover for the Three Himalayan River Basins, 2002–2010

Basin	Total land area (sq.km)	Average snow cover area		Mean elevation (masl)
		(sq.km)	(%)	
Indus	1,116,347	167,992	16.7	1,587
Ganges	1,001,087	47,742	4.8	894
Brahmaputra	528,082	107,121	20.	4 3,191

Source: Gurung et al. 2011

Changes in maximum seasonal snow cover area and maximum seasonal water storage capacities between the periods 1961-1990 and 2001-2010 for the basins as assessed by Savoskul et al. (2013a) using the monthly data from terrestrial water budget data archive of Delaware University, USA are presented in Table 2.3. It may be noted that the reduction of maximum seasonal snow cover area was up to 5-10%, while the maximum seasonal water storage capacity decreased by 9-21% in all the three basins. Changes in the snow budget will consequently have long-term socioeconomic and environmental implications for agriculture, water-based industries, environment, land management, water supplies, and many other development activities.

Table 2.3. Changes in average maximum seasonal snow area and water storage capacity in the last 50 years

Basin	Maximum seasonal extent (long-term mean for 1961-1990)			Difference*	Maximum seasonal water storage capacity (long-term mean for 1961-1990)			Difference*
	Month	Area(km^2)	Share in basin total area (%)		Month	Volume (km^3 w.e.)	(% of MAF)	
Indus	February	341,191	28	-10	March	49	21	-21
Ganges	January	59,134	6	-2	March	9	2	-18
Brahmaputra	February	184,678	27	-5	March	17	2	-9

Source: Savoskul et al., 2013a

*Difference between 1961-1990 and 2001-2010 (% of 1961-1990 value)

2.2 Baseline (1961-90) Status of the Glacier Systems

Glacier inventories of the first generation (e.g., ICIMOD 2007; WGMS and NSIDC 2009) that are based on topographic and airborne imagery-based surveys of individual glaciers conducted mainly between 1960s and 1980s, the period when changes in glacier systems were relatively moderate, in general are considered to be a suitable source for representing the baseline 1961-90 status of glaciers in High Asia (Cogley 2009a, 2012).

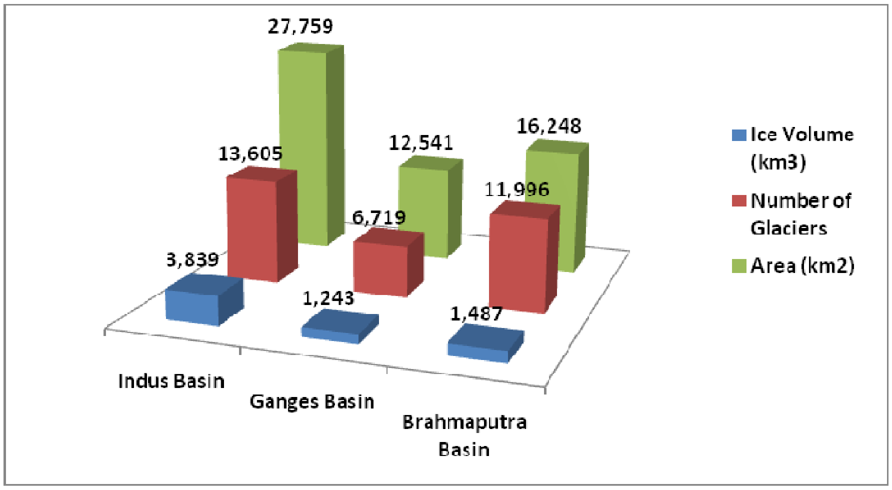
The baseline (1960-90) status of the glacier system in the selected river basins in terms of their numbers, aeral coverage and ice mass are given in Table 2.4 and shown in Fig. 2.3.

Table 2.4 Baseline (1961-90) Status of the Glacier Systems in the three Himalayan River Basins

Basin	Number of Glaciers	Area (km^2)	Ice Volume (km^3)
Indus Basin	13,605	27,759	3,839
Ganges Basin	6,719	12,541	1,243
Brahmaputra Basin	11,996	16,248	1,487

Source: Savoskul et al., 2013a

It should however be noted that thre is considerable uncertainity in the estmation of the ice volume based on the areal extent of glaciers in the regions



Source: Savoskul et al., 2013a

Fig. 2.3 Baseline (1961-90) Status of the Glacier Systems in the three Himalayan River Basins

2.3 Observed Change in Himalayan Glacier Systems

Regarding the changes in glacier system, retreating of terminus of glaciers drew much attention earlier the world over. As a result, data on temporal change in the position of glacier terminus of a number of prominent / readily accesible glacier are available (Kulkarni 2014). However the data on changes in glacier length do not provide much information from the point of view of meltwater contributions and total dynamics of glaciers (Savoskul et al., 2013a).

2.3.1 Observed Change in Extent of Himalayan Glaciers

Recent changes in glacier systems are characterized using estimated annual rates of areal reduction and ice loss derived from data published by the World Glacier Monitoring Service (WGMS) and a compilation of sources based on remote sensing extending from 1960s to 2000s. It is shown that the total glacier area reduction in the study basins in this period is within 14-28% range, and ice volume loss is within 11-40% range.

Comparison of the data from Bajracharya and Shrestha (2011) for 2005+3 period and data on glacier status in the baseline period 1961-1990 as given in Table 2.5 indicates that the glacier area has reduced by 28% and 24% in the Ganges and Indus basins, respectively, and only by 14% in the Brahmaputra Basin, suggesting annual glacier reduction rate of approximately 0.8 - 0.9%/year (the Ganges and Indus basins) and 0.5%/year (the Brahmaputra Basin) (Savoskul et al., 2013a)

Table 2.5 Change in Glacier Status between the baseline period (1960-90) and Later period (2001 -2010)

Basin	Glaciated area 1961-1990 Period (km^2)	Glaciated area 2001-2010 Period (km^2)	Areal Reduction (%)	Areal Reduction (% / yr)	Source
Indus	27,759	21,193	24	-0.78	Savoskul et al., 2013a; Bajracharya and Shrestha, 2011
Ganges	12,541	9,012	28	-0.93	
Brahmaputra	16,248	14,020	14	-0.48	

Source: Savoskul et al., 2013a

In the Nepal Himalayas, between 2001 and 2010, the number of glaciers is found to have increased by 17 % while the glacial area and ice mass have reduced by 21 % and 36 %, respectively. Other records of glacier changes in the HKH region derived from small samples also confirm that glaciers are in a general state of retreat from 1960s onwards, with the rates of areal reduction varying in extremely wide intervals between different study sites, i.e., in the Indian part of the Indus Basin: 0.23-0.53%/ year; in the Ganges: 0.07-1.30%/year; and in the Brahmaputra: 0.01-1.10%/year.

The basins' coverage by various sources tends to suggest high spatial variability of glacier areal reduction in the region. The basin average annual rates of areal reduction between 1961-1990 and 2001-2010 have been, in general, two to three times lower in the Brahmaputra basin than the areal reduction rates in the Ganges and Indus basins.

It is found that structural diversity of a glacier system determines how it responds to climate change. The Indus Basin is shown to have the largest and most diverse glacier system in terms of all parameters like size, slope, aspect, etc.

2.3.2 Observed Changes in Glacir Volume

Data on the volumetric changes of glaciers in the study basins are much more rare and sporadic compared to the data on areal changes. Glacier ice volume for the three HKH basins in 2005+3 is evaluated by Bajracharya and Shrestha (2011). However, the method employed for this assessment gives much lower estimates with up to threefold disparities compared to the methods used in the inventories of the first generation for the glacier status in 1961-1990 (ICIMOD 2007; WGMS and NSIDC 2009). Thus the currently available datasets appear inadequete for a reliable assessment of ice volume changes between 1961-1990 and 2001-2010.

2.3.3 Observed Changes in Glacier Mass-Balance

Mass balance of a glacier is one of the key parameter to understand the influence of climate change. Measurements of mass balance using field parameters are however a difficult and major task. The records of glacier mass-balance monitoring of a short duration are available for five glaciers in the HKH region located in the Ganges Basin (Zemp et al. 2009a). The mass balance evaluations derived from RS evidence (Berthier et al. 2007; Kulkarni et al. 2007; Bolch et al. 2011; Gardelle et al. 2012; Kääb et al. 2012) provide a reasonably good coverage for the Indus and Ganges basins, and Lower Brahmaputra Basin, but their duration is limited only to the past decade. More methodologically consistent data on glacier mass-loss in the HKH region cover from 1 to 15% of basins' glacier-covered areas, with the largest samples being representative only for the past decade. The analysis of data suggests that glaciers in richly nourished areas of the HKH region, particularly south-facing valleys of the Ganges and Indus basins in Central and Western Himalaya, tend to lose mass more rapidly, i.e., at a rate of about 600-900 mm/ year than glaciers in Eastern Himalaya, where the corresponding figures are 400-700 mm/year. The lowest annual mass-loss rates of around 100-300 mm/year among available records are apparently from poorly nourished cold areas in the Upper Brahmaputra.

To overcome the lack of continuous mass balance data for glaciers for a long-term, mass balance was also estimated for some glaciers using accumulation area ratio (AAR) and equilibrium line altitude (ELA) (Kulkarni et al., 2014). The altitude of transient snowline was estimated using area weighted method of Satellite data of AWiFS and TM sensors of IRS and Landsat respectively. In addition, satellitebased geodetic method was used to estimate mass balance of many glaciers in western Himalayas.

Such an analysis suggested an overall loss of 19 ± 7 m of glacier ice for a period between 1975 and 2011. The investigation has also shown that mean loss in glacier mass in Indian Himalaya accelerated from –9 ± 4 to –20 ± 4 Gt/year from the decade 1975–85 to 2000–2010. This is a significant acceleration in mass loss, considering the amount of water stored in the Indian Himalaya.

The important indicator of mass balance is ELA. The ELA in western Himalaya has been noted to have shifted upward by 300 m in the last 40 years. This has significantly affected the accumulation area of many glaciers located in low altitude and due to lack of formation of new ice, these glaciers are likely to face terminal retreat.

2.4 Hydrological Role of Meltwater in the Total Runoff

While peer-reviewed papers on glacier runoff for the Himalayan river basisns are limited few, analysis of publications on modeling runoff from large- and medium-scale Himalayan glacaited catchments indicates that not many of these dealt with modeling glacier runoff per se and many even confuse between 'snowmelt' and 'glaciar -melt'and very few report, if at all, deals glacier runoff separately from snow melt.

Savoskul et al. (2013a) by using the glacier mass budget-based methods and hydrograph separation techniques in semi-distributed models, which they consider better suited than temperature-index method, have assessed the snowmelt and glacier-melt runoff separately for Himalayan river basins during the base period as well as their changes in the subsequent decade.

In their report, the term 'melt-water resources' has been used to cover glacier systems and seasonal snow cover. The report uses 1961-1990 status of melt-water resources as the baseline and compares with the 2001-2010 using the following characteristics: specific glacier runoff (average depth of annual discharge from glacier-covered area), basin total glacier runoff, shares of renewable and nonrenewable components in glacier runoff, total seasonal surface snowmelt from non-glaciated areas, portion of seasonal snowmelt lost for the recharge of groundwater aquifers, the contribution of glacier runoff and seasonal snowmelt to mean annual flow (MAF).

2.5 Global Change Impacts on Himalayan Snow and Glacial Melt Runoff

According to the study, for the three basins studied, i.e. Indus, Ganges and Brahmaputra, the total annual glacier runoff for the period of 1961-1990 was 41 km^3, 16 km^3 and 17 km^3 respectively. But in the recent periods of 2001-2010, total glacier runoff was found reduced to 36 km^3, 15 km^3 and 16 km^3 respectively for the three basins. Liewise, basin total seasonal snowmelt from non-glaciated areas was 44 km^3, 7 km^3, and 17 km^3, respectively, and corresponding values have changed over the course of the past 50 years to 38 km^3, 6 km^3, and 14 km^3, respectively, of which 25-50% is considered lost to groundwater aquifers and only the remaining 50-75% enter the streamflow. According to their study, while change in glacial melt and snow melt for Indus basin in percentage is almost equal, the change in snow melt for Ganges and Brahmaputra basins in percentage is much more than the corresponding figures for change in glacial melt. Their results on recent changes in the glaciers and seasonal snow and their contributions to Mean Annual Flow (MAF) are presented in Table 2.6.

Table 2.6 Recent changes in the glaciers and seasonal snow and their contributions to Mean Annual Flow (MAF)

BASIN	PERIOD	Part of basin area (%) covered by		Glacial melt (km^3)	Snow melt (km^3)	Contribution to MAF (%)	
		Glaciers	Seasonal Snow			Glacier runoff	Seasonal Snowmelt
INDUS	1961-1990	2.6	28	41	44	18	19
	2001 -2010	1.8	25	36	38	15	16
	CHNAGE	***-30.8 %***	***-10.7 %***	***- 12.19 %***	***- 13.64 %***	***-16.7 %***	***-15.8 %***
GANGES	1961-1990	1.2	6	16	7	4	2
	2001 -2010	0.9	6	15	6	3	1
	CHNAGE	***-25 %***	***0 %***	***- 6.25 %***	***- 14.28 %***	***-25 %***	***-50 %***
BRAHMAPUTRA	1961-1990	2.7	27	17	17	2	2
	2001 -2010	2.2	26	16	14	2	2
	CHNAGE	***-18.5 %***	***-3.7 %***	***- 5.88 %***	***- 17.65 %***	***0 %***	***0 %***

It is clear from the table that while Indus and Brahmaputra basins have similar percentage of area under glaciers and snowmelt, the reduction in the glacier and snow cover area are more pronounced in Indus basin. Besides, in all the three basins the reduction in glacier area is more pronounced that the snow cover area. However, the contribution of glacier melt and also snow melt to run-off is much higher in Indus basin compared to Brahmaputra basin, showing the greater role of precipitation in Brahmaputra basin. Within the Indus basin even though seasonal snow covers 28% of the total area, much than the 2.6 % occupied by glaciers during 1961-90, the contribution of two sources to Mean Annual Flow is almost same. But a question arises, has the contribution of glacier melt to the runoff increased in any of the basins in the recent decade? The answer is surprisingly, no.

For the Ganges basin, heavy summer precipitation apparently almost solely determines MAF volume for the basin. Maximum seasonal snow area in the Ganges basin makes just 6% of the entire basin area. Similar situation is noted for the Brahmaputra basin, where the lower parts of the basin i.e. Southeastern Tibet and Eastern Himalayas where nearly 75% of the basin's glaciers are located, witness heavy summer monsoon rains. Regarding Indus basin, precipitation is more evenly distributed between the seasons, but is found highly variable spatially – similar to Brahmaputra, where annual precipitation in some catchments is tenfold (3,000 mm) of that in the other glacier-covered parts of the basin (300 mm).

For the Ganges basin, the very high flow during about four months of the monsoon period, that is several folds of flow in the remaining eight months of dry period, almost solely determines MAF volume for the basin. Hence the expression of glacial and snow melt in terms of percentage of MAF can be quite misleading. It is worth noting that the proportion of glacaial and snow melt actually becomes highly significant on seasonal rather than annual flow basis. Accordingly the impact of climate change on the role of melt runoff also becomes more prominent on seasonal rather than annual water availability.

Again from the Table 2.7 based on the study, it is clear that, in the recent decades non-renewable component in all three basins have gone up while renewable and total volume of water from glacier melt have come down. It is also noteworthy that, even though Brahmaputra basin has more area under glacier cover than the Ganges basin (see Table 2.6), the volume of water from non renewable glacier flow was more in both periods in the Ganges basin. Besides, the percentage of increase in nonrenewable glacier runoff component for the Ganges basin during 2001-10 is highest among all three basins, signifying that glaciers are melting fastest in Ganges basin.

Table 2.7 Contribution of renewable and non-renewable components to glacial runoff

Basin	Period	Glacier runoff components		Total Glacier runoff (km^3)	Total Glacier runoff contribution to MAF (%)
		Renewable (km^3)	Nonrenewable (km^3)		
INDUS	1961-1990	33.0	8.14	41.2	18
	2001 -2010	24.5	11.62	36.1	15
	CHANGE	*- 25.8 %*	*42.7 %*	*-12.4 %*	*-16.7 %*
GANGES	1961-1990	11.0	4.74	15.7	4*
	2001 -2010	8.1	6.95	15.0	3*
	CHANGE	*-26.4 %*	*46.6 %*	*-4.5 %*	*-25 %*
BRAHMAPUTRA	1961-1990	12.7	4.29	17.0	2*
	2001 -2010	10.6	5.05	15.7	2*
	CHANGE	*-16.5 %*	*17.7 %*	*-7.6 %*	*0 %*

Thus the glaciers and seasonal snow perceived as natural water reservoirs are according to available literatures are gradually becoming, in CC-impact assessments, reservoirs with diminishing storage and flow regulation capacity, both on intra-annual and inter-annual scale. Obviously, the other potential changes of precipitation regime coupled with effects of temperature rise on evapo-transpiration will impact future hydrological regimes of the major rivers much more significantly, affecting both MAF and flow seasonality.

Accelerated melting of snow and glaciers in the Himalayas has, it seems, adversely affected the water storage capacity of the mountains. Decreased melt water contribution to the river flows particularly during non-monsoon dry season has consequent negative impact on run-of-river type hydropower generation, agriculture and even community water supply during dry period when the demand of water is relatively higher.

2.6 Glacial Lakes and Associated Hazards

Glacier thinning and retreat in the Himalayas has resulted in the formation of new glacial lakes and the enlargement of existing ones due to the accumulation of meltwater behind loosely consolidated end moraine dams that had formed when the glaciers attained their Little Ice Age maxima. Accelerated glacial melt increases the risk of avalanches and floods, and causes lakes formed from melting glaciers to expand. Because such lakes are inherently unstable and subject to catastrophic drainage, they are potential sources of danger to people and property in the valleys below them. The torrent of water and associated debris that sudden lake discharges produce when the loosely cosolidated end morane breaches is known as a glacial lake outburst flood (GLOF). Many Himalayan basins report fast growing lakes greatly increasing the threat of glacial lake outburst floods (GLOFs). Glacial lakes bursting their banks can have catastrophic consequences for people, agriculture and hydropower infrastructure downstream. It is estimated that there are over 8,000 glacial lakes in the Hindu Kush-Himalayan region with more than 200 of them identified as potentially dangerous (Ives et al., 2010).

Nepal, for example, has experienced 24 GLOF events in the recent past, several of which have caused considerable damage and loss of life, for example, the Bhote Koshi Sun Koshi GLOFs of 1964 and 1981 and the Dig Tsho GLOF of 1985. The 1981 event damaged the only road link to China and disrupted transportation for several months, while the Dig Tsho GLOF destroyed the nearly completed Namche Small Hydroelectric Project, in addition to causing other damage farther downstream. The source of the former event was inside the Tibet Autonomous Region of China, indicating the necessity for international regional cooperation to address the dimension of the problem.

Likewise, recently on 16 and 17 June 2013, heavy rains together with moraine dammed lake (Chorabari Lake) burst caused flooding of Saraswati and Mandakini Rivers in Rudraprayag district of Uttarakhand and the two events caused devastation in the Kedarnath area of the Manda-kini River basin (Dobhal et al., 2013).

In 1997, the Tsho Rolpa in Dolakha District in Nepal reached a critical stage. To mitigate the chances of its breaching, a spillway was constructed by Nepal’s Department of Hydrology and Meteorology (DHM) with support from the Dutch government. This temporary solution, which involved constructing a trapezoidal channel, lowered the water level by three meters in two years and thereby reduced the risk of breach of the lake. While the impacts of GLOFs are localized loss, the regional risks are increased sedimentation in rivers that can alter their hydraulic characteristics and depletion of storage volume due to increased sediment inflow into a reservoir. Turbines of the hydropower plants operating in the river, if any, get severly damaged by the sediment flow.

Glacial lakes, however, are not only sources of potential danger; they are also an important potential natural resource, which has yet to be investigated effectively. Monitoring glacier and water hazards, promoting community resilience and preparedness for disaster risk reduction, and ensuring the sharing of upstream-downstream benefits are priority areas. As glaciers and glacial lakes are related to both water resources and to water-related natural hazards, they need to be mapped and monitored to assess both their potential hazard and their resource value.

2.7 Discussions

Himalaya, the abode of snow, with the third largest reservoir of snow and ice after Arctic/Greenland and Antarctic regions is the source of all the major perennial rivers in Asia and thus provides fresh water to billions of people living in mountains, valleys, hills and plains in the region. The Indus, Ganges and Brahmaputra are the three major Himalayan river basins In the South Asia (SA) and are the source of fresh water to almost a billion people living in the northern part of South Asia. In terms of inhabitants, the Ganges river basin with over 454 million people living in has the highest population density followed by the Indus river basin with an inhabitation of over 212 million people.

Apparently the water resources of this region are currently facing threats from a multitude of driving forces. Global warming is severely impacting the amount of seasonal snow and snow cover as well as the extent and mass of glaciers in the Himalayas with resultant severe consequences on highland and downstream water availability in both the short and long term.

Recent studies in the three major Himalayan river basins seem to indicate a reduction of maximum seasonal snow cover area by 5-10% and a decrease in the maximum seasonal water storage capacity by 9-21% during the last four decades. Changes in the snow budget will as a result have long-term socioeconomic and environmental implications for agriculture, water-based industries, environment, land management, water supplies, and many other development activities.

Likewise, the total glacier area reduction in the study basins in this period is found to range between 14-28%, and ice volume loss to lie within 11-40% range. Other records of glacier changes in the HKH region derived from small samples also confirm that glaciers are in a general state of retreat from 1960s onwards, with the rates of areal reduction varying in extremely wide intervals between different study sites, i.e., in the Indian part of the Indus Basin: 0.23-0.53%/ year; in the Ganges: 0.07-1.30%/year; and in the Brahmaputra: 0.01-1.10%/year.

Regarding the changes in glacier system, retreating of terminus of glaciers earlier drew much attention and as a result, data on temporal change in the position of glacier terminus of a number of prominent / readily accesible glacier are available. However the data on changes in glacier length are found of little relevance from the point of view of glacier dynamics and water storage properties of glaciers.

The various studies on the basins' coverage thus tend to suggest high spatial variability of glacier areal reduction in the region. The basin average annual rates of areal reduction between 1961-1990 and 2001-2010 have been, in general, two to three times lower in the Brahmaputra basin than the areal reduction rates in the Ganges and Indus basins. It is found that structural diversity of a glacier system determines how it responds to climate change. The Indus Basin is shown to have the largest and most diverse glacier system in terms of all parameters like size, slope, aspect, etc.

Data on the volumetric changes and mass balance of glaciers in the study basins are much more rare and sporadic compared to the data on areal changes. Similar to the data on glacier areal reduction, the data on mass-balance changes show consistency in two respects: apart from the data for Karakoram glaciers, all the available records for other basins indicate that glaciers were losing mass and that the rates of mass-loss had high spatial and temporal variability.

Thus the currently available datasets appear inadequete for a reliable assessment of ice volume changes and mass balance between 1961-1990 and 2001-2010. One investigation has shown that mean loss in glacier mass in Indian Himalaya accelerated from –9 ± 4 to –20 ± 4 Gt/year from the decade 1975–85 to 2000–2010. This is a significant acceleration in mass loss, considering the amount of water stored in the Indian Himalaya.

Regarding the roles of snow melt and glacial melt in the Himalayan river system, while peer-reviewed papers on glacier runoff for the Himalayan river basisns are limited few, analysis of publications on modeling runoff from large- and medium-scale Himalayan glacaited catchments indicates that not many of these dealt with modeling glacier runoff per se and many even confuse between 'snowmelt' and 'glaciar -melt'and very few report, if at all, deals glacier runoff separately from snow melt.

One of the studies using a set of selected analytical tools has come up with figures for the total annual glacier runoff (sum of glacier melt and seasonal snow melt) for the three basins, i.e. Indus, Ganges and Brahmaputra covering the period of 1961-1990 to be 41 km^3, 16 km^3 and 17 km^3 respectively. The total glacier runoff in the recent periods of 2001-2010, was likewise found to have reduced to 36 km^3, 15 km^3 and 16 km^3 respectively. Similarly, total seasonal snowmelt from non-glaciated areas in the three basins was found to be 44 km^3, 7 km^3, and 17 km^3, respectively, and corresponding values to have changed over the course of the past 50 years to 38 km^3, 6 km^3, and 14 km^3, respectively, of which 25-50% was considered lost to groundwater aquifers and only the remaining 50-75% entering the streamflow.

Furthermore, considering the renewable and non-renewable componets of the glacier runoff, it ihas been found that, in the recent decades non-renewable component in all three basins have gone up while renewable and total volume of water from glacier melt have come down. While Brahmaputra basin has more area under glacier cover than the Ganges basin, the volume of water from non-renewable glacier flow was more in both periods in the Ganges basin. Besides, the percentage of increase in nonrenewable glacier runoff component for the Ganges basin during 2001-10 is highest among all three basins, signifying that glaciers are melting fastest in the Ganges basin.

Thus in the Himalayas the glaciers and seasonal snow perceived as natural water reservoirs are gradually becoming, according to available literatures on CC-impact assessments, reservoirs with diminishing storage and flow regulation capacity, both on intra-annual and inter-annual scale. Obviously, the other potential changes of precipitation regime coupled with effects of temperature rise on evapo-transpiration will impact future hydrological regimes of the major rivers much more significantly, affecting both MAF and flow seasonality.

Accelerated melting of snow and glaciers in the Himalayas could adversely affect the water storage capacity of the mountains. Decreased melt water contribution to the river flows particularly during non-monsoon dry season would have consequent negative impact on run-off-river type hydropower generation, agriculture and even community water supply during dry period when the demand of water is relatively higher. Likewise, formation of new glacial lakes and growth in size of the new and old glacial lakes are leading to higher potential GLOF hazards.

Thus there is currently a severe knowledge gap on the short and long-term impacts of climate change on snow, glacier dynamics and rnoff in the Himalayas and their implications on availability of the water and water induced hazards such as floods, flash floods and droughts in the Himalayas, and their downstream river basins.

There is an urgent need to close this knowledge gap through the establishment of monitoring schemes for detection of changes in snow, ice, and water; downscaling of climate models; utilisation of hydrological models for prediction of future water availability; and development of basin wide scenarios which also take water demand and socioeconomic development into account.

3.0 Methodology

Before presenting the research methologies adopted in the three selected river basins, brief notes on the participating institutions as well as those on the selected basins are provided in the next sections.

3.1 Participating Institutions

While four institutions from four countries in the region had initially agreed to work in the project as collaborating institutions (Box - A), only three institutions, namely **GCISC**, **GBPIHED** and **IDI** cooperated and actively participated in the three selected representative research basins namely, **Hunza** basin, **Upper Bhagirathi** basin and **Koshi** basin respectively. As a result of non-cooperation of one of the project partner, project activities during the year-1 got stalled and the year-2 activities of the project got started only in the last quarter of the year 2011.

Box A

Participating Countries & Institutions

China:	The Institute for Tibetan Plateau Research (TPI)
India:	The G. B. Pant Institute of Himalayan Environment & Development (GBPIHED)
Nepal:	The Institute for Development and Innovation (IDI)
Pakistan:	The Global Change Impact Studies Centre (GCISC)

3.2 Project Study Basins

In the Initial Meeting of the Project Partner Institutions held on 13 to 14 November 2008 in Kathmandu, three representative research basins along the length of the Himalaya from east to west were selected for investigating the impacts of global change on snow, glaciers runoff in the basins. These selected basins (Fig. 3.2.1) include the Koshi basin in the east, Upper Bhagirathi basin in the center and Hunza basin in the west and were selected on the basis of their locations, glacier coverage, socio-economic importance and availability of past data. While the replenishment of snow in the western basin Hunza happens mostly in winter due to the westerlies, the eastern basin Koshi gets its snow replenishment mostly in summer due to the south-westerly monsoon. Likewise, the northern and southern side of the Himalaya have different precipitation pattern which influence the hydrograph of the river. All the three chosen basins are the highly glaciated ones. Glaciers like Hispar, Batura and Passu in the Hunza basin; Gangotri and Dokriani in the Upper Bhagirathi basin; and Khumbu and Imja in the Koshi basin are some of the well studied major glaciers in the region. The Koshi basin with Mount Everest, the highest mountain on earth, almost at its centre is the most rugged and the one with highest glaciers. While the river Bhagirathi originates from the terminus of Gangotri glacier and the river Koshi with its tributeris originating in the Nepal

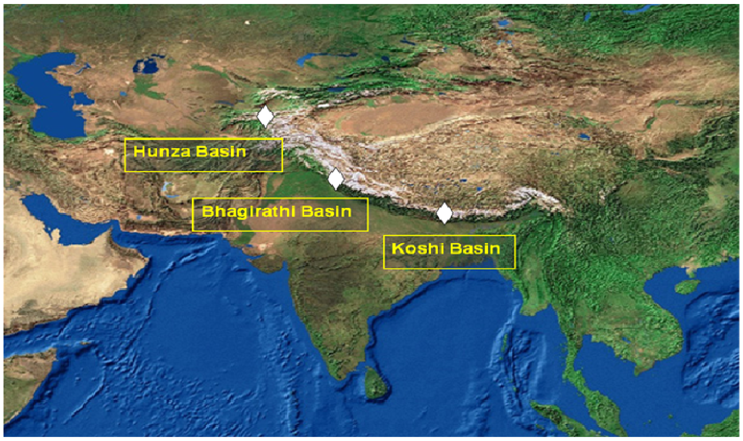


Fig. 3.2.1 Selected Study Basins - Hunza, Upper Bhagirathi and Koshi

Himalayas and the Tibetan plateau joins the Ganges river in India, and Hunza river in the Karakoram region constitutes an important tributary to the Indus river originating from the northern side of the Himalayan range in the Tibetan plateau.

3.3 Research Approach and Research Framework

The conceptualized research framework that was followed in the Project is shown in Fig.3.3.1.

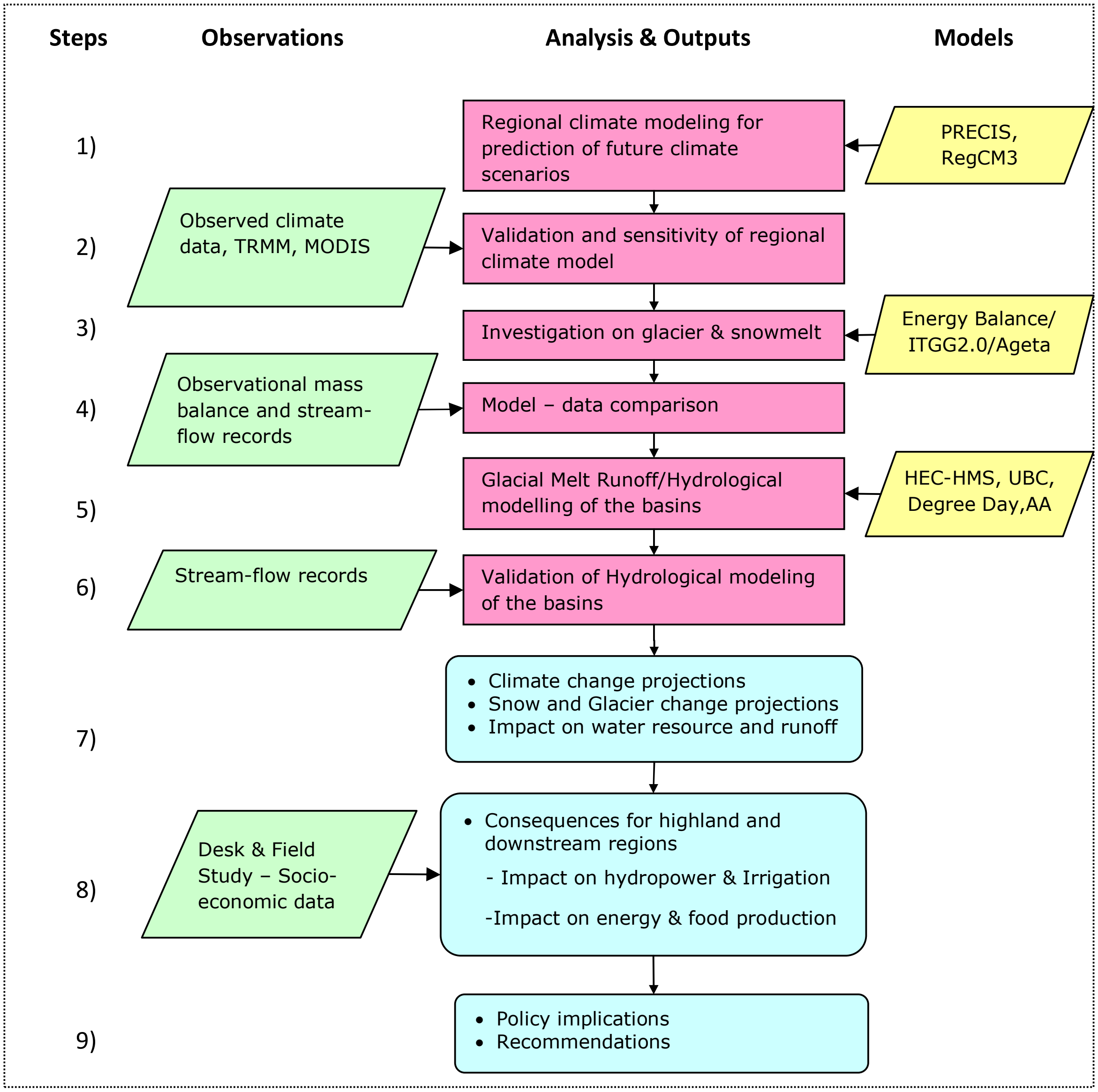


Fig. 3.3.1 Research Framework

The research approach adopted for assessing melt water resource as well as their current and future role in the various aspects of regional water cycle and water availability in the study basins in nutshell is shown in Fig.3.3.2. Of the available two approaches of downscaling GCMs, the statistical downscaling approaches though simple from the point of view of computation, have several limitations and associated uncertainties particularly in the data sparse areas (Ghosh and Misra, 2010). Hence the dynamic downscaling approaches although computation intensive were used to derive RCMs and used for assessing hydrologic implications of global climate change. Regional

Climate Models (RCMs) run at the basin scales are used after necessary calibration and validation to provide meteorological conditions for contemporary as well as future periods. The obtained meteorological profiles with necessary bias corrections are then used to run suitable hydrological models to assess the impacts of climate change on the water availability in the selected basins both in space and time. Their consequent implications for highland and downstream communities are next studied using chosen appropriate tools.

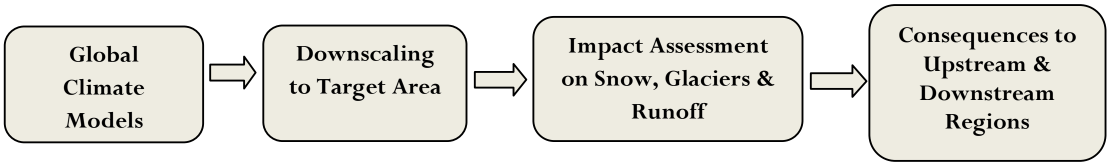


Fig. 3.3.2 Adopted Research Approach

3.4 Adopted Research Metodologies in the Selected Study Basins

The adopted methodologies for studying the Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the selected Himalayan river basins are presented here briefly. The details on the adopted methodologies are provided in the Supplementary Materials on the respective river basins in the Annex.

3.4.1 Koshi Basin

The basin, located in the eastern part of Nepal has been selected as the study basin in the eastern Himalayan range. The dynamical downscaling of GCMs namely HadAM3P for PRECIS and ECHAM 4 for RegCM3 were taken on for the selected basin for IPCC SRES A2 at 50 km resolutions. Likewise, for the Koshi basin, PRECIS was also run at 25 km resolution and WRF as test run at 9 km resolution. Average values of projected change in temperature and precipitation for the three decades namely 2020s, 2050s and 2080s were obtained and used in ascertaining the impacts of climate change on the snow and glacial melt and consequent changes in the runoff in the seven tributeries of the Koshi river as well as in the total basin.

A conceptual precipitation runoff model is used to simulate the daily runoff from 22 glacierized sub-watersheds of the Koshi basin. Snow and glacier melt are calculated by surface energy balance and mass balance modes. The glacier melt under the debris layer is estimated from thermal resistance to critical thermal resistance ratio. The ratio has been estimated from surface temperature of the debris obtained from spatial modeling of the Landsat. A simple empirical relation is used to define the type of precipitation. The precipitation as rainfall, snow and glacier melt in all bands are averaged and used as input to the conceptual TANK model for runoff simulation. The estimated runoff from the melts is then routed downstream to basin outlet in plain via seven major tributaries using HEC-HMS, a semi- distributed rainfall-runoff model. The likely impact on the same in future due to climate change is also analyzed by using projected climate data from PRECIS after bias correction.

Considering population growth, climate change and environmental degradation as key pressures impacting on the water system, vulnerability of water system in the middle and high mountain watersheds in Koshi Basin has been considered and GIS based vulnerability maps have also been produced by adopting the publised methodology used elsewhere (Yusuf and Francisco, 2009) for such vulnerability mapping.

In order to formulate an integrated approach towards the use of the Water Resources of Koshi basin and also to find out the consequences of global change impact on the resources to upstream and downstream regions, an approach of integrated optimization models including all the major confluences of the tributaries as well as all the major existing/planned demand points along the Koshi river system were used with three separate objective functions, namely i) to minimize the sum of deficit in demand satisfaction; ii) to maximize the sum of net benefit for different purpose of water use without considering the climate change effect; and iii) to maximize the sum of net benefit for different purpose of water use considering the climate change effect as simulated by hydrological model using RCM. General Algebraic Modeling System (GAMS) model was used to integrate the basin hydrology with economic parameter to develop separate scenarios that fulfill the chosen objective

3.4.2 Upper Bhagirathi basin

The Upper Bhagirathi basin, located in the state of Uttarakhand in India, has been selected as the study basin in the middle Himalayan range. For the study, observed hydro-meteorological data for 1999-2008 have been used. MODIS terra (MOD10A2) 8-day snow cover products for eleven years (2000-2010) were used for studying changes in snow cover area (SCA) in the study basin. The temporal snow cover was derived from Normalized Difference Snow Index (NDSI) method. Using Digital Elevation Model (DEM), the entire study basin was divided into nine elevation zones and SCA for each zone was estimated. Mann Kendall method and linear regression method have been employed to identify the trends in SCA during the last decade.

PRECIS RCM data of temperature and precipitation for two different scenarios (base period: 1961-90 & future scenario: 2070-2100) have been used for analysis of changes in climate in the past and as well as for the projection in the future. Snowmelt Runoff Model (SRM), a temperature index model, was used to assess the impact of changing climate on snow-melt and runoff.

3.4.3 Hunza basin

PRECIS Model Run

Hunza basin was the selected western basin to the west of Himalayan range. Data from PRECIS driven with GCM ECHAM4 at 50 km resolution were compared over the test period 1961 – 1990 with meteorogical data and validated with CRU climatological data. After necessary bias correctons, projected data for temperature and precipitation were obtained for chosen three decades of 2020s, 2050s and 2080s.

Application of UBC Watershed Model

UBC Watershed Model (Quick and Pipes, 1976) has been selected to calibrate the flows of Hunza River. This semi-distributed model takes less meteorological data (Daily Max & Min Temperature, Precipitation) and calculates the snowmelt and glacier melt components separately which is one of the main characteristics required to model the Hunza River Basin mainly fed by glacier melt. Details on the model and its structure are provided in Spppلemenatry Materials S3 on Hunza basin. Three different datasets have been prepared i) observed station data ii) climate data using regional climate model iii) physiogeographical data.

Observed Meteorological Data

To calibrate and validate the UBC watershed model observed data of Gilgit and Gupis stations have been obtained and prepared in the model readable format. Geographical location of these stations along with their length of the data record used in this study is given in Table-1.

Climate Data Preparation

PRECIS Regional Climate Model output (Max & Min Temperature, Precipitation) is post-processed to prepare climate variables for input in the UBC Watershed Model. In contrast to the PRECIS gridded output, UBC takes only the point data input for climatic parameters. To convert the gridded output into point data whole PRECIS grid over Hunza Basin has been bifurcated into two parts from the mid latitude of the basin keeping in view the small basin area, its high altitudinal range and steep slopes. These upper and lower portions are then been spatially averaged out and their daily time series are generated for base climate (1960-1990) as well as three future climates 2020s (2010-39), 2050s (2040-69) and 2080s (2070-99) resulting in two climate stations lying within the study basin.

Bias Correction

To obtain the realistic discharges from the hydrological model, biases associated with the regional climate model output are necessary to be addressed, quantified and corrected. Keeping in view the PRECIS model biases for temperature and precipitation over Hunza River Basin cited above under heading “Validation of PRECIS output” climate data series has been corrected for these biases.

Physio-geographical Dataset

The DEM (Digital Elevation Model) for the Hunza River basin has been taken from the ASTER global dataset at horizontal resolution of 30 meters available on internet.

On the basis of DEM, the whole watershed area has been divided into eight elevation zones called elevation bands required as an input to the Hydrological Model (UBC). Cumulative area within each elevation zone has been calculated.

Physio-geographical characteristics such as Glaciated Area, Forest Cover, Density Forest Canopy, Impermeable Area and Orientation Index along with the land area under each elevation zone have been calculated from the Land Cover and DEM gridded datasets from USGS.

3.4.4 Consequences of Global Change Impact on the Himalayan Water Resources to Upstream and Downstream Regions

Consequences in view of various perspectives like altitudinal variations in water sources and usages, altitudinal population distributions, impacts on total runoff of major rivers and people’s livelihood in genaral are considered using also the relevant secondary sources and data. The impact of climate change on the water related infrastructure development in Koshi basin is also presented as case study depicting the upstream downstream consequences.

The inputs for the GAMS model that consist of hydrological data (supply data), reservoir data, agricultural data, demand data, hydropower data, economic data, and environmental data were obtained from the relevant secondary sources. In addition, the hydro-meteorological data from RCM - PRECIS and HEC-HMS hydrological model from the present study were used to develop scenarios incorporating the impacts of climate change.

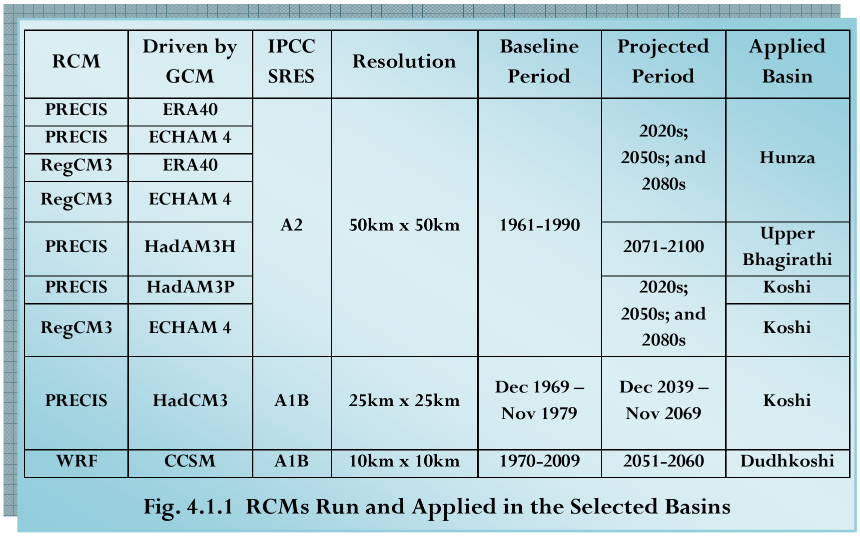
4.0 Results & Discussion

4.1 Regional Climate Models (RCMs)

For regional climate change impact studies, properly downscaled regional climate models (RCMs) are required in order to provide fine-resolution climate parameters for driving hydrological models to make future predictions of changes in the hydrological regimes.

Of the available two approaches of downscaling GCMs, the statistical downscaling approaches though simple from the point of view of computation, have several limitations and associated uncertainties particularly in the data sparse areas (Ghosh and Misra, 2010). Hence the dynamic downscaling approaches although computation intensive were used to derive RCMs and used for assessing hydrologic implications of global climate change. Regional Climate Models (RCMs) run at the basin scales are used after necessary calibration and validation to provide meteorological conditions for contemporary as well as future periods. The obtained meteorological profiles with necessary bias corrections are then used to run suitable hydrological models to assess the impacts of climate change on the water availability in the selected basins both in space and time.

The various RCMs downscaling different GCMs for certain IPCC SRES together with their resolutions are shown in Fig. 4.1.1. Some of them after validation and necessary bias correction have been used to project the changes in the temperature as well as precipitation in the selected basins over chosen periods. One of the Regional Climate Model (RCM) used in this study is PRECIS (Providing Regional Climate for Impact Studies) developed by the Hadley Centre of the UK Meteorological Office. The PRECIS RCM is based on the atmospheric component of the GCMs and is extensively described in Jones et al. (2004). The atmospheric dynamics module of PRECIS is a hydrostatic version of the full primitive equations and uses a regular longitude-latitude grid in the horizontal and a hybrid vertical coordinate.



RCM	Driven by GCM	IPCC SRES	Resolution	Baseline Period	Projected Period	Applied Basin
PRECIS	ERA40	A2	50km x 50km	1961-1990	2020s; 2050s; and 2080s	Hunza
PRECIS	ECHAM 4					
RegCM3	ERA40					
RegCM3	ECHAM 4					
PRECIS	HadAM3H				2071-2100	Upper Bhagirathi
PRECIS	HadAM3P				2020s; 2050s; and 2080s	Koshi
RegCM3	ECHAM 4					Koshi
PRECIS	HadCM3	A1B	25km x 25km	Dec 1969 – Nov 1979	Dec 2039 – Nov 2069	Koshi
WRF	CCSM	A1B	10km x 10km	1970-2009	2051-2060	Dudhkoshi

Fig. 4.1.1 RCMs Run and Applied in the Selected Basins

4.1.1 Koshi Basin

The dynamical downscaling of different GCMs namely HadAM3P for PRECIS and ECHAM 4 for RegCM3 were taken on for the selected Koshi basin in Nepal for IPCC SRES A2 at 50 km resolutions. The projected temperatures and precipitaion for the Koshi basin in Nepal as obtained by using the two chosen RCMS are presented in Figs. 4.1.2 & 4.1.3.

While the monotonic rise in projected change in temperature, though at different slopes and intercepts, are evident in both the RCMs projections, the projected change in precipitation hardly follow any trend. Also the change projected under Reg CM3 is much lower (the shown right hand side scale).

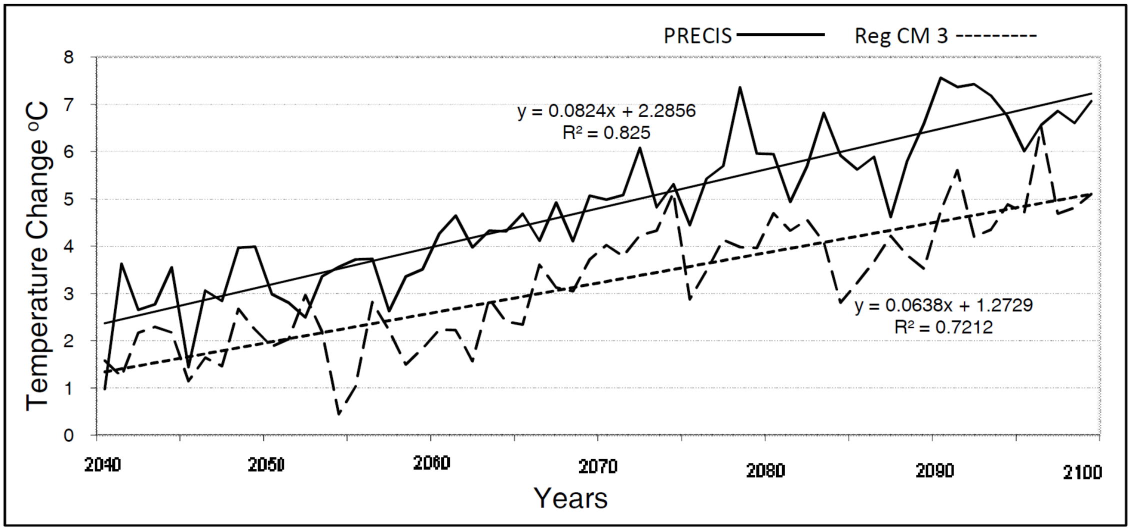


Fig. 4.1.2 RCMs Projected Annual Mean Temperature Change in Koshi Basin

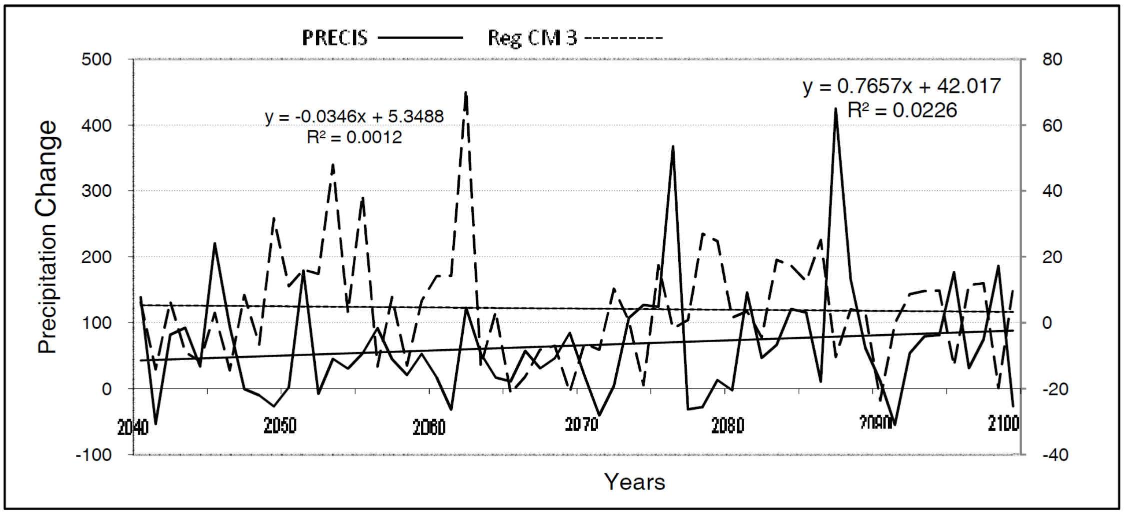


Fig. 4.1.3 RCMs Projected Total Precipitation Change in Koshi Basin

The projected variations with spatial distribution for the Koshi basin for 2020s, 2050s and 2080s as determined by using PRECIS at 50 km resolution are presented in Figs. 4.1.4 & 4.1.5 for temperature and precipitation respectively. The higher trend of mean temperature changes in the high mountains in the north (Fig. 4.1.4) and the reduction in total precipitation therein (Fig. 4.1.5) are notable.

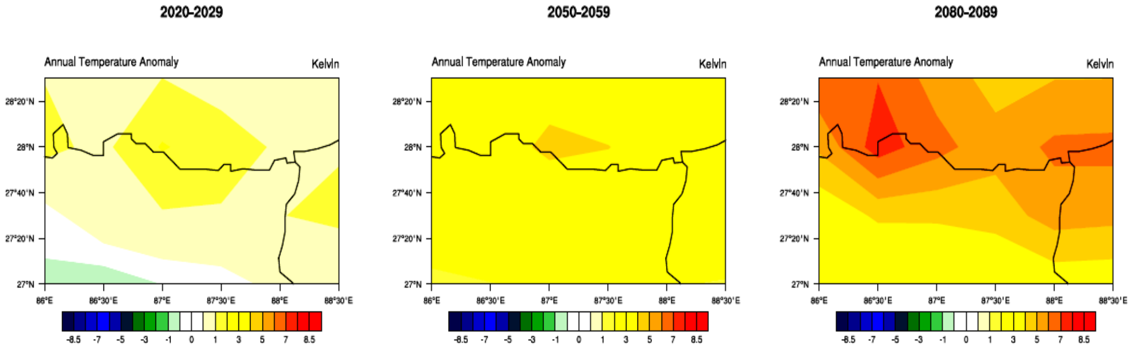


Fig. 4.1.4 Projected temperature change in Koshi basin

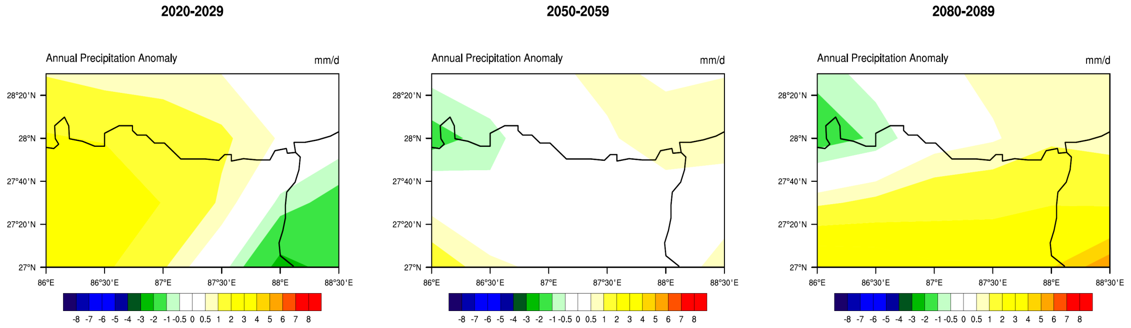


Fig. 4.1.5 Projected annual precipitation change in Koshi basin

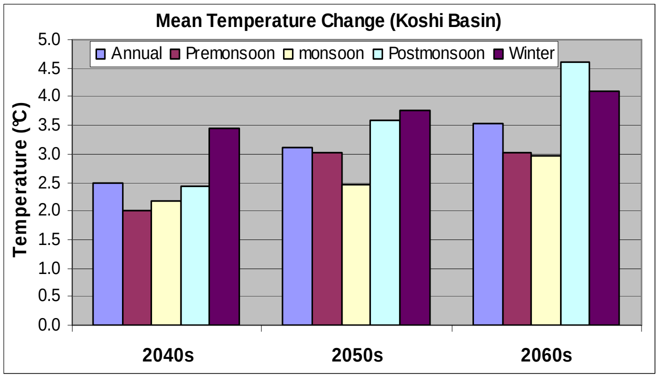


Fig. 4.1.6 Projected seasonal mean temperature change for Koshi Basin in different decades

Likewise, the projected annual and seasonal mean temperature change for the Koshi basin in three decades as indicated by PRECIS run at 25 km resolution is presented in Figs. 8. Annual mean temperature change over the three decades show increasing warming trend i.e. rise of 2.5^{0}C, 3.1^{0}C and 3.5^{0}C for the decades of 2040s, 2050s and 2060s respectively from the baseline period. The projected mean seasonal rise in temperature is highest in winter for 2040s and 2050s but in 2060s post-monsoon seasonal rise is projected to become the highest due to rapid rate of temperature rise in this season and slower rate of rising in winter season. Similarly, lowest rise in temperature is projected during pre-monsoon in 2040s and during monsoon in 2050s and 2060s. This shows that amplitude of projected seasonal warming over different sub-region might vary in different decades and this could be especially true for smaller regions.

The projected annual and seasonal mean precipitation change in absolute and percentage values for the Koshi basin in three decades as indicated by PRECIS run at 25 km resolution is presented in Fig. 4.1.7. Koshi Basin average annual mean precipitation change shows no decadal trend. In fact these values are very close to each other (about 7%). Projected absolute change in precipitation is highest

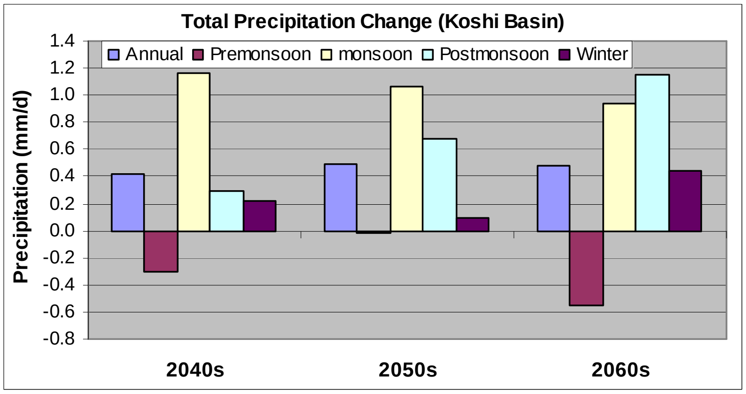
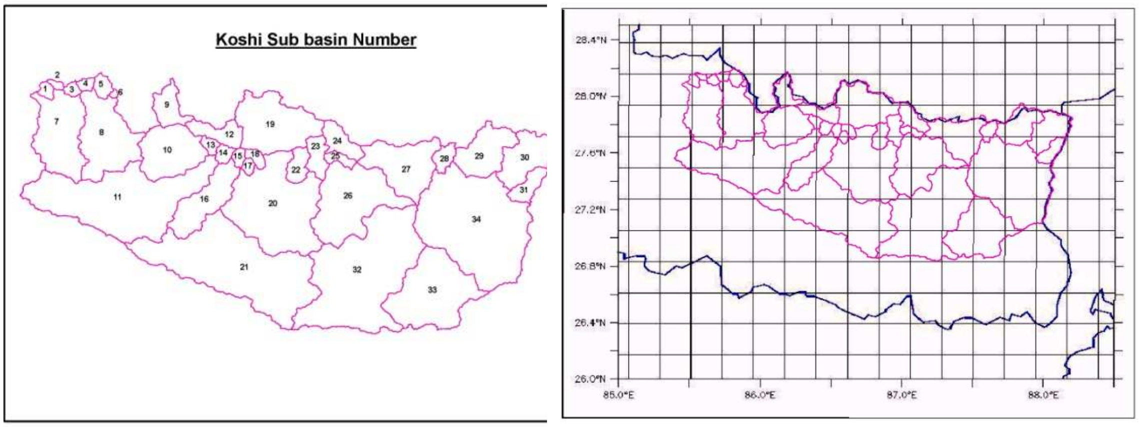


Fig. 4.1.7 Projected seasonal mean precipitation change for Koshi Basin in different decades

during monsoon for 2040s and 2050s and highest during post-monsoon in 2060s. Large inter-decadal decadal variability in projected precipitation change is noted for all seasons except for monsoon. For example, post-monsoon projected change jumps from 0.3 mm/d (10%) in 2040s to 1.2 mm/d (40%) in 2060s. Therefore considerable inter-decadal variation could be expected in seasonal change.

Data Extraction for Hydrological Model and Bias Correction

In connection with hydrological modeling of snow and glacial melt runoff, Koshi basin is subdivided into 34 sub-basins. In order to project hydrological change in the basin as a result of climate change, each sub-basin area-average temperature and precipitation are obtained from PRECIS output as a weighted average over the grid boxes covering the sub-basins (Fig. 4.1.8). The weights are determined as the fraction of the sub-basin area falling within a specific grid box, using a 0.22^0 grid (Leander et al, 2007).


a)

b)

Fig. 4.1.8 Koshi Sub basin

a) Numbers; b) Overlay onto model grid at 0.22º resolution

Bias Correction

Many techniques are available and more are emerging for bias correcting RCM generated daily climate data which are primary input in hydrological models. Of the various approaches, the following method has been used for bias correction to input PRECIS RCM daily climate data in hydrological model.

Method of Scaling

For each sub-basin, simulated baseline annual mean RCM temperature and precipitation data are scaled to observed annual mean using constant scaling factors derived thereof. The scaling factors derived for the baseline simulation of a RCM are also applied to adjust future simulations of the same RCM (e.g. Graham et al., 2007). This method is applied in this study for correcting bias in PRECIS daily temperature and precipitation data for baseline and future.

Arithmetic mean of temperature scaling factors from 34 subbasins is -0.6ºC having spread from -6.5ºC to +6.9ºC. Similarly, arithmetic mean of precipitation scaling factors from 34 subbasins is 0.5 with spread from 0.2 to 1.4. To generate bias corrected baseline and future daily time series for each subbasin; corresponding scaling factor is added to corresponding daily temperature time series and multiplied in case of daily precipitation time series.

WRF Model Runs

The results of WRF Model runs for Koshi basin provide greater spatial details (9km)as compared to PRECIS results (Fig. 4.1.9). However because of different constraints, PRECIS results with 25 km resolutions were used to study hydrological impacts in Koshi basin.

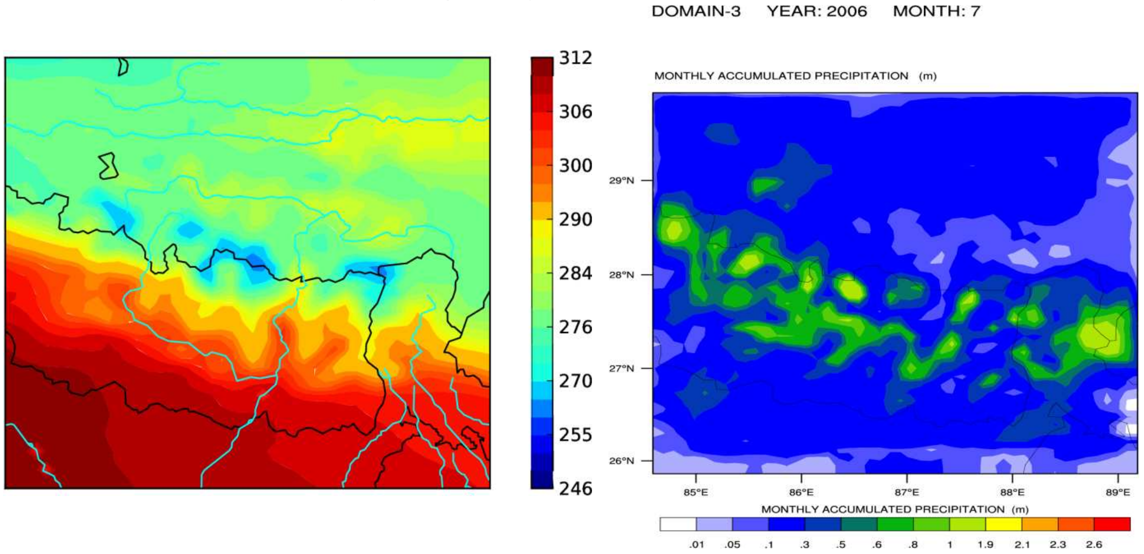


Fig. 4.1.9 WRF Test Run For Koshi Basin

4.1.2 Upper Bhagirathi Basin

4.1.2.1 Trends in precipitation

In mountainous areas, trend characterization of precipitation is challenging due to inherent variability across space and time, therefore, it is difficult to predict a significant long term change. The distribution of rainfall in the upper Bhagirathi basin is also highly influenced by prevailing seasonal and altitudinal variations. About 66-75% of the total annual rainfall occurs in the months of July and August in the area. Lower altitudinal areas of the study basin receive rainfall during summer monsoon whereas upper part is a rain shadow areas as it receives very less rainfall and the precipitation occurs mainly in the form of snow. Though the MK tests fail to detect any significant trend, the overall regression analysis (Fig. 4.1.10), in general, shows that the rainfall has decreased by an average of 10-15 mm in the last 8 years in the region. Further, the PRECIS simulated rainfall data of 30 years (1961-90) has been categorized into four seasons namely: pre-monsoon, monsoon, post-monsoon and winter for analysis. Though the results are not very significant, the linear regression analyses show (Figs. 4.1.11 & 4.1.12) a decreasing trend of rainfall, both annually and seasonally during the last 30 years in the study region. Pre-monsoon period shows more decreasing trend (2-7% form annual average) in rainfall in comparison to other seasons. However, the post-monsoon and winter seasons in particular are the periods of least rainfall in the region. During these seasons no significant trend is observed mainly on account of the fact that the rainfall itself is insignificant, and that the precipitation occurs mainly in the form of snow. The analyses of future rainfall scenario using PRECIS output data for the years 2071-2100, also project a decreasing trends of rainfall, both annually and seasonally (except for winter which shows some increasing trends; Fig.4.1.12). The projections indicate an average 3-4 mm decline in the pre-monsoon, 5-8 mm decline in the monsoon period, and 6-9 mm decline in the post-monsoon rainfall, and 2-5 mm increase in winter rainfall.

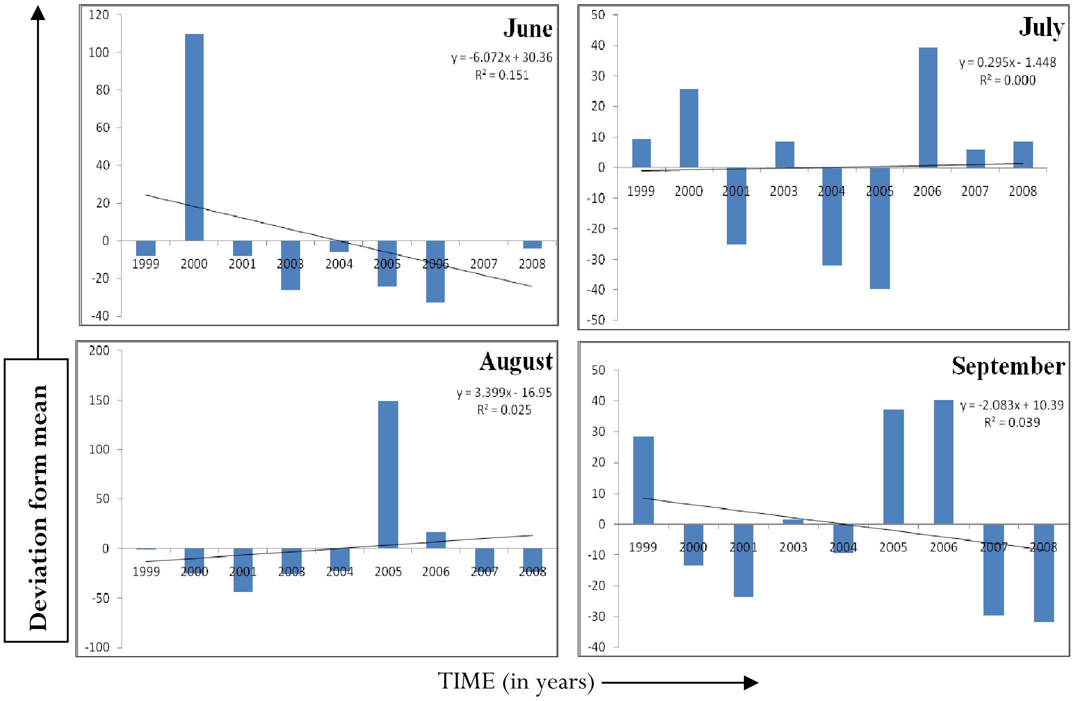


Fig. 4.1.10 Trends of average rainfall observed at the gauging station near Gomukh

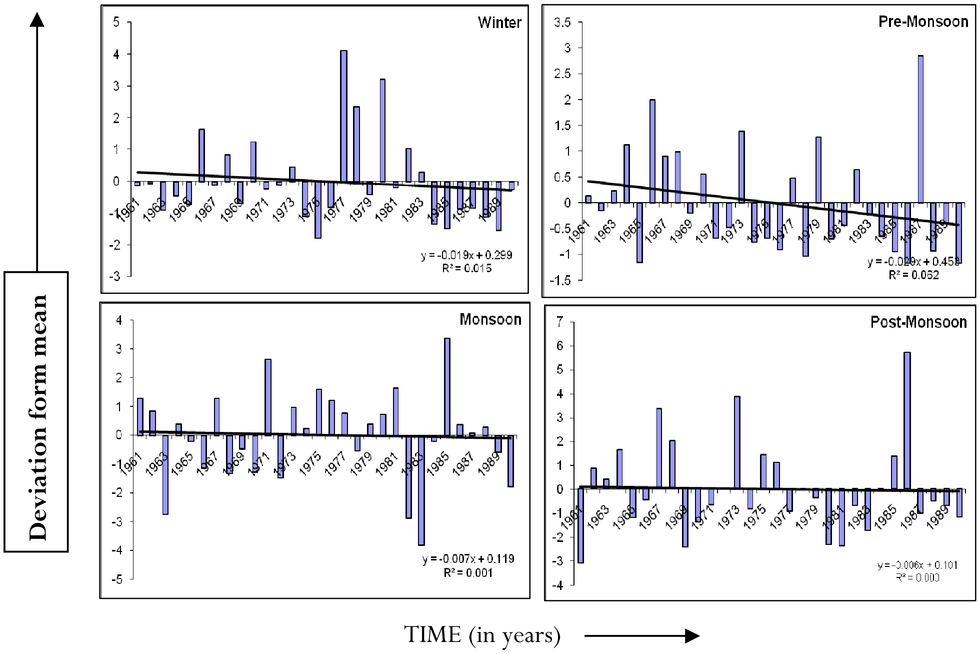


Figure 4.1.11. Trends of simulated daily average rainfall patterns using PRECIS RCM data

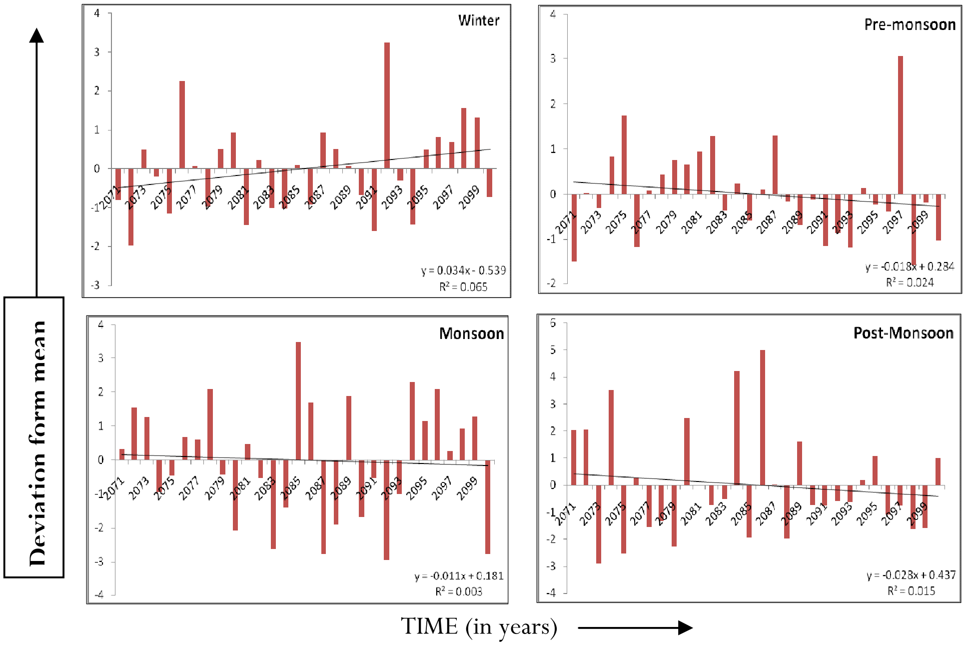


Figure 4.1.12. Future Trends of projected average rainfall patterns using PRECIS RCM data

4.1.2.2 Trends in Temperature

Temperature starts rising during April to July in the upper Bhagirathi basin and begins to fall on the onset of monsoon. Mixed trends have been observed in case of temperature recorded at the gauging site (4000m amsl). The recorded data show increase in mean temperature till 2006, but decrease in last the two years, i.e., for 2007-08 (Fig.4.1.13). Due to limited availability of data and that too only for the ablation period, the changing trend(s) of temperature cannot be analyzed effectively. However, the PRECIS RCM data for temperature clearly show an increase in temperature, both annually and seasonally (Figs. 4.1.14 & 4.1.15). The PRECIS RCM data show that the pre-monsoon temperature has increased by 2-3^{0}C, while the average temperature for monsoon period

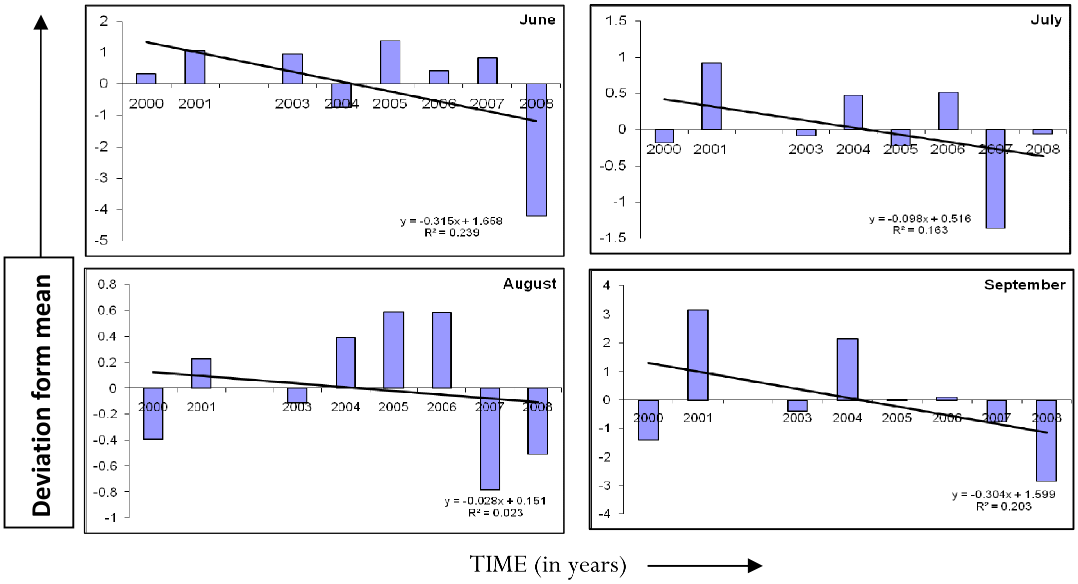


Figure 4.1.13. Trends of daily average Temperature observed at the gauging station near Gomukh

has increased by 1-2^{0}C in the region. Similarly, an increase of 3^{0}C in the post-monsoon temperature and 3-4^{0}C rise in the winter temperature has been observed in the last 30 years. The PRECIS output data of daily mean temperature for A2 scenario has also been analyzed, and the future projections have been depicted in Fig. 22. The analyses show an increasing trend of temperature, both annually and seasonally. The PRECIS output data projects 2-4^{0}C increase in temperature during winters, 3-5^{0}C rise in the pre-monsoon, 1-2^{0}C rise during the monsoon, and 3-4^{0}C rise in temperature in the post-monsoon periods.

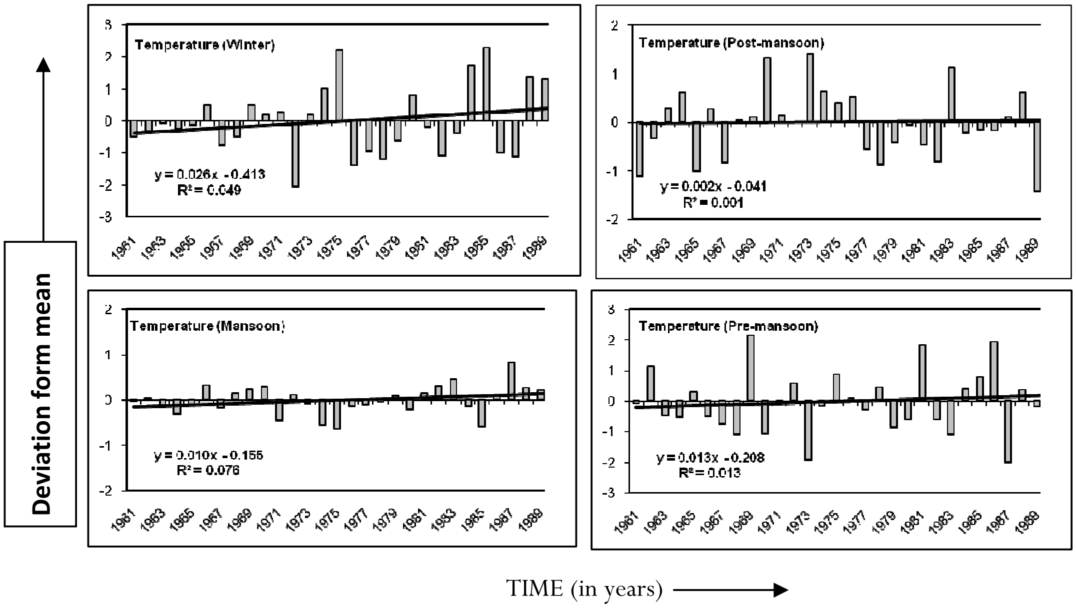


Fig. 4.1.14 Trends of simulated average daily Temperature using PRECIS RCM data

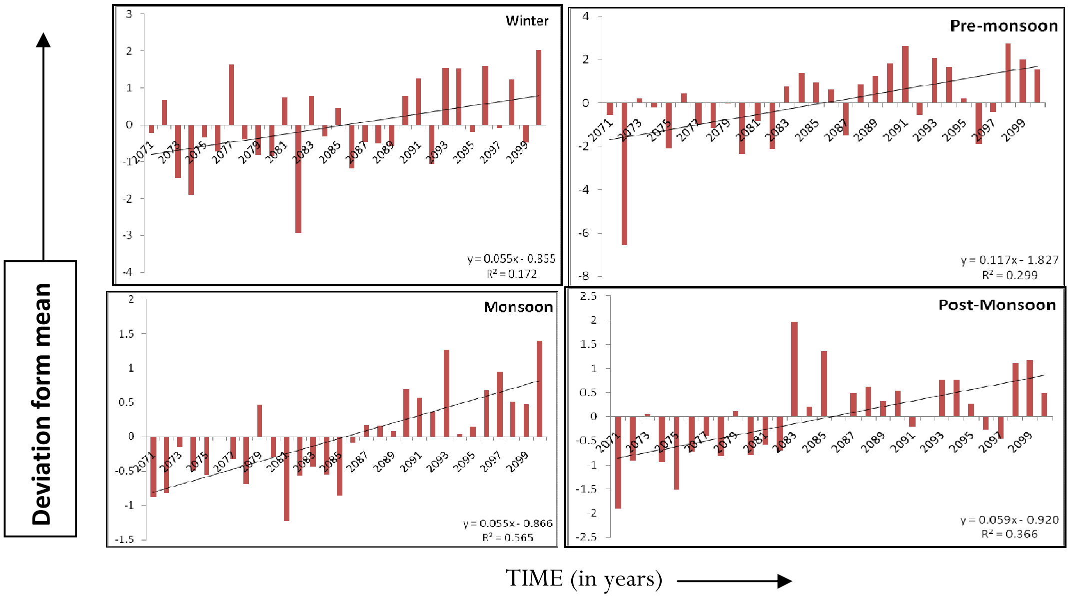


Fig. 4.1.15 Future trends of Projected average temperature using PRECIS RCM data

4.1.3 Hunza Basin

4.1.3.1 Validation of PRECIS Output over Hunza River Basin

Before using the PRECIS data into hydrological model for further studies, its validity for the Hunza Basin has been investigated. Downscaled data has been first regridded to regular latitude/ longitude grids (dx=dy=50km) and then compared with monthly mean temperature at 0.5 degree resolution of CRU data set (New et al, 1999). For validation of time series data, observed meteorological data of four stations for Hunza Basin have also been used (See Table 1). This is done by first averaging all the stations' data into one time series and is then compared with the PRECIS simulated time series. For model validation, biases are calculated for annual and seasonal mean precipitation and temperature by comparing PRECIS output with CRU climatology. Figure-9 shows the spatial patterns of averaged climatology of CRU and modeled (driven with ECHAM4 GCM) for precipitation and temperature along with the calculated model biases.

It is observed from the analysis of PRECIS output that the model simulated almost realistically the 30- years area-averaged/spatial pattern of temperature and precipitation. Large variation in temperature and precipitation has been found in their spatial patterns over the basin. The model's biases have been found in both climatic parameters (temperature and precipitation) however model response in simulating temperature is found better than in precipitation. In case of temperature, model shows 3 to 9 degree Celsius of cold bias over the Hunza River Basin. Perhaps these higher biases are mainly due to the complex topography and the model's inability to consider the orography above 5500 masl over the HKH region.

In case of precipitation, the spatial pattern shows that the model overestimates precipitation over the Hunza River Basin however pattern of precipitation seems to be well captured by PRECIS.

Annual cycles of precipitation and temperature are calculated from the area average time series over Hunza Basin and are shown in Fig. 4.1.16 & 4.1.17 respectively. Model has over estimated precipitation in both summer and winter, whereas biases in summer are less than both for annual and winter seasons. Higher estimates of precipitation in winter season seem to be logical as precipitation input is dominated in winter season. Secondly, the flow observed at Dainyor Bridge did not match to the precipitation values measured at valley bottom stations and suggest much higher precipitation on higher elevations. It is also in agreement with the higher snow accumulation in the order of 700-1000mm above 4500 meters amsl reported by numerous expeditions (Hewitt 1968). In the case of temperature, there are cold biases through out the year over the basin except during spring season where model estimates match well with CRU data.

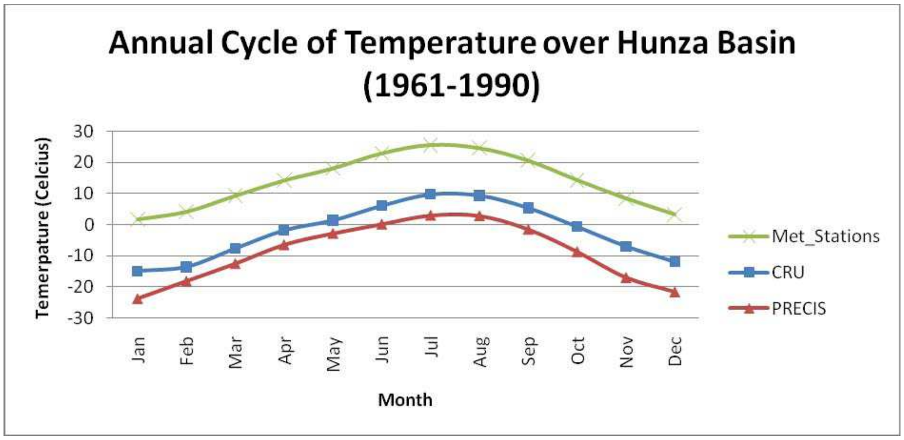


Fig. 4.1.16 Annual Cycle of Temperature for Met Stations, CRU &PRECIS over Hunza River Basin for the Period 1961-1990

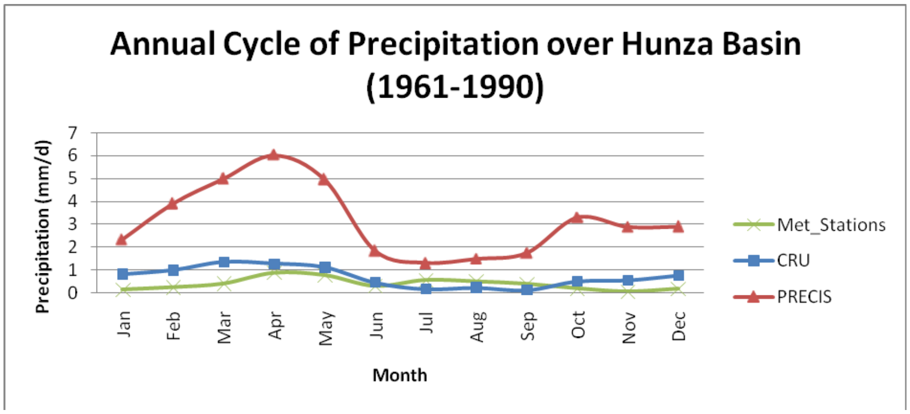


Fig. 4.1.17 Annual Cycle of Precipitation for Met_Stations, CRU &PRECIS over Hunza River Basin for the Period 1961-1990

4.1.3.2 Climate Change Projections

Climate change scenarios provide the best-available means of exploring how human activities in future may change the composition of the atmosphere, how this may affect global climate, and how the resulting climate changes may impact upon the environment and human activities. Here, the future changes in the temperature and precipitation over the Hunza Basin have been calculated for three climates (2020s, 2050s & 2080s) on annual as well as seasonal basis by comparing with the base climate (1961-1990). Annual cycles of temperature and precipitation for future climates (2020s, 2050s & 2080s) are calculated by averaging the values over the basin Fig. 4.1.18 & 4.1.19 respectively. The temperature cycles of base and three futures have same patterns but with the increase of around 5.5°C by the end of the century. For precipitation, the increase is visible in winter and spring whereas decrease in fall and summer.

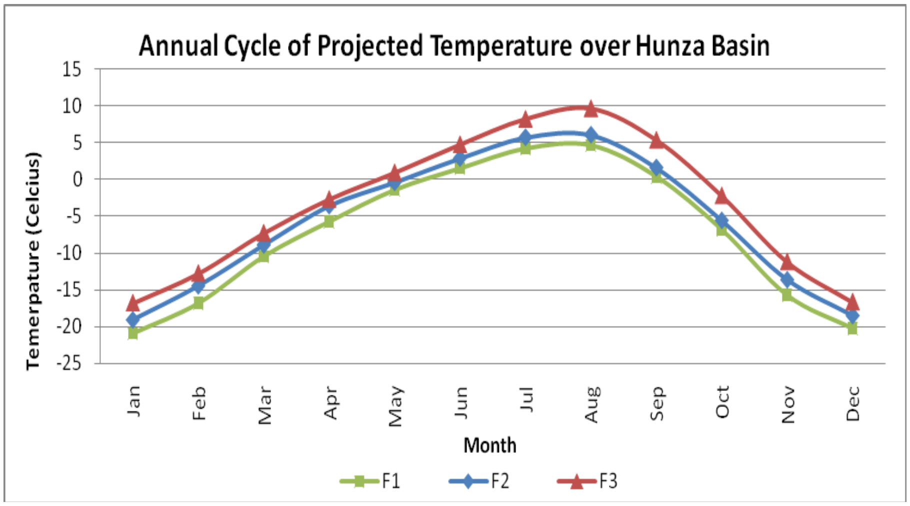


Fig. 4.1.18 Annual Cycles of Temperature for F1 (2020s), F2 (2050s) & F3 (2080s)

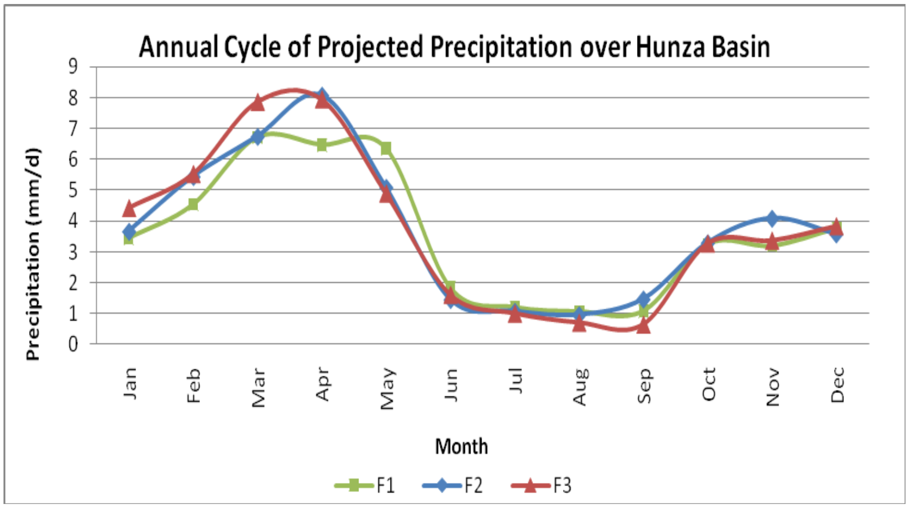


Fig. 4.1.19 Annual Cycles of Precipitation for F1 (2020s), F2 (2050s) & F3 (2080s)

Annual as well as seasonal analysis of temperature and precipitation change has been shown in Table-S3.2. Over the Hunza Basin, the annual temperature rise is 5.48°C by the end of the current century which is far more than the projected temperature increase for A2 globally i.e. 4.0oC. In case of precipitation about 10% increase has been observed by the end of the current century.

The seasonal analysis of temperature shows higher temperature increase in fall and winter than the spring and summer temperatures. In case of precipitation, increase has been observed for spring and winter seasons through out the century but greater increase is observed in winter than spring (i.e. 34% with respect to base period). However, summer precipitation is found to be decreasing up to 26% by the end of present century.

Likewise, climate change projections for IPCC SRES A2 using the PRECIS based on downscaling of GCM ECHAM4 for annual as well as seasonal temperature and precipitation change over Hunza basin for the various projection periods are shown in Table 1.

Table 4.1.1. PRECIS Climate Projection for A2 over Hunza basin

		Δ Temperature ^{o}C			Δ Precipitation %		
		2020s	2050s	2080s	2020s	2050s	2080s
Annual		1.58	3.21	5.48	4.25	9.34	9.94
Seasonal	Spring(MAM)	1.39	2.97	4.25	10.22	12.37	17.15
	Summer(JJA)	1.48	2.93	5.58	-9.42	-22.76	-26.46
	Fall(SON)	1.66	3.17	6.37	-12.21	3.47	-14.70
	Winter(DJF)	1.78	3.75	5.72	13.65	23.06	33.97

Over the Hunza Basin, the projected annual temperature rise of 5.48°C by the end of the current century seems far more than the global projected temperature increase of 4.0^{o}C for A2. In case of precipitation about 10% increase has been observed by the end of the current century. The seasonal analysis of temperature shows higher temperature increase in fall and winter than the spring and summer temperatures. In case of precipitation, increase has been observed for spring and winter seasons throughout the century but greater increase is observed in winter than spring (i.e. 34% with respect to base period). However, precipitation in summer and fall are found to be decreasing by up to 26% and 15% respectively by the end of present century.

4.2 Snow and Glacial Melt and Runoff in the Study Basins

Global change impact on snow and glaciers together with the melt runoff in the selected study basins namely Koshi, Upper Bhagirathi and Hunza basins, were studied by using different models and methods. The results of the studies in details are provided in the attached “Supplementay Materials”. Here the major aspects of the results are presented and discussed.

4.2.1 Snow and Glacial Melt and Runoff in the Koshi Basin

Koshi basin, the selected study basin in Nepal, is surrounded by the ridges separating it from the Brahmaputra in the north, the Gandaki in the west, the Mahananda in the east, and by the Ganges in the south. The Koshi river, along with its tributaries including some originating in Tibet, drains a total area of 69,300 km^2 up to its confluence with the Ganges in India (29,400 km^2 in China, 30,700 km^2 in Nepal and 9,200 km^2 in India). The Koshi river has seven major tributeries – the Indrawati, Sun Koshi, Tama Koshi, Likhu, Dudh Koshi, Arun, and Tamor (fig.). All the major tributaries join before passing out through the outlet at Chatara, approximately 48 km north of the Indo-Nepal border. The catchment area of Koshi river within Nepal estimated upto Chatara is 25,923 km^2 that is about 18% of total area of the Country. The highest elevation in Koshi basin is 8,848m (Mt. Everest) and the lowest elevation is 140m at Chatara.

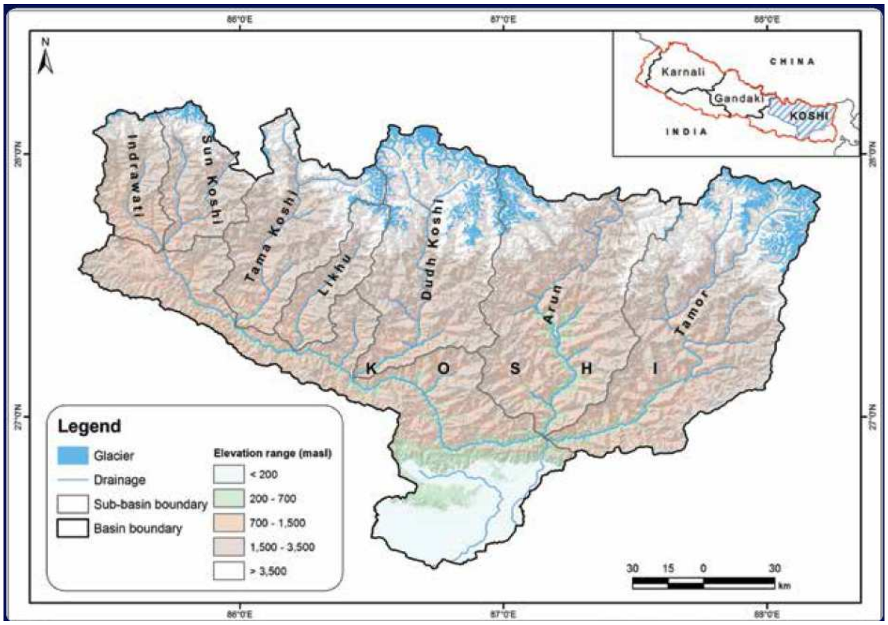


Fig. 4.2.1.1 Koshi Basin in Nepal with its Seven Tributeries

The Koshi basin has significant coverage of active glaciers and glacier lakes. The tributaries of Koshi River encircle Mt Everest from all sides and are fed by the world's highest glaciers. They contained 845 glaciers with a total area of 1,103 km^2 and estimated ice reserves of 111 km^3. The 19 large glaciers (2% of the total number) with an average area of 28.9 km^2 contributed to 50% of the glacier area and 73% of the estimated ice reserves. Less than 6% of the glaciers were valley basin type with average area 14.2 km^2 and contributed 62% of the total glacier area and 83% of the estimated ice reserves. Valley glaciers contributed more than 50% of the total glacierized area in the Dudh Koshi and Tamor sub-basins.

One-third of the glaciers (287) and slightly more than a third of the glaciated area (391 km^2) were within the Dudh Koshi sub-basin. The Dudh Koshi sub-basin contained the largest glacier in Nepal, the Ngojumba glacier, with an area of 78.7 km^2.

4.2.1.1 Snow and Glacier Dynamics

Investigatations on seasonal and interannual snow cover extension and dynamics on the Koshi river basin (57,800 km^2) by analyzing ten years of 8-days MODIS snow products (MOD10-V005) from 2000 to 2010 indicated snow cover extent exhibiting interannual variability mainly in high mountains sub-basins with the variability decreasing at the lower sub-basins. Althouh primary results from some other study indicated that snow is sensitive to the seasonal change of temperature (Gao et al., 2010), no significant trend in snow cover duration was observed during the considered period (2000-2010) at annual or seasonal scales, neither at basin scale, nor depending on elevation (Zin et al., 2010).

Likewise, the published literatures on glacier numbers, area and estimated ice reserves in the Koshi basin during the decadal periods from 1980 to 2010 have all revealed the melting of glaciers in the Koshi basin, leading to increase in the numbers of glaciers apparently due to melting of original glacier causing its fragmaentation, and decrease in the overall area and estimated ice reserves of glaciers in the basin (Table 4.2.1).

Table 4.2.1.1 Changes in Glaciers on Koshi Basin from ~1980 - 2010

Glacier	Decade (Year)				Dcadal Glacier Change							
	~1980	1990	2000	2010	~1980-1990		1990-2000		2000-2010		~1980-2010	
Number	736	806	829	845	+70	+10%	+23	+3%	+16	+2%	+109	+15%
Area (km^2)	1,499	1,294	1,213	1,103	-205	-14%	-82	-6%	-110	-9%	-396	-26%
Estimated Ice Reserves (km^3)	159	133	124	111	-26	-16%	-9	-7%	-13	-11%	-48	-30%

Source: ICIMOD, 2001, 2005 & 2011.

4.2.1.2 Snow and Glacial Melts and Runoff

A conceptual precipitation runoff model has been used to simulate the daily runoff from 22 glacierized sub-watersheds of Koshi basin identified by using satellite imagery of the basin for that purpose. Snow and glacier melt were calculated by surface energy balance and mass balance modes. The glacier melt under the debris layer is estimated from thermal resistance to critical thermal resistance ratio. The ratio has been estimated from surface temperature of the debris obtained from spatial modeling of the LANDSAT. A simple empirical relation is used to define the type of precipitation. The precipitation as rainfall, snow and glacier melt in all bands are averaged and used as input to the conceptual TANK model for runoff simulation. The estimated runoff from the melts is then routed downstream to basin outlet in plain via seven major tributaries using semi- distributed rainfall-runoff model. The analysis indicated that snow and glacier melt alone contribute maximum up to 20% of dry season flow to sustain the livelihood of downstream people. The likely impact on the same in future due to climate change is also analyzed.

For the comprehensive catchment modeling of whole Koshi basin, daily precipitation records of 27 rainfall stations within the basin for period of 1st Jan 2002 to 31st Dec 2006 were used. For calibration and validation purposes, discharge data of basin outlet station “Chatara” was selected. The data for period of 1st Jan 2002 to 31st Dec 2003 was used for calibration and the data for period 1st Jan 2005 to 31st Dec 2006 was used for validation of the model.

The daily discharge data of stations ‘Uwagaon’(station No. 600.1) and ‘Busti’(station No. 647) for period 2002-2006 were used as input to the model to represent the discharge entering from upper part of the basin that lies in Tibetan territory. Fig 4.2.1.2 represents the locations of hydro-meteorological stations.

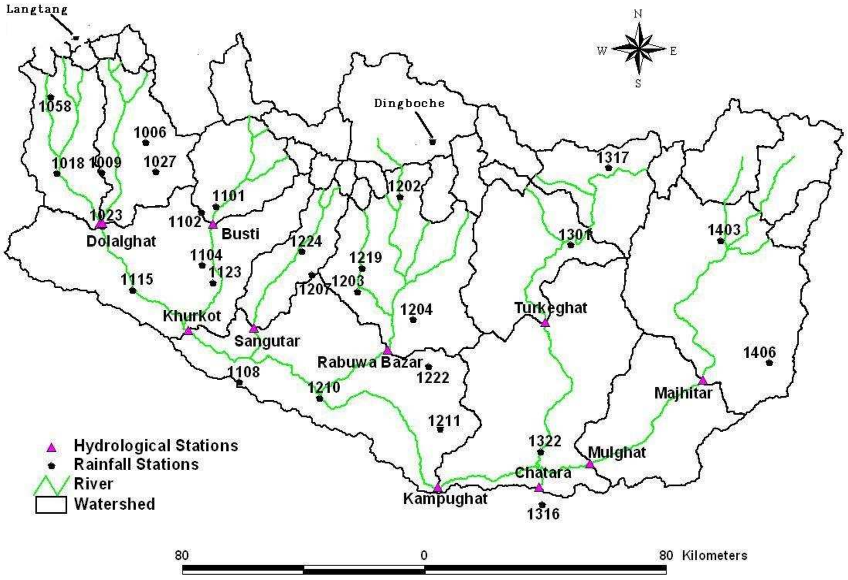


Fig. 4.2.1.2 Locations of hydro-meteorological stations in Koshi Basin

4.2.1.3 The modeling approach

The study area (Fig.4.2.2.3) was divided into 12 sub-basins (ID: 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 36 and 37), at stream gauging stations. Seven out of those delineated twelve sub-basins contain snow and glaciated areas. The areas above 4000m altitude above amsl of those seven sub-basins were further subdivided into 22 sub-watersheds (ID: 14 to 35) to assess the dynamics of snow and glaciers. Since those 22 glacierized watersheds have significant snow and glacier coverage, discharge at outlets of these sub watersheds were estimated using energy budget method aided with a lumped TANK model.

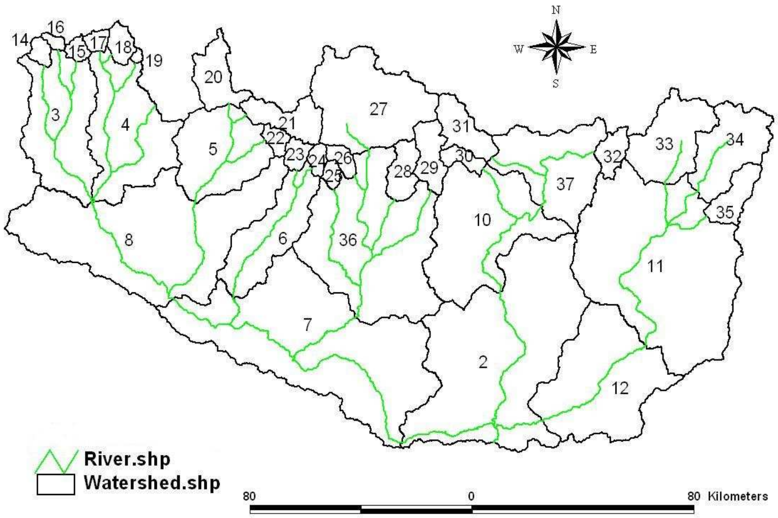
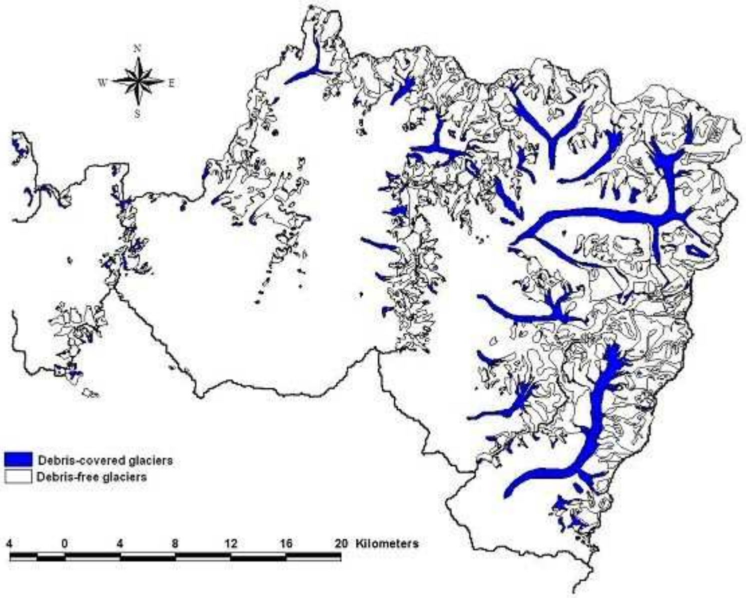


Fig. 4.2.1.3 Delineation of Sub-basins and glaciated sub-watersheds of Koshi basin

For this purpose, each of the glaciated sub-watersheds was divided into 20 altitudinal bands (Fig 4.2.2.4) of 300m interval. The characteristics of each altitude band including mean area, area of debris-covered maps were obtained from landuse maps, topographical maps and Landsat imagery using GIS and Image processing. These meteorological data such as solar radiation, wind speed, relative humidity and surface data such as albedo and density were assumed independent of temporal & spatial variations for the study area. Monthly adiabatic lapse of mean temperature (2.8 to 5.4°C.km^{-1} in DHM, 2002) was used to derive the temperature at higher altitudes.



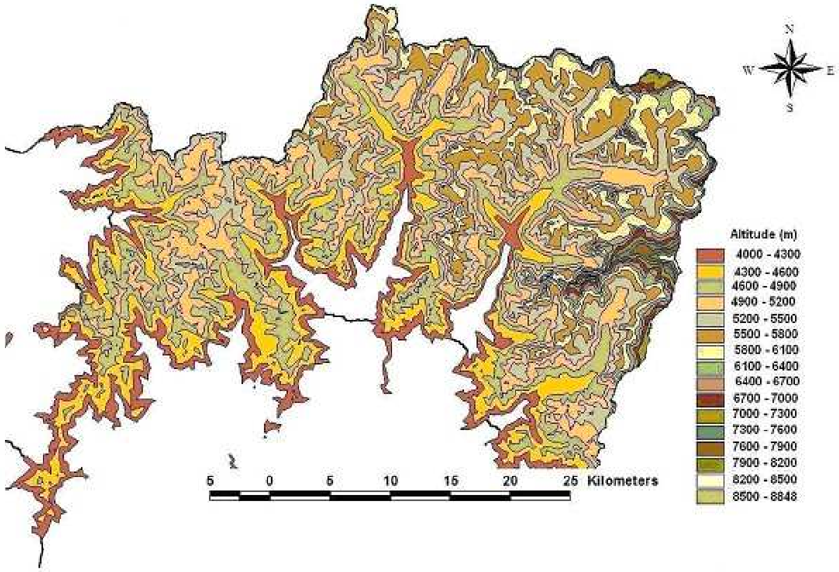


Fig 4.2.1.4 Glaciated Sub-Watersheds Divided into 16 Altitudinal Bands of 300m Interval

Surface Energy Balance Model

The energy available to melt snow/glacier was calculated using surface energy balance model from the available meteorological data. For the estimation of glacier melt under a debris layer, effective thermal resistance (R) was calculated by following Nakawo and Young Model (1982). The surface temperatures were extracted using the simplified plank function (Chen et al., 2006) accounting no variation of calibration constants. Digital numbers (DNs) of band 6 of Landsat -7 ETM+ image were converted to radiance luminance (R_{TM6}, $mWcm^{-2}sr^{-1}$) and satellite brightness temperature in Kelvin, T(K).

The response of the watershed at Dingboche and Langtang gauging stations due to precipitation, snow and icemelt were simulated using Tank model. The calibrated parameters of TANK model fitted for Langtang Gauging station were used for simulating runoff from watersheds nos. 14 to 20. While the runoff from the remaining sub watersheds was simulated, using the TANK model parameters calibrated for Dingboche gauging station.

For comprehensive semi-distributed catchment modeling, basin model was developed using HEC-GeoHMS and HEC-HMS developed by US Army Corps. While generating basin model the simulated discharges of 22 glacerized sub watersheds were supplied to respective 7 sub basins downstream. Three more sources were added as boundary flow to represent the flow entering from Tibetan part of the basin. Fig. 4.2.2.5 illustrates the basin model for Koshi basin at Chatara.

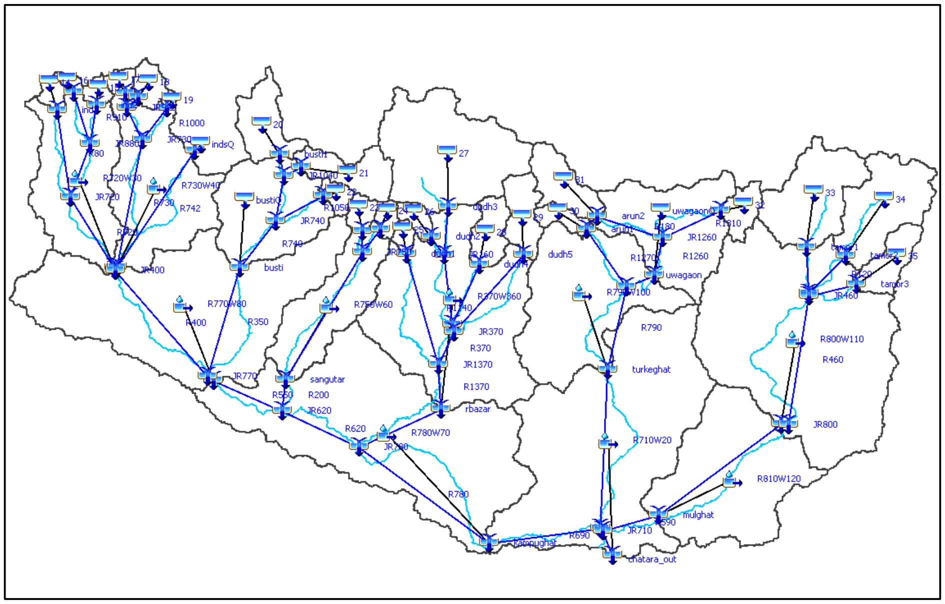


Fig 4.2.1.5 Semi-distributed Basin Model in HEC-HMS

4.2.1.4 Snow and Glacial Melt in Koshi Basin

The total melt volume comprising of glacial melt as well as snowmelt over bare ground area for the year 2002 were calculated for all smaller glaciated parts of the basins. The melt volume for seven sub-catchments of Koshi basin is then found out by summing up the ones from the associated respective individual smaller basins and is shown graphically in percentages in Fig. 4.2.1.6.

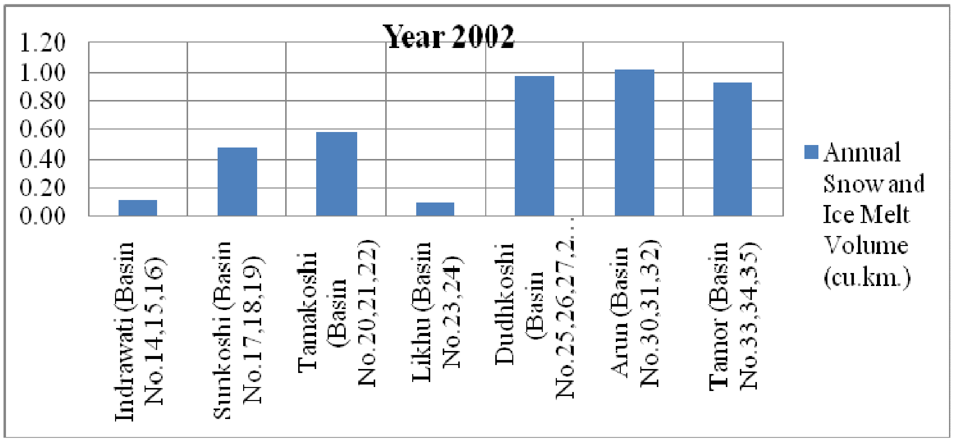


Figure 4.2.1.6 Annual Volume of Snow and Ice Melt in Different Sub-basins of Koshi Basin in Nepal

The estimated runoff from the melts is then routed downstream to basin outlet in plain via seven major tributaries using a semi- distributed rainfall-runoff model namely HEC-HMS model. Monthly maximum and minimum as well as total snow and ice melt contributions of the seven tributeries of the Koshi basin in percentages of total flow at the lowermost downstream station 'Chatara' are all shown in Fig. 4.2.1.7 The numerical values at the outlet station as well as at the intermediate stations are given in Table 4.2.1.2 The analysis indicated that snow and glacier melt alone contribute maximum up to 20% of dry season flow. The contribution of snow and glacier melt discharge to annual flow at 'Chatara' is found to be about 8.46% with a maximum monthly contribution of 22.52% in May and a minimum monthly contribution of 1.86% in January. The snow and glacier melt discharge from Dudh Koshi sub-basin is found quite significant. It has maximum contribution to annual flow at Chatara (2.51% out of total 8.46%). Whereas glacierized watersheds of Indrawati sub-basin have minimum contribution to annual flow at Chatara (0.15% out of total 8.46%).

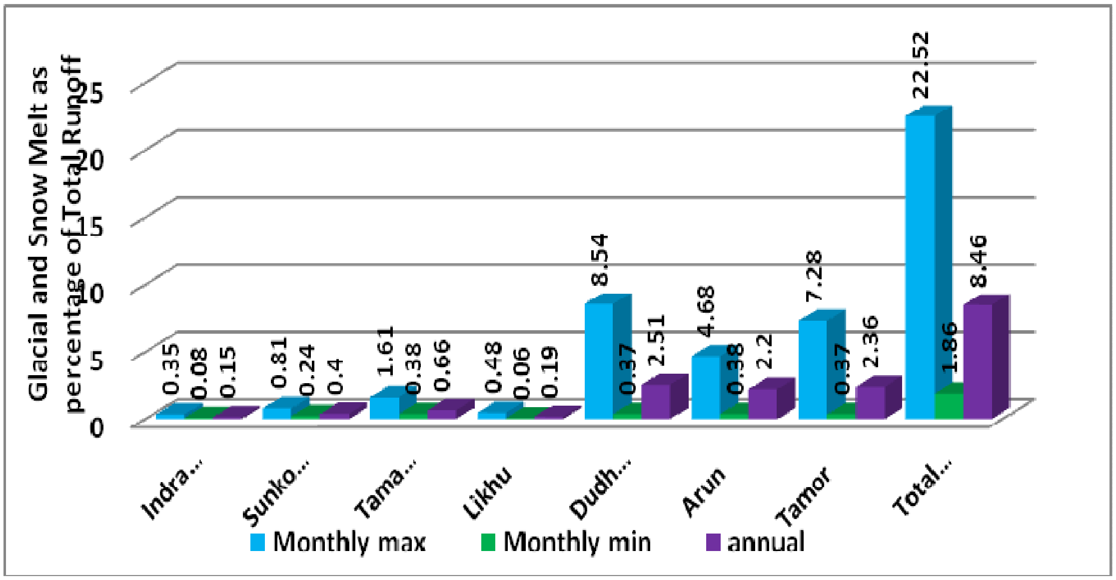


Fig. 4.2.1.7 Maximum and Minimum Percentages of Snow and Ice Melt Contributions in Total Flow at Chatara

Dudh Koshi, Arun and Tamor basins are three major tributaries, which share 84% in terms of contribution of snow and glacier melt to outlet of Koshi basin at Chatara. As almost half of the Arun river basin lies in Tibet that is not included in this analysis, its cryospheric melt contribution would obviously be much more than indicated here in this analysis.The estimated runoff from the melts is then routed downstream to basin outlet in plain via seven major tributaries using a semi- distributed rainfall-runoff model namely HEC-HMS model. The analysis indicated that snow and glacier melt alone contribute maximum up to 20% of dry season flow.

Table- 4.2.1.2 Contribution in Percentage of Glacierized Sub-Watersheds of Each Sub-Basins to the Total Flow at Downstream Stations

Sub-basins		Indrawati	Sunkoshi	Tama koshi	Likhu	Dudh koshi	Arun	Tamor	Overall Contribution
Station Name	monthly								
Indrawati (Dolalghat)	max	28.80	-	-	-	-	-	-	28.80
	min	1.83							1.83
	annual	3.66							3.66
Sunkoshi (Dolalghat)	max	-	7.70	-	-	-	-	-	7.70
	min		2.36						2.36
	annual		3.56						3.56
Busti	max	-	-	17.78	-	-	-	-	17.78
	min			5.17					5.17
	annual			7.55					7.55
Khurkot	max	1.28	3.11	5.80	-	-	-	-	9.99
	min	0.30	0.78	1.34					2.43
	annual	0.46	1.25	2.09					3.80
Sangutar	max	-	-	-	36.68	-	-	-	36.68
	min				1.64				1.64
	annual				8.96				8.96
Rabuwa bazar	max	-	-	-	-	74.01	-	-	74.01
	min					3.93			3.93
	annual					16.37			16.37
Kampughat	max	0.96	2.19	4.32	1.30	17.77	-	-	24.40
	min	0.20	0.53	0.90	0.14	0.97			2.95
	annual	0.30	0.80	1.33	0.37	5.05			7.85
Uwagaon	max	-	-	-	-	-	25.88	-	25.88
	min						0.90		0.90
	annual						14.92		14.92
Turkeghat	max	-	-	-	-	-	19.15	-	19.15
	min						0.93		0.93
	annual						9.45		9.45
Majhitar	max	-	-	-	-	-	-	31.97	31.97
	min							2.73	2.73
	annual							17.91	17.91
Mulghat	max	-	-	-	-	-	-	26.40	26.40
	min							1.80	1.80
	annual							8.84	8.84
Chatara	max	0.35	0.81	1.61	0.48	8.54	4.68	7.28	22.52
	min	0.08	0.24	0.38	0.06	0.37	0.38	0.37	1.86
	annual	0.15	0.40	0.66	0.19	2.51	2.20	2.36	8.46

4.2.1.5 Projected Runoff

Sensitivity test of snow and glacier melt contribution was carried out for increase per year in air temperatures of 0.02^0C, 0.04^0C, 0.08^0C and 0.12^0C. The results of the simulation for these scenarios are presented in Table 4.2.1.3

Table-4.2.1.3 Annual Snow and Glacier Melt Contribution (In %) for Increased Temperature Scenarios

Station Name	Increase in Temperature (∇T°C)				
	0.00°C	0.02°C	0.04°C	0.08°C	0.12°C
Indrawati (Dolalghat)	*3.66*	*3.66*	*3.67*	*3.68*	*3.72*
Sunkoshi (Dolalghat)	*3.56*	*3.57*	*3.59*	*3.61*	*3.66*
Busti	*7.55*	*7.57*	*7.58*	*7.61*	*7.69*
Khurkot	*3.80*	*3.81*	*3.82*	*3.84*	*3.89*
Sangutar	*8.96*	*8.98*	*9.03*	*9.10*	*9.17*
Rabuwa bazar	*16.37*	*16.39*	*16.49*	*16.58*	*16.63*
Kampughat	*7.85*	*7.86*	*7.90*	*7.95*	*8.00*
Uwagaon	*14.92*	*14.98*	*15.08*	*15.32*	*15.45*
Turkeghat	*9.45*	*9.48*	*9.55*	*9.71*	*9.80*
Majhitar	*17.91*	*17.94*	*18.03*	*18.15*	*18.21*
Mulghat	*8.84*	*8.86*	*8.91*	*8.97*	*9.01*
Chatara	*8.46*	*8.48*	*8.53*	*8.61*	*8.66*

The likely impact on the same in future due to climate change as analyzed by using projected climate parameters from the RCMs are presented below.

The hydrological model (HEC-HMS) after necessary caliberation and validation (Fig. 4.2.1.8 a & b) was used with projected meteorological parameters derived using RCM-PRECIS to assess the impacts of climate change on the runoff in the Koshi river. The comparions of projected flows in m^3/sec in the three tributeries in the decades from 2040s to 2070s, for example, are shown in Fig. 4.2.1.9 a-c

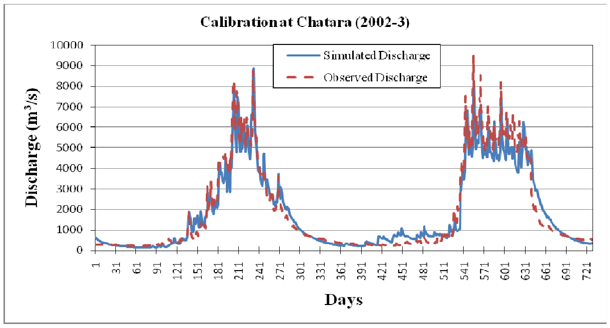


Fig. 4.2.1.8 (a) Calibration at basin outlet

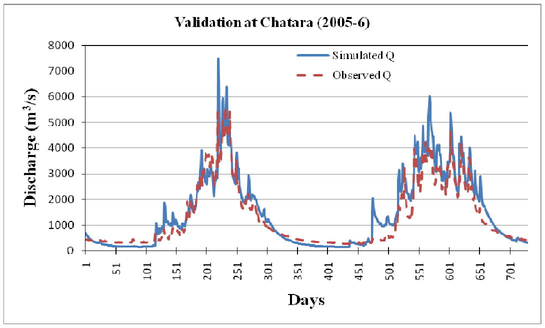


Fig. 4.2.1.8 (b) Validation at basin outlet

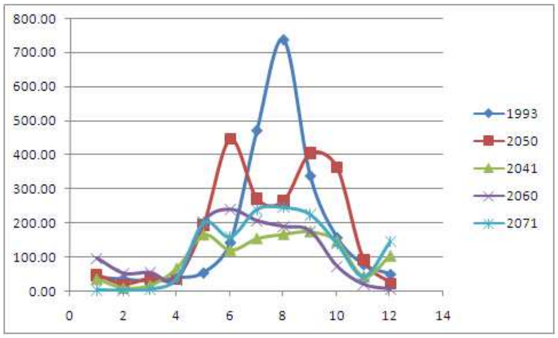


Fig. 4.2.1.9 (a) Comparison of projected flows for Dhudh Koshi

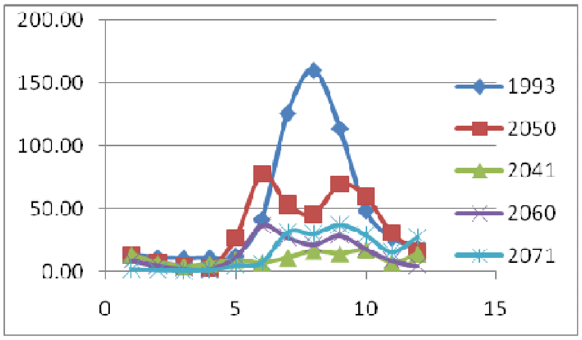


Fig. 4.2.1.9 (b) Comparison of projected flows for Likhu

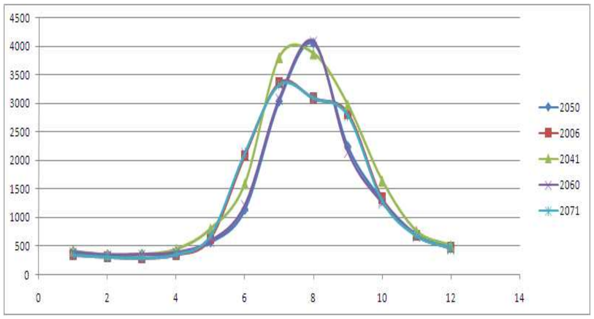


Fig. 4.2.1.9 (c) Comparison of flows of Saptakoshi at Chatara

Noteworthy changes can clearly be seen in the above hydrographs based on projected flows for the rivers Dudh Koshi and Likhu rivers, wherein snowmelt and glacier-melt constitute significant components. Meanwhile, hydrographs based on projected flows for the Saptakoshi river at Chatra, wherein snowmelt and glacier-melt do not figure as significant components, show signs of only minor changes with slight shift in the peak towards later parts of the year. Thus impacts of climate change become clearly prominent in the areas proximate to snow and glaciers, while the impact wanes in the areas far away.

4.2.1.6 Discussion

This study has thus focused on the snow and glacier melt estimation and hydrological modeling of the glacierized watersheds of Koshi basin for runoff simulation using the geographical information system, image processing in conjunction with the conceptual precipitation runoff modeling tools. The study has incorporated preprocessing and spatial analysis of the Digital Elevation Model (DEM) for the automated delineation of watersheds, processing of Landsat image for glaciations of debris covered glaciers and extraction of surface temperature, analysis of hydro-meteorological data, use of surface energy balance model for snow and glacier melt estimation including mass balance, and finally hydrological modeling of the watersheds for total runoff simulation.

The energy-balance model coupled with mass balance of snow has accordingly been used to calculate snow accumulation, snow and glacier ablation from all bare area, debris-free and debris-covered areas in each altitude bands of the watershed and averaged specific melt and rainfall shall be calculated. The energy fluxes estimations are driven by meteorological parameters and surface conditions. Assumption is made that all rain and melt water flows as surface runs off and refreezing of percolating water is not considered.

Projected meteorological parameters derived from RCM-PRECIS for the sub-basins were further used to drive the hydrological model (HEC-HMS) to determine the change in the runoff in the sub-basins as the impacts of climate change. But potential changes in glacier area or volume in the projected periods are not however considerd in such exercise. Moreover, the model grid at 0.22º resolution of the used RCMs are as yet coarse to represent the real temperature at the snow and glacited regions of the sub-basins in a rugged topography of the Himalayan regions.

Attempts were thus made to assess the climate change impacts on snowmelt, glacialmelt and runoff in the Koshi basin in a comprehensive way.

The study has shown that the contribution of snow and glacier melt discharge to annual flow at Chatara, the outlet of Koshi basin, is about 8.46% with a maximum monthly contribution of 22.52% in May and a minimum monthly contribution of 1.86% in January. The snow and glacier melt discharge contribution from the different glacierized watersheds to the flow at outlet however varies considerably with Dudh Koshi, for example, contributing 2.51% and Indrawati just 0.15% out of total 8.46% on the annual basis. Likewise, the maximum and minimum snow and glacier melt discharge contributions from the different glacierized watersheds as well as their timings are different for different watersheds.

4.2.2 Snow and Glacial Melt and Runoff in the Upper Bhagirathi River Basin

The Upper Bhagirathi river basin (UBRB), located in the state of Uttarakhand, has been selected as study basin in India. Location map of the study area is presented in Fig. 4.2.2.1. The upper Bhagirathi basin of the river Bhagirathi begins from Gaumukh, the snout of the Gangotri glacier, and ends at in Gangotri Township at a distance of 18 km. The UBRB's total glacierized area is about 258.56 sq. km, which is approximately 34% of total glacierized area of Bhagirathi catchment.

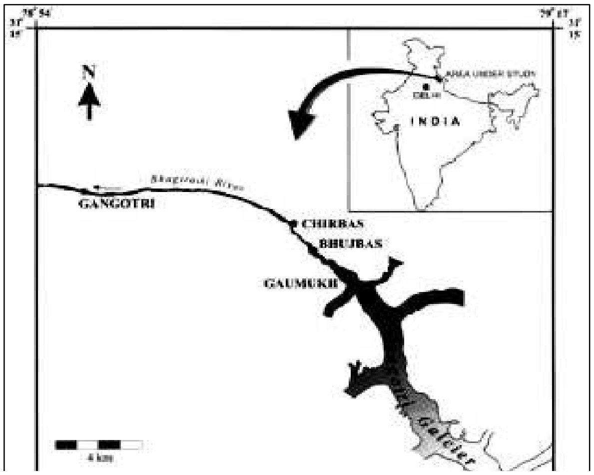


Fig. 4.2.2.1 Location map of the study area

Gangotri glacier, originating from Chaukhamba peaks (7138 masl), is 30.2 km long with a glacierised area of about 143.58 km^2. It is one of the most prominent glaciers in Central Himalaya, which is the source of the river Bhagirathi, a major tributary of Ganges, emanating from the Gangotri group of glaciers in Uttarkashi district of Uttarakhand. The catchment area of Bhagirathi (upstream to Gangotri) falls in the mountainous Higher and Trans Himalayan region.

In order to understand the distribution pattern of snow and glaciers with respect to topographic features, topo-maps of Survey of India (SoI) were used in the present study to prepare Digital Elevetion Model (DEM) for the upper Bhagirathi Basin at horizontal resolution of 40m. The prepared DEM was then used to derive area elevation map (Fig. 4.2.2.2).

4.2.2.1 Hypsometric analysis

The DEM of the study area is used for preparation of elevation map and area-elevation curve using Geographical Information System (GIS). The GIS technique is used to customize the tool for automatic extraction of area under different elevation zones for the upper Bhagirathi basin. Using this tool, area-altitude distribution and the summary table is generated which is further analyzed to generate hypsometric curve (Fig. 4.2.2.3) for the study basin. Percentage of area covered in each elevation zone of the study basin is given in Fig. 4.2.2.4 which is further used to estimate zonal mean elevation as an input in the hydrological model. Distribution of basin area along with altitude variation indicates that the

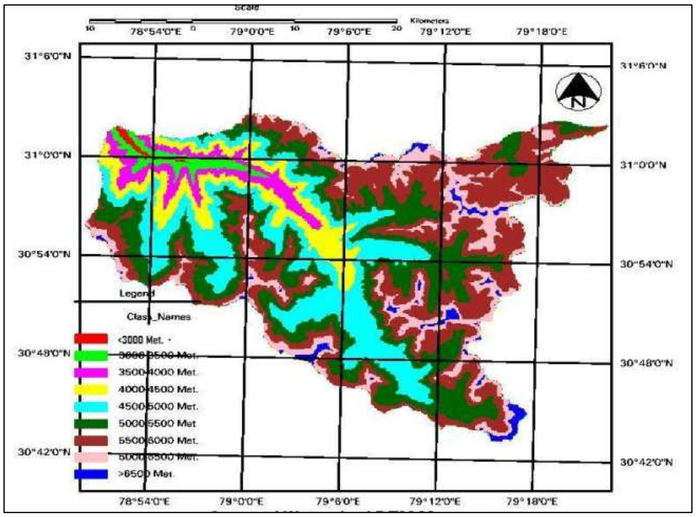


Fig. 4.2.2.2 UBRB Area Elevation Map

upper Bhagirathi basin lies within the elevation range 2600-7200 m and more than 70% of the basin area ranges between 4500 to 6000m elevations. It also depicts that 86% of area is covered under middle and lower elevation zones where as only 14% is covered under higher elevation zones which remains covered by permanent snow throughout the year. Summary of basin area under each elevation zone is given in Table 4.2.2.1.

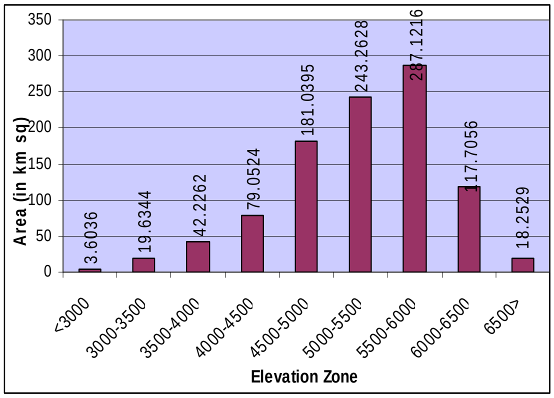


Figure 4.2.2.3 Area under different elevation zones

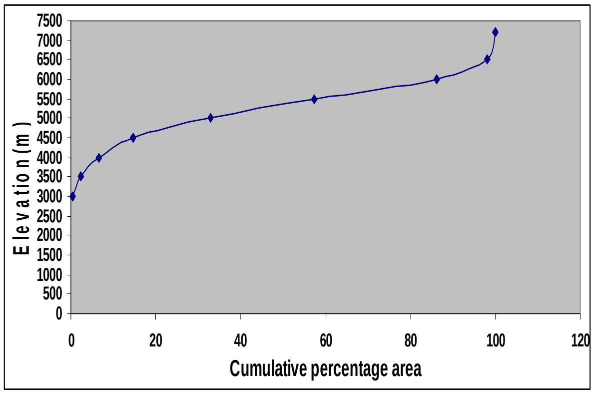


Fig. 4.2.2.4 Area altitude distribution curve for the upper Bhagirathi Basin

Table 4.2.2.1 Area-elevation characteristics of upper Bhagirathi river basin (UBRB)

Elevation Zone	Elevation range (in m)	Zone Area (in Km^2)	% Area	Cumulative Area (%)	Categorization of zones
Zone 9	<3000	3.6036	0.363303	0.363303	Lower Zone
Zone 8	3000-3500	19.6344	1.979476	2.342779	
Zone 7	3500-4000	42.2262	4.257107	6.599886	
Zone 6	4000-4500	79.0524	7.969803	14.56969	
Zone 5	4500-5000	181.0395	18.25181	32.8215	Middle Zone
Zone 4	5000-5500	243.2628	24.52496	57.34645	
Zone 3	5500-6000	287.1216	28.94666	86.29311	
Zone 2	6000-6500	117.7056	11.86669	98.1598	Higher Zone
Zone 1	6500>	18.2529	1.840197	100	
	Total	991.899			

4.2.2.2 Snow Cover and Its Analysis

Seasonal snow covers major part of the UBRB during winter. MODIS Terra 8 day composite snow cover products (MOD10A2) for the eleven years from 2000 to 2010 have been used as the source of snow cover information in the basin. They were used to study accumulation and depletion of snow at the different elevation zones including the seasonal changes in snow cover extensions in the basin.

A. Trends in Seasonal Snow Cover (SCA)

To understand the seasonal variation of SCA in upper Bhagirathi basin, the data were analyzed for four different seasons, namely; autumn (October-November), winter (December-March), spring (April-June), and summer (July-September). Mann-Kendall methods were first used to find trend in snow cover during the last decade. But as it did not reflect any statistically significant trend, linear regression method was adopted to identify trend in SCA in various seasons during past decade

(2000-2010). The linear regression method indicated an increasing trend in the mean annual SCA in all the elevation zones during last decade.

B. Changes in Seasonal Snow Cover (SCA) in Different Altitudes

Seasonal variation in snow covered area in different altitudinal zones was analyzed for each season (i.e. autumn, winter, spring, and summer) during past decade and the results are presented in Fig. 4.2.2.5. During the last decade, the SCA in autumn season shows varying degree of increase in higher and middle elevation zones with particularly higher rate of increase (13-21%) in middle zones (4500-5500m), whereas in lower zones 2-9% decline in SCA has been observed. In winter season, SCA has increased during past decade in all the elevation zones. During winter, the rate of increase of SCA in higher zones is comparatively very low (2-3%) than the increase in middle zones (4-10%) and in the lower elevation zones where 14-21% increase in SCA is observed during 2000-2010. From the analysis it is observed that, in spring season, 2-3% increase in higher zones, 6-14% increase in middle zones and 2-6% decline in SCA is observed in lower elevation zones. In case of summer season, non-significant increase in SCA in upper zones (approx. 7%) and a significantly greater increase (11-13%) in middle elevation zones is observed. Since, in the lower elevation zones very rare events of solid precipitation occur during the summer season, therefore, during summer the SCA in such altitudes is almost negligible; hence no variation (increase or decrease) is observed.

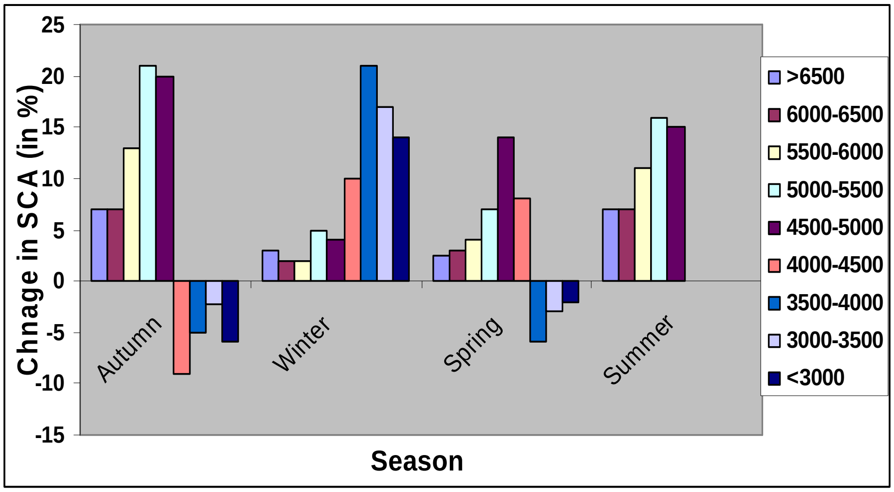


Fig. 4.2.2.5 Percentage Change In SCA In Different Seasons In Different Altitudinal Zones Of UBRB During 2000 - 2010

C. Decadal variation in SCA

The decadal variation in snow cover in upper Bhagirathi basin, for 2000-2010, has been estimated using mean annual snow cover area derived from standard Terra 8-day MODIS snow product. The observed variations (as presented in Fig. 4.2.2.6, a-d) show that the mean annual SCA in all elevation zones of the basin is increasing. These overall trends in mean annual SCA are statistically not significant; the mean annual values for three different time periods (i.e. for year 2000, 2005 and 2010) were further analyzed to investigate temporal variation in SCA and results are plotted in Fig. 4.2.2.7 (a&b). The plots show that over a span of eleven years, the SCA has changed in the basin according to different elevations in the basin. In upper elevation zones, variation in SCA during 2000-2010 is very small (almost 3%). However, in case of middle elevation zones (4500-6000m), the annual mean SCA has increase by 8-15%. Whereas, in lower elevation zones (i.e. zones <4500m), completely different pattern of SCA has been observed where an increase in SCA from 2000 to 2005 and thereafter depletion in SCA has been observed. The analysis shows that, in lower elevation zones, where mean annual SCA first increased from the year 2000 to 2005 by 11-14% and then has decreased during 2005 to 2010 by 6-8%, are more sensitive to climatic variation.

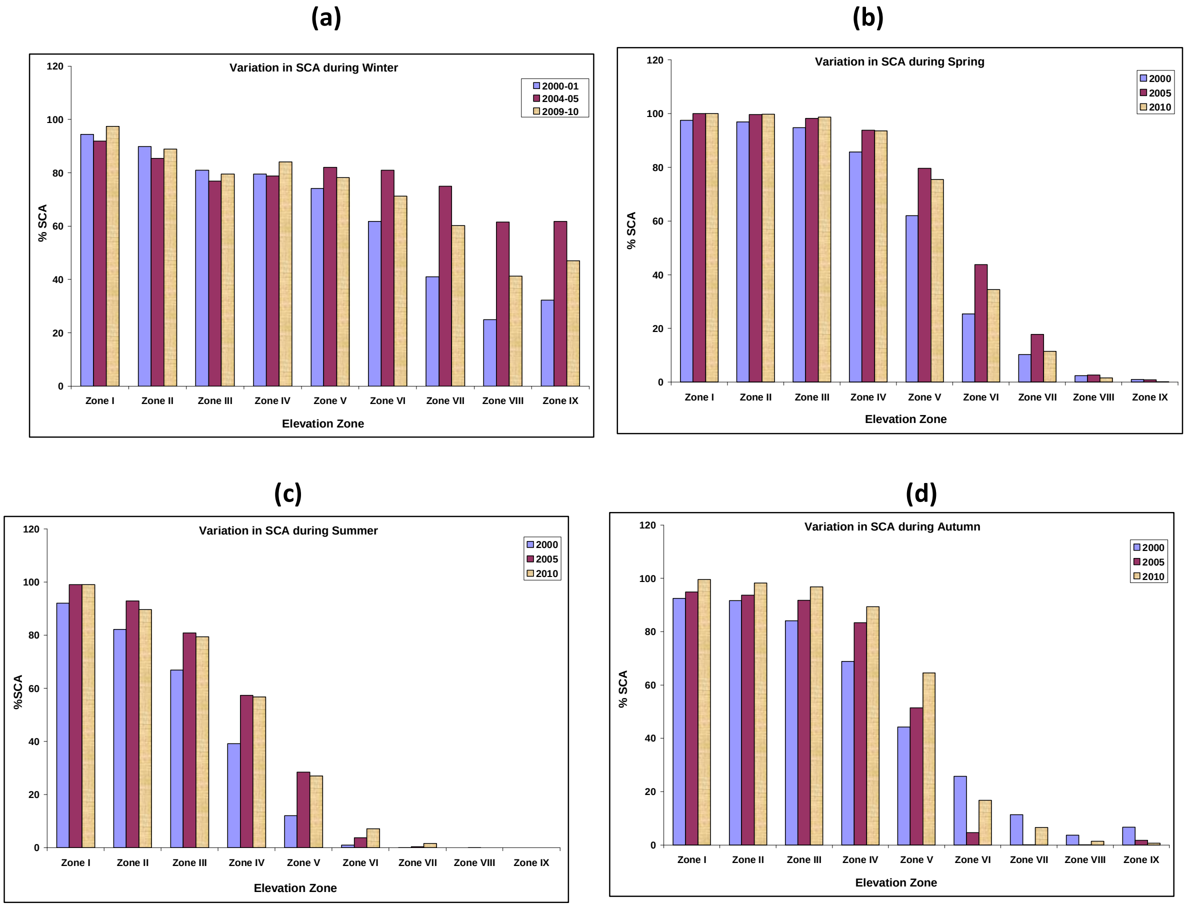
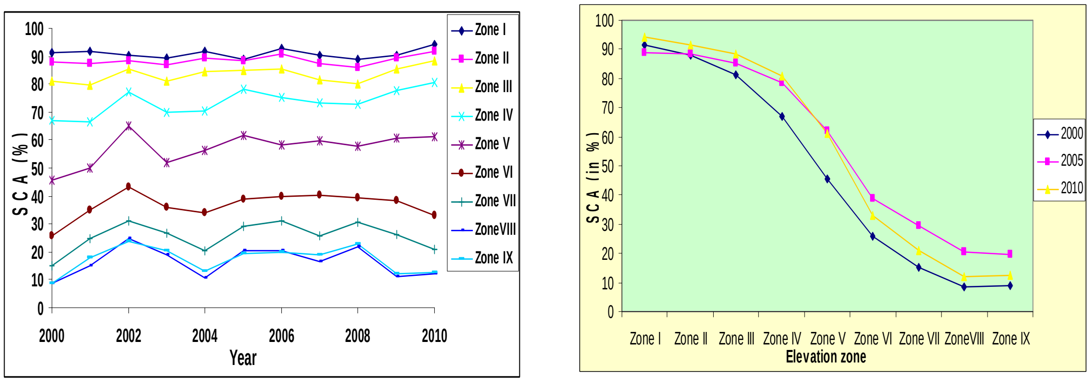


Fig. 4.2.2.6 (a-d). Seasonal variation in SCA in different altitudinal zones of UBRB during 2000-2010



(a) (b)

Fig. 4.2.2.7 (a & b). Decadal variation in SCA in different altitudinal zones of UBRB during 2000-2010

D. Snow cover depletion analysis

The snow depletion curve, which depicts accumulation and ablation behavior of seasonal snow, serve as an important input to the hydrological models for estimating regional snow and glacier melt runoff. The SCA in each elevation bands were plotted against the elapsed time to construct depletion curves for various elevation bands in the basin. Snow depletion curves plotted for ablation in the years 2000 and 2010 are shown in Fig. 4.2.2.8 (a) and 4.2.2.8 (b) respectively. Snow depletion curves plotted for ablation years clearly depict a shift in duration of ablation and accumulation over past 11 years. It is observed that, the ablation of snow in lower and middle elevation zones, which earlier used to begin by mid of May, now starts in first week of May. Similarly, the accumulation of snow, which used to start by first week of September, now is being observed during end of September. Because of this, total duration of ablation period has been extended by almost one month over past one decade. This extension of ablation causes more expose of snow & glacier covered areas which results into shift towards earlier spring melt and high melting of snow and ice. Similarly, consistent with the observations in HKH region (Gurung et al., 2011,) the plotted curves show that the duration of ablation in higher zones has also increased and beginning of snow depletion is found to be delayed with elevation across the basin. In the middle and lower latitudes, ablation happens through melting which is due to direct heat supplied by the solar radiation.

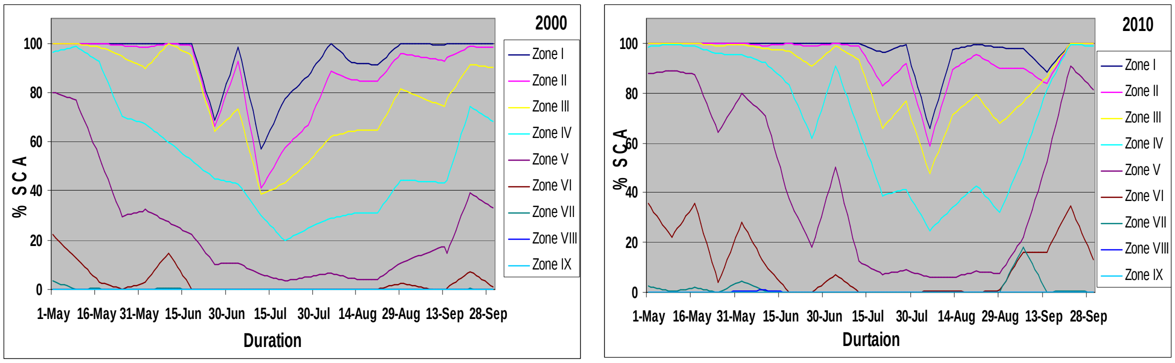


Fig. 4.2.2.8 Snow cover depletion pattern in altitudinal zones of UBRB during (a) 2000 & (b) 2010

Since, the timing and volume of spring runoff is affected by many variables including accumulated snow pack depth, its distribution, and the retention of snow pack over time, therefore, assessment of snow accumulation and depletion is essentially required for management of water resources in the region where a large part of the annual precipitation falls as snow.

4.2.2.3 Glaciers and Their Changes

The Gangotri Glacier, main glacier of UBRB and second largest Himalayan glacier after Siachen, is located in upper Bhagirathi basin with geographical extends 79°17'18''to 79°4'55 ''E and 30°43'10'' to 30°55'50 ''N. This glacier is 30.2 km long and its width varies from 0.5 to 2.5 km. It is a valley-type glacier, with an estimated volume of over 28 km^3. It originates at a height of about 7100 m above asl, its terminus is at an altitude of about 4000 m asl. There are numerous small-sized glaciers which feed and contribute into the main glacier to form the Gangotri group of glaciers (Fig. 9). The total spread of the ice volume including its tributaries is about 39.18 km^3.

The small-sized glaciers, named as tributary glaciers are generally transverse to the main glacier and vary from NE-SW and NW-SE in orientation. Meru and Ghanohim are the tributary glaciers which feed the main glacier from left and Raktavarn, Chaturangi, Swachhand and Manda feed from the right. Depending upon their present-day location with respect to the main glacier, these tributary glaciers are classified into two categories, active tributary glaciers (those which are still connected to the main glacier, contributing ice budget to it and are also forming the new landforms) and inactive tributary glaciers (those which are now detached from the main glacier but were connected to it in the past. These are neither contributing ice budget to the main glacier nor forming any new landform). Presently the inactive tributary glaciers are only contributing in the melt water coming out of them. However, the inactive tributary glaciers are modifying the pre-existing landforms only because of their melt water.

Gangotri glacier has attracted attention of scientific community and has been under systematic monitoring by GSI since 1935. There are, however, different views on the rate of retreat of the Gangotri glacier. As per the measurements conducted by GSI, it is apparent that the snout of Gangotri glacier has been receding at variable rates for the last 75 years. There was acceleration in the retreat in the mid-seventies and only a marginal slowing down in the nineties**.** The average rate of retreat since 1956 is ~ 30 m/a (Srivastava, 2004). The total retreat from 1935-96 is about 1400 m and is almost remained static from 2007-09 (Raina 2009).

4.2.2.4 Application of Snowmelt Runoff Model

The SRM model (the method discussed in detail in Supplementary Materials 2) was run on discharge data for the period 2000-2008. The available dataset is split into two parts; data for the initial five years (i.e. for 2000-2004) were used for calibration of the model. After successful calibration of the model, next four year's independent data (i.e. for 2005-2008) were used for validation purpose to check model performance by simulating the daily discharge without changing the model parameters. Comparison of daily observed and simulated discharge for calibration period for the year 2004 and simulation period for the year 2008 are shown, for example) in Figs. 4.2.2.9 and 4.2.2.10 respectively. The efficiency and performance evaluation of the model is depicted by the coefficient of determination (R^2) and deviation in runoff volume (% D_v) computed for both calibration and validation period. For the calibration period, the coefficient of determination (R^2) is found varying between 0.67 and 0.83, whereas for validation period it is found varying between 0.79 and 0.91. Robustness and efficiency for model simulations are summarized in Table 4.2.2.2. Fig. 4.2.2.9 and 4.2.2.10 representing the cases of calibration and validation depict that, though the model performs fairly well to capture pattern of low flow, it underestimates the peaks observed in melt runoff during the ablation season both in the calibration and simulation processes. From the figures it is evident that the discharge rises from June onwards and reaches to its peak by July which further starts decreasing from September onwards. The peaks depicted by the hydrograph shows fluctuations in the streamflow observed at the monitoring site, which may be caused by outburst of some water bodies, variation in melting rate of various tributary glaciers, and rise in the temperature in late summer. Events related to high flow mostly occurred in the months of July and August confirming that these events were caused by opening up drainage network and excessive melting of snow and

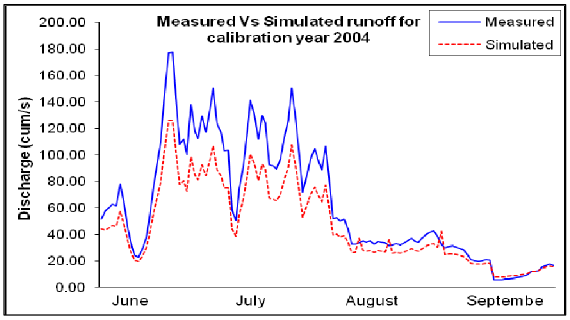


Fig. 4.2.2.9 Measured and simulated daily discharge of study basin for calibration period 2004

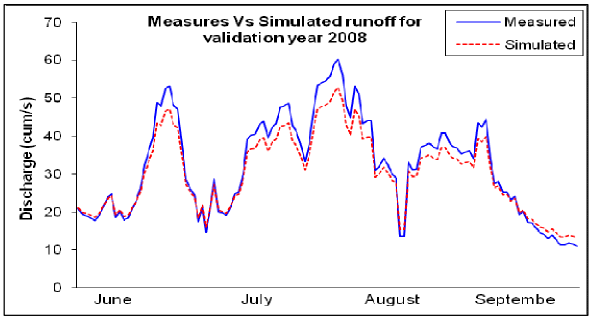


Fig. 4.2.2.10 Observed and simulated daily discharge of study basin for valiation period 2008

ice on account of rising temperature. The analysis also shows applicability of SRM, a temperature index model, for simulation of discharge from snow dominated Himalayan basin where limited hydro-meteorological data are available. The following simulations also shows that model can also be used for a real-time short term (such as daily or weekly) forecast as well as for longer time (e.g. monthly or seasonally) of runoff volume if precise forecast of required input variables (such as rainfall, temperature, snow cover) is available. The real-time forecast of the melt runoff can be useful for management of water resources and other biotic components in upstream as well as in the downstream.

Table 4.2.2.2 Model efficiency for calibration & simulation of runoff for the study basin

Model Processes	Year	R^2	%Dv
Calibration	2000	0.76	11.34
	2001	0.83	8.43
	2002	0.71	16.62
	2003	0.77	12.19
	2004	0.67	18.72
Simulation	2005	0.81	9.56
	2006	0.79	10.09
	2007	0.89	7.36
	2008	0.91	6.34

4.2.2.5 Runoff Simulations under changed climate

Following the estimated increase in future climate using PRECIS RCM data analyses for 2070-2100 for the study basin and projected increase in the Himalayas, estimated by other researchers, for 2050 and 2080, two different temperature scenarios (i.e. T+2^{0}C & T+4^{0}C) are assumed and adopted to evaluate the effect of a temperature increase on runoff simulations for projected changed climate. SCA for both the future temperature scenario is required for each zone for computation of melt runoff under warmer climate. The future course of depletion curves of the snow coverage is estimated from the modified depletion curves (MDC). These curves are automatically derived by SRM from the conventional curves (CDC) by replacing the time scale with cumulative daily snowmelt depths as computed by the model. MCD for future climate are derived to estimate new values of SCA under warmer climate as per the procedure of SRM model. Fig. 4.2.2.11 and Fig. 4.2.2.12 show

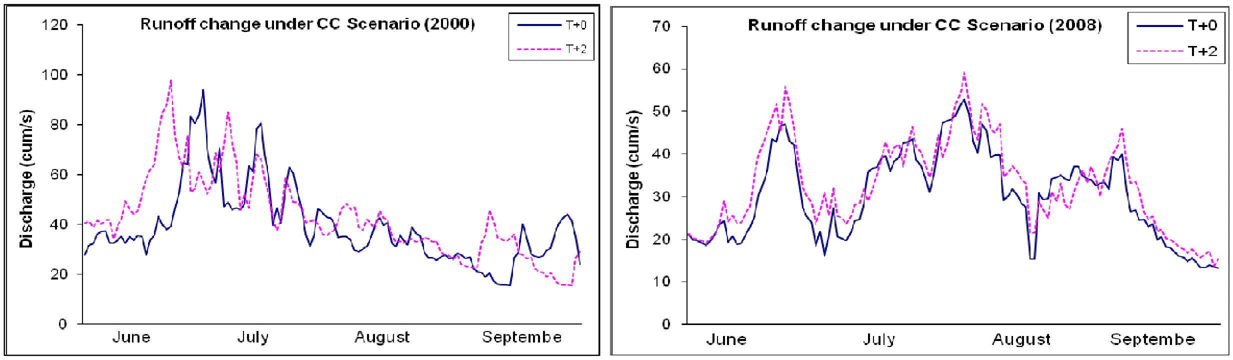


Fig. 4.2.2.11 Simulated runoff under present and future climate change scenario (T+2^{0}C) in the upper Bhagirathi Basin

the climate-affected runoff computed by original precipitation, temperature (T+2^{0}C & T + 4^{0}C) and snow covered areas compared with the original runoff simulation. The model run is started by discharge computed on 1 June with the increased temperature scenario. Simulated results under warmer climate show that the daily runoff is increased for both the scenarios. It is observed from Fig. 4.2.2.11 and Fig. 4.2.2.12 that for all years, snowmelt in UBRB increase with increase in temperature. However the magnitude of changes in snowmelt runoff for a particular year depends on the climatic conditions. Visual inspection of simulations (depicted in Fig. 4.2.2.11 and Fig. 4.2.2.12) shows that under warmer climate scenario, snow/glacier melt runoff cause an earlier response to the total stream flow and a change in flow distribution of UBRB. Maximum increase in stream flow is observed in springs or early summer season, which is reflected by shift in peaks of the hydrographs, which may occur because of increased melting of snow because of rise in temperature. Figures also depicts that in UBRB the snow melt is more sensitive to the increase in temperature than the glacier melt and hence produces an early response to the total stream flow.

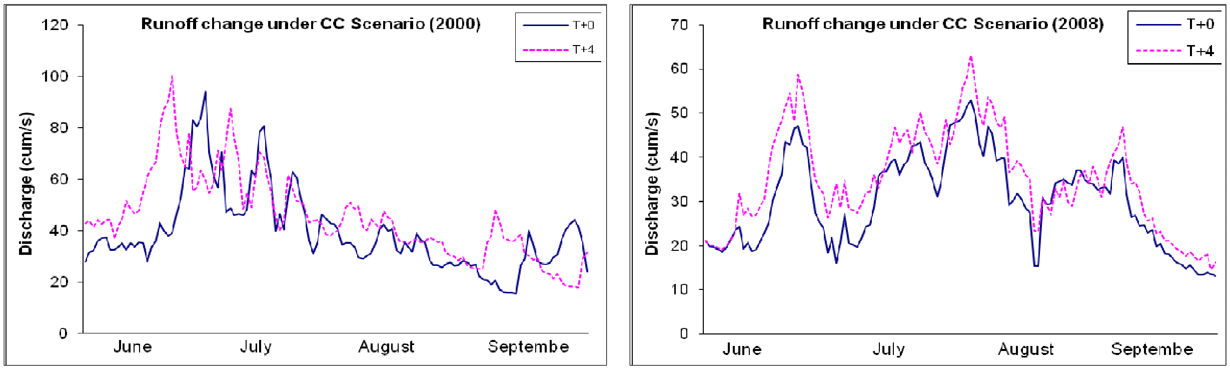


Fig. 4.2.2.12 Simulated runoff under present and future climate change scenario (T+4^{0}C) in the upper Bhagirathi Basin

Based on projected climatic changes over the upper Bhagirathi basin, an increase in temperature by 2^{0}C is estimated to increase in snowmelt runoff by approximately 3-22% in UBRB. Similarly, under warmer climate, an increase in temperature by 4^{0}C would increase in snowmelt runoff by approximately 9-30% in the Upper Bhagirathi river basin (Table 4.2.2.3). Comparison of change in total runoff under different climate change scenarios for the ablation season of the period 2000-2008 is presented in Fig. 4.2.2.13. Simulations carried out for the study period (2000-2008) shows that, compared to the simulations carried out for present climate (T+0^{0}C), maximum increase in runoff percentage is observed in later years of the study period with maximum rise of 21.9% for 2006 under T+2^{0}C scenario and 30.2% for 2008 under T+4^{0}C. The Upper Bhagirathi river basin has significant number of small tributary glaciers; warmer climatic condition may result into early melting of seasonal snow and hence more exposure of glaciated area which ultimately may increase retreat of glaciers and thereby affecting the smaller tributary glaciers adversely. One of the most important impacts of future climatic change to the society is expected on regional water availability in terms of time and

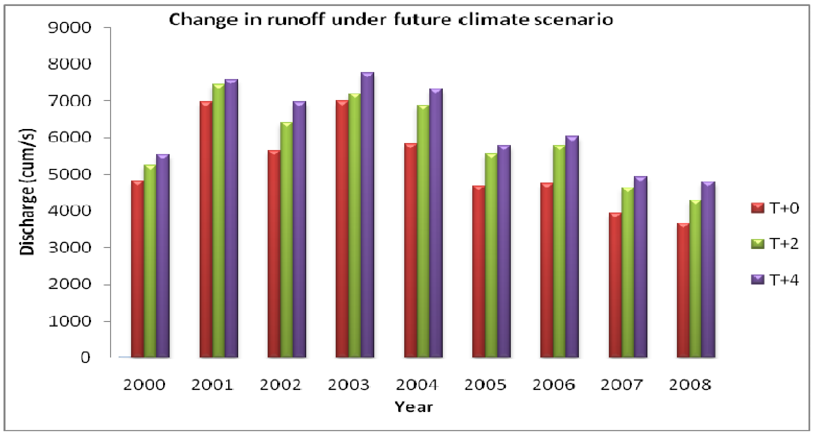


Fig. 4.2.2.13 Comparison of change in total runoff under different climate change scenarios for the ablation season of the period 2000-2008.

magnitude, which may lead to major alternation in the regional water system in UBRB and areas downstream.

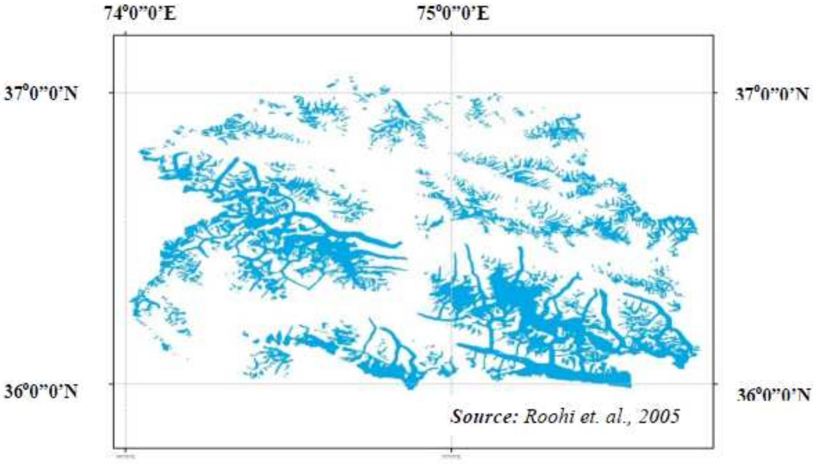
Table 4.2.2.3 Projected change in runoff from upper Bhagirathi basin under two different climate scenarios

Year	% increase in T+2^{0}C scenario	% increase in T+4^{0}C scenario
2000	8.59	14.9
2001	6.84	8.75
2002	13.5	23.7
2003	2.72	11
2004	18.2	25.8
2005	18.9	23.7
2006	21.9	26.8
2007	17.6	25.2
2008	16.6	30.2

4.2.3 Hunza Basin

The watershed chosen for exploratory analysis at the western edge of the Himalaya is the Hunza River Basin, which lies at the western edge of the high Karakoram mountain range between35.5-37^{o}North and 74-76^{o}East. The total area of the basin up to Dainyor Bridge is about 13,680 Sq. km with an elevation range of about 1500 to 7500 meters above mean sea level (a.m.s.l). The Hunza River originates from the western Karakoram and flows towards south west connecting its small tributaries of Chabursan, Khunjerab, Ghujerab, and Shunsha River and is measured at Dainyor Bridge(35o55'North, and 74o 22'East)just before its confluence to the Gilgit River.

Hunza is one of the highly glaciated basins in Karakoram Range with more than 30% of its area under perennial snow and ice. It hosts almost 1050 small and large glaciers, which constitute more than 800km^3 of ice reserves. Spatial distribution of these reserves is shown in Fig. 4.2.3.1



Source: Roohi et. al., 2005

Fig. 4.2.3.1 Spatial Distribution of the Glaciers in Hunza River Basin

Hunza Basin is very arid and any rainfall influence is largely masked by glacial inputs as the surface hydrology of the basin dominates mainly by glacial melt. The average annual discharge of the Hunza River is about 350m3/s (1966-1990) which accounts for more than 13% of the inflow to the downstream Tarbela reservoir. The largest part of the total annual runoff is generated in summer months by the melting of glaciers and the seasonal snow cover which is strongly dependent on concurrent energy input represented by the temperature which in turn strongly influenced by the altitude.

The average annual precipitation observed at valley based stations amounts to 150mm most of which falls in the form of snow during winter under westerly depressions. However these valley bottom stations do not seem to fully representative of the climatic conditions of the elevated zones of the basin. The observed flows at Dainyor Bridge, for instance, do not match with average precipitation recorded at valley bottom stations and suggest much higher precipitation at higher elevations. How precipitation increases with the elevation is not known but some snow pit studies above 4000 meters above mean sea level (amsl) suggest accumulation of snow in the range of 1000mm to more than 3000mm. However, these estimates apparently depend upon the location of snow pit site and time of investigation.

4.2.3.1 DEM for Hunza Basin

The DEM (Digital Elevation Model) for the Hunza River basin (Fig. 4.2.3.2) has been taken from the ASTER global dataset at horizontal resolution of 30 meters available on internet.

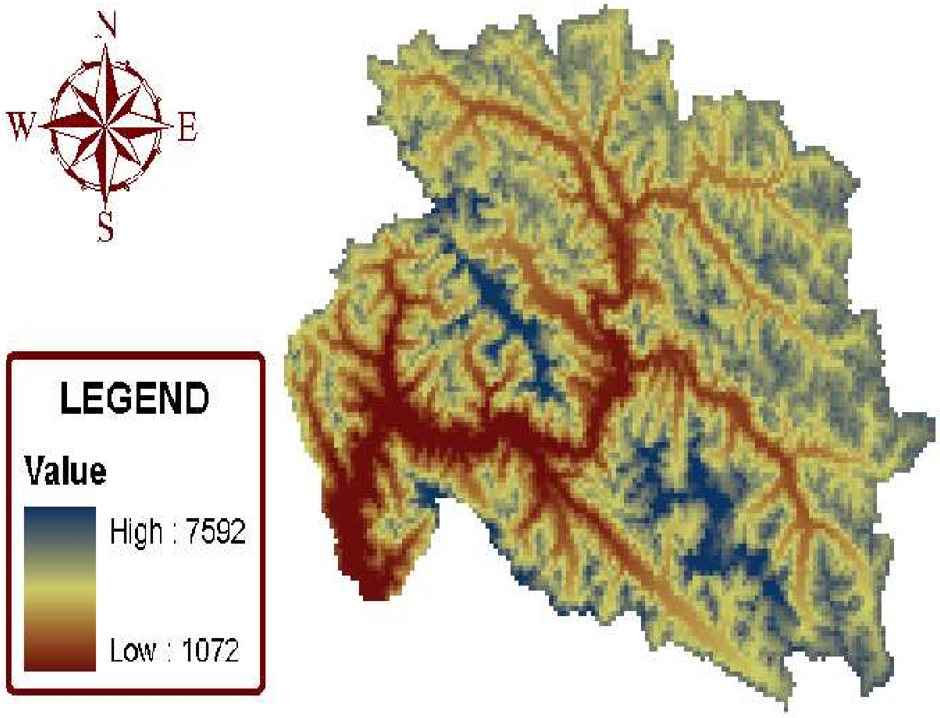


Fig. 4.2.3.2 Digital Elevation Model Hunza Water

On the basis of DEM, the whole watershed area has been divided into eight elevation zones called elevation bands required as an input to the Hydrological Model (UBC). Cumulative area within each elevation zone has been calculated (Fig. 4.2.3.3).

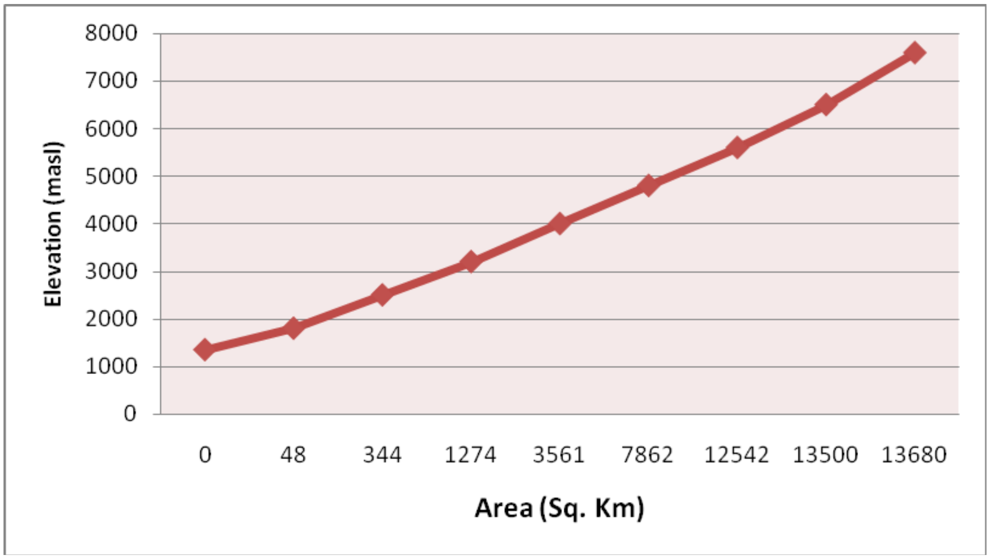


Fig. 4.2.3.3 Cumulative Area under each Elevation Zone - Hunza Basin

Physio-geographical characteristics such as Glaciated Area, Forest Cover, Density Forest Canopy, Impermeable Area and Orientation Index along with the land area under each elevation zone have been calculated from the Land Cover and DEM gridded datasets from USGS.

4.2.3.2 Application of UBC Model

The UBC Watershed Model has been selected to calibrate and project the flows of Hunza River. The UBC Watershed Model developed by University of British Columbia, Canada and designed primarily for the calculation of stream flow from mountainous watersheds where stream flow consists of snowmelt, rain and glacier outflow is already found to be more than satisfactory in its performance on the whole Upper Indus Basin (UIB) and its different tributaries. This semi-distributed model takes less meteorological data (Daily Max & Min Temperature, Precipitation) and calculates the snowmelt and glacier melt components separately, which is one of the main characteristics required to model the Hunza River Basin mainly fed by glacier melt.

Model Calibration/Validation

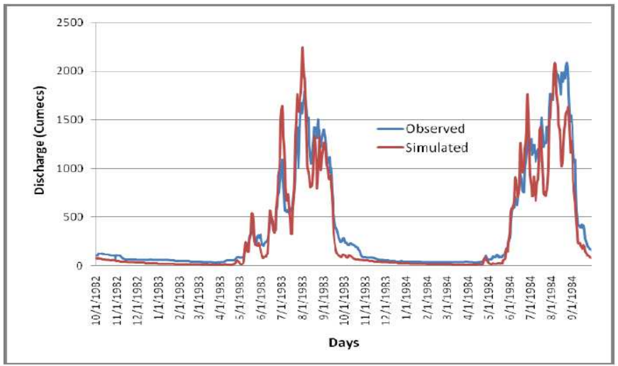


Fig. 4.2.3.4 Calibration of UBC Model over Hunza River Basin(1981-1990)

The UBC watershed model has been calibrated for 10-years period (1981-1990) using daily values of max. & min. temperature and precipitation of Gilgit and Gupis stations obtained from Pakistan Meteorological Department (PMD). For the whole calibration period (1981- 1990), the Nash-Sutcliffe efficiency is 0.83 and the coefficient of determination is 0.86. Calibration graph for the year 83-84 and 84-85 is shown in Fig. 4.2.3.4

Table 4.2.3.1 Validation of UBC Model over Hunza River Basin

Table 4.2.3.1 Validation of UBC Model over Hunza River Basin

Period	Efficiency	Coeff. Of Determination
1966-1970	0.90	0.91
1966-1990	0.80	0.83

The calibrated model is then validated over the period of five years (1966-70) as well as for the whole period (1966-1990). For five years period, Nash-Sutcliffe efficiency and the coefficient of determination are 0.90 and 0.91 respectively. For the whole validation period, the Nash-Sutcliffe efficiency and the coefficient of determination reduce to 0.80 and 0.83 respectively. The detailed validation results are shown in Table 4.2.3.1. The graphs for validation year 1966-67 and 1967-68 are given in Fig. 4.2.3.5.

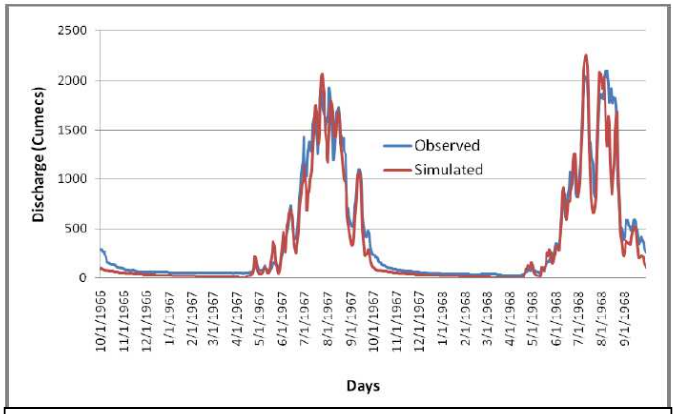


Fig. 4.2.3.5 Validation of UBC Model over Hunza River Basin(1966-70)

Overall performance of the UBC watershed model in simulating the base climate discharge is found to be satisfactory. Average observed and simulated discharges for the base climate have been compared in Fig. 4.2.3.6.

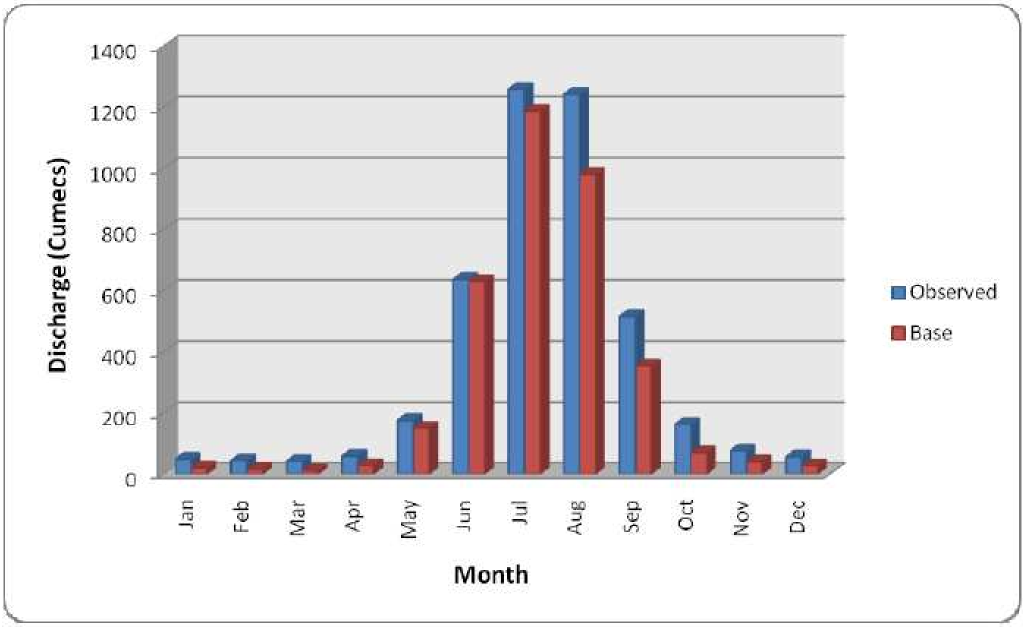


Fig. 4.2.3.6 Model Performance for the whole period (1966-1990)

4.2.3.3 Future Water Availability under Different Scenarios

Here future water availability is assessed using simple delta rule approach without glacier changes for the period of 2020s, 2050s and 2080s with respect to the base period. Also changes in different runoff components like snowmelt, glacier melt and rainfall have been assessed separately. The graphs are shown in Fig. 4.2.3.7 (a-c). The values for annual and seasonal flows for the above periods in cumecs and changes with respect to base flow in percentage are provided in Tables 4.2.3.2 and 4.2.3.3 respectively.

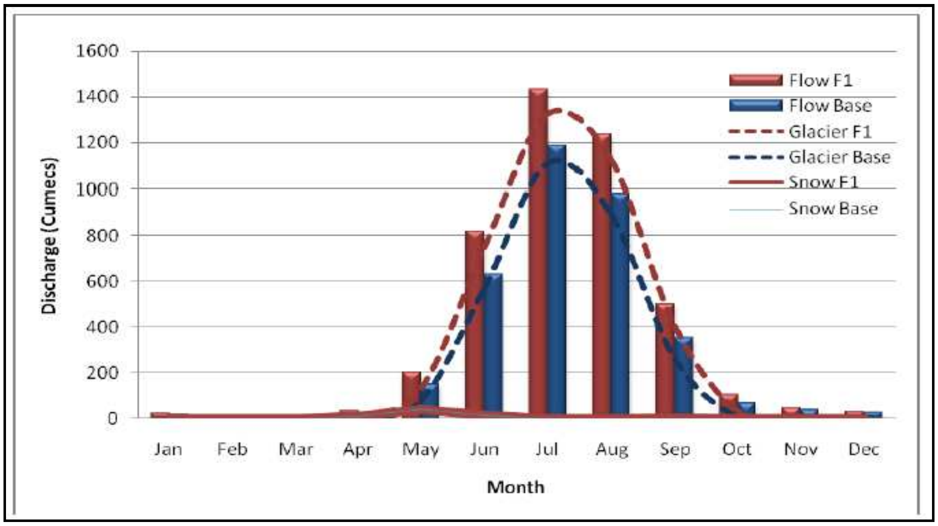


Fig. 4.2.3.7 (a) Component-wise change in 2020s with respect to base

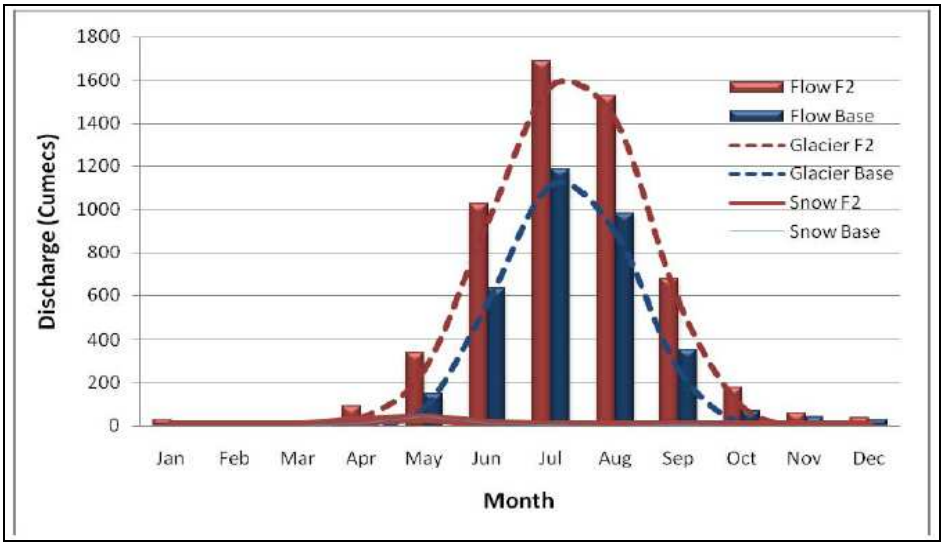


Fig. 4.2.3.7 (b) Component-wise change in 2050s with respect to base

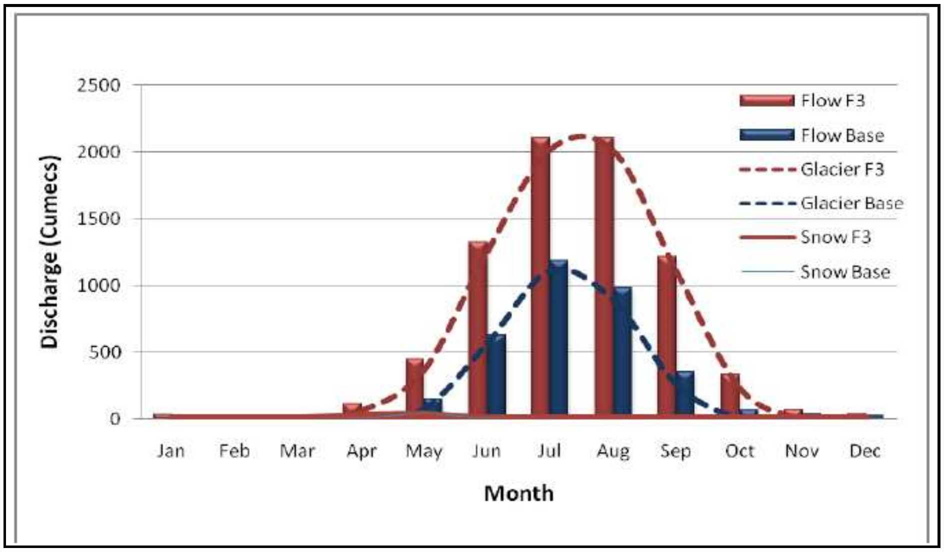


Fig. 4.2.3. 8 (c) Component-wise change in 2080s with respect to base

Table 4.2.3.2 Changes in Annual & Seasonal Flows in Cumecs with respect to Base under Simple Delta Rule Approach (without Glacier Change)

		BASE			F1 (2020s)			F2(2050s)			F3 (2080s)		
		Flow	Snow	Glacier	Flow	Snow	Glacier	Flow	Snow	Glacier	Flow	Snow	Glacier
		(Cumecs)			(Cumecs)			(Cumecs)			(Cumecs)		
Annual Average		292.6	6.0	243.7	371.7	6.0	314.5	473.0	6.0	407.9	654.0	4.4	588.3
Seasonal	Spring	62.7	18.3	29.0	83.8	17.9	47.7	148.3	20.0	99.1	195.8	16.9	145.4
	Summer	933.2	5.1	856.4	1162.7	5.6	1065.8	1411.9	3.8	1309.1	1845.9	0.5	1757.6
	Fall	154.5	0.6	89.2	217.0	0.5	144.4	304.3	0.3	223.3	539.9	0.1	449.5
	Winter	20.2	0.0	0.0	23.4	0.0	0.0	27.6	0.0	0.0	34.3	0.1	0.7

Table 4.2.3.3 Component-wise % Change with respect to Base Components under Simple Delta Rule Approach (without Glacier Change)

		F1 (2020s)			F2(2050s)			F3 (2080s)		
		Flow	Snow	Glacier	Flow	Snow	Glacier	Flow	Snow	Glacier
		%			%			%		
Annual Average		27.0	0.1	29.1	61.6	0.3	67.4	123.5	-26.5	141.4
Seasonal	Spring	33.8	-2.3	64.4	136.7	9.0	241.5	212.5	-7.6	401.0
	Summer	24.6	10.3	24.4	51.3	-25.8	52.9	97.8	-89.5	105.2
	Fall	40.5	-16.7	61.9	97.0	-50.1	150.4	249.5	-78.9	404.0
	Winter	15.7	700.8	43078.1	36.6	2007.8	454879.2	69.6	5035.1	7174644.6

Analysis shows significant increase in the Hunza River flows through out the century with increase in the glacier melt contribution. Significant early melting of glaciers has also been found.

4.3 Consequences of Global Change Impacts on Snow, Glaciers and Runoff in the Himalayan River Basins to Highlands and Downstream Areas

4.3.1 Altitudinal Variations in Water Sources, Usages and Conseqences

The Himalayan region spans great variations in local climate, even across small distances. Due to the high mountains, steep slopes and deep valleys, obtaining sufficient water supply for domestic usage and agriculture is often a matter of making highly local adjustments to the surroundings.

The water resources used by people come either:

a. from the direct use of precipitations, such as in rainfed agriculture,
b. from the local discharge of water in a stored form (soil humidity from permafrost thaw or snow melting) and from springs and water courses on the slope,
c. from the flow of water, the origin of this flow being either the discharge of stored water (glacier and snow melting, groundwater outflow, etc.) or the run-off of rainwater

Availability and uses of water in the Himalayas differ according to its origin in the various altitudinal zones. As for example, such origin and uses in the four altidudinal zones along North-South Transect across the Everesest (Figure 4.3.1) are briefly described below. That is also true of such altitudinal zones in the other parts of the Himalayan range. Impacts of global change on the water availability and their consequences in those altitudinal zones are also briefly discussed.

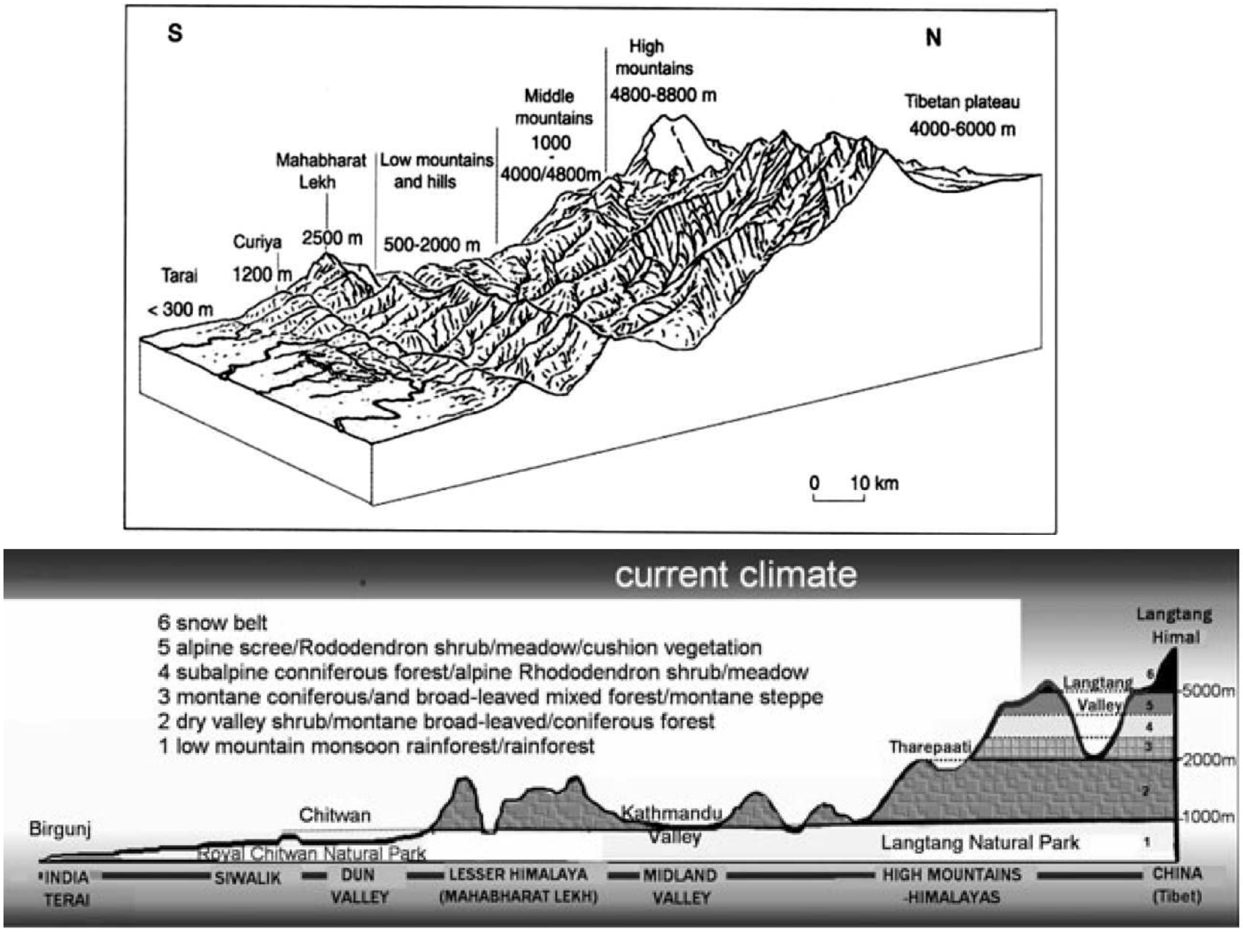


Fig.4.3.1 Altitudinal and ecological variations along the North-South Transect across Everest and Langtang Himal

A. **In the high mountains (**at and above 4,000m) characterised by the significant presence of the cryosphere in the headwaters, water is either in an icy state (glacier, frozen torrent, permafrost), in the form of snow (falling during winter, beginning of spring or even monsoon season at high altitude) or liquid fluid when the temperature or stream turbulence permits. Thus, the streaming water used comes either from the melting of a glacier, the melting of snow, resurgence of groundwater, or rainfall (about 800mm per year). Any change in one of these parameters will have some impact on the discharge of streams and therefore on the operation of water mills and of micro-/hydroelectric power stations, on the consumption of domestic water, on the irrigation of agricultural fields. In regions where tourism is already an established enterprise, new usages (shower in lodges, watering of vegetable plants, purification of drinking water, bottled water) and an increase in the demand for water supplied by springs and streams, have led to social pressure on accessing the resource in some places. For people in the high Himalayas, as for instance, the low-lying glaciers are particularly important for the local water supply in the spring, before the arrival of the monsoon rains. Precipitation that falls in the form of snow over the glaciers is stored there over the winter. When spring and summer come, the melted water runs down from the mountains to the valleys where people use it for domestic purposes and cultivate the land. As far as precipitation distribution and pattern (either snow or monsoon rain) or temperature (influencing permafrost thaw, snow melting or frost creation) are concerned, they have a significant impact on plant growth and cropping activities such as potato farming and grass harvesting. Moreover, any change in the duration, period or thickness of the snow cover, which both serve to protect soil and crops against frost, and to supply soil with humidity may have different effects on plant growth and on the use of high-altitude pastures. These changes would have major consequences on the local livelihood and economy. Finally, the melting of permafrost in this belt may increase slope instability and cause landslides.

B. **In the middle mountains**-defined by long slopes ranging from 4,000m to 1,000m in altitude which are intensively exploited (fields, forest, pasture) and with mainly a westerly and easterly exposure-the climate is characterised by snowy precipitations above 2,200m in winter, storms during spring, and plenty of rainfall during the monsoon (June to September). Annual rainfall is quite high (1,500 to 2,600 mm). In such areas, there is no glacier, so that fluctuations in glacier melting will have no direct effect on the populations' activities (except for Glacial Lake Outburst Flood which may destroy land located near the river). However, fluctuations in snow cover and frost, as well as any change in the monsoon pattern, may have a major impact on the population's activities (like those described above), especially those regarding the use of water and agriculture during the dry season. As the rivers originating from high Himalayas flow through deep gullies, people living in the middle mountains have in general little access to them and they commonly rely on water stored in the mountains as ground water and springs and on streams orininating from them.

C. **In the low mountains and hills**-characterised by shorter slopes ranging from 2,500-2,000m to 500m with a northerly and southerly exposure—the climate is less humid. These mountains benefit neither from the melting of snow nor from that of glacier as they are snow-free and glacier-free. Moreover, rainstorms during the spring are less frequent and less abundant. The sowing of rainfed crops, such as corn, relies on rainfall during the months of April and May, and can therefore be delayed or even abandoned some years. This belt is characterised by a very long dry season and a shortage of water for vegetation and domestic consumption over a period of many months. Populations face major water supply issues since most rain falls during the monsoon. Thus, any change in the rainfall pattern but mainly in the monsoon flow would have significant consequences in this belt.

D. **In the mid hills** climate change may increase instances of frequent and high intensity rainfall as well as decrease in the number of rainy days. These events can exacerbate occurrence of landslides and mass wasting processes that can directly lead to loss of lives, infrastructures, agriculture and local asset base. These events can disrupt roads, highways and other communication systems affecting mobility and flow of information. Nepal's mid hills also experience floods caused by breach of temporary landslides creating a dam blocking a river. High intensity cloudburst acts as triggers of such events locally known as *bishyari.* The result is likely to be overall resilience depletion.

E. **In the Terai plain** at the foothills of the Himalayas, two areas can be identified: (1) one that benefits from the rivers flowing from the high mountains - only four outlets of such river basins exist the Terai plain in Nepal. In this case, glacier and snow melting would have consequences on the river flow and would directly impact irrigation and hydroelectricity generation; (2) one that is watered by rivers coming from the first or second range of mountains (Churia or Mahabarat), but not from the high mountains. The flow here relies mainly on monsoon rainfall and its fluctuations would have the most significant impact on farmers' activities.

Note on Regions depending upon non-snow-fed rivers: It also needs to be noted that hile the threat of changes in snow dynamics is real, it is clear that those living in non-snow-fed rivers that originate in the Mahabharat and Chure ranges will be vulnerable to other types of hazards than changes in snow-melt dynamics. That is also true of the population in Uttar Pradesh and Bihar who live in the immediate downstream regions of these rivers. The challenges of these rivers and catchments involve depleting local water sources and increasing dry spells. These changes directly affect drinking water systems as discharges of sources that are tapped to feed these systems through community based units are is lowered. Altered rainfall pattern would change flow dynamics and may result in high surface runoff, reduced infiltration and low base flow with serious consequences on farmer-managed and agency built irrigation systems. Changes in flow dynamics also imply risks to hydropower systems of all types. These impacts become manifested through inter-linked systems, for example when a hydropower system generates lower energy than designed due to altered hydrological behavior that climate change is likely to bring. In such case, vulnerabilities will be transferred to a much larger population.

4.3.2 Altitudinal Distribution of Population and Consequences

The distribution of population over the altitudinal zones provides an indication of the number of pepole affected by the hydrological changes in the Himalayan runoff as a result of global change impacts on the snow and glaciers in the Himalaya. While almost 94 percent of the total populations living in the Indus, Ganges and Brahmaputra basins live at elevation zone of less than 1,000m amsl, nearly fifty million live in the higher elavation zones with about one and half million liviving at altitudes higher than 4,000 amsl. In Nepal, about one-third of the total population live at high elevation zone 1,000m – 4,000m and a little over one hundred thousand live at higher elevation zone at or above 4,000m. The distributions of population according to elevation zones in the three basins along with the same for the India, Nepal and Pakistan are shown in Table 4.3.1.

The impact of changed runoff regime and widening gaps between water supply and demand are disproportionately distributed within the region among different communities and sectors of society and it primarily falls more on poor, marginalised, subsistent farmers and the economic units which are directly dependent on natural system. The poorer, marginalised, people of the high mountains, subsistence farmers are likely to suffer the earliest and the most (Jianchu et al, 2007).

Table 4.3.1 Population in Himalayan River Basins by Elevetion and by Country

Country	Basin	Population by Elevation Zone		
		< 1,000 m	1,000 to 4,000 m	> 4,000 m
India	Ganges Brahmaputra	459,157,952	7,502,996	77,447
	Indus	26,539,558	9,431,329	103,821
	Share of Basin Population Living in the Elevetion Zone	**96.6 %**	**3.4 %**	**0.04 %**
Nepal	Ganges	19,239,788	9,604,421	107,634
	Share of Basin Population Living in the Elevetion Zone	**66.5 %**	**33.2 %**	**0.4 %**
Pakistan	Indus	134,747,024	13,159,600	197,836
	Share of Basin Population Living in the Elevetion Zone	**91.0 %**	**8.9 %**	**0.1 %**
Total Population living in the elevation Zone in Indus, Ganges and Brahmaputra Basin		744,907,842	49,964,626	1,407,597
Share of Basin Population Living in the Elevetion Zone in Indus, Ganges and Brahmaputra Basin		**93.5 %**	**6.3 %**	**0.2 %**

The changes in meltwater from snow and glaciers resulting from the global change and subsequent changes in water system have multi-facet impacts on society and economy because of direct linkage of water with people, ecosystem, economy and society. Though the annual change in per capita water availability due to the change in meltwater may not be very much significant, their seasonal effect particularly during non-monsoon season seems substantial.

4.3.3 Changes of Snow and Glacial Water Melt in the Himalayan Rivers and Consequences

4.3.3.1 Ganges River Basin

The Ganges River Basin is one of the most densely populated basins in the world (443 persons/km^2). The basin is fed by major headwaters in the Himalayas – the Bhagirathi, Alaknanda, Karnali, Gandaki and Koshi – and many other tributaries that drain the Himalayas and the Vindhya and Satpura ranges. The basin faces severe water scarcity for five months of the year (January-May). Most of the blue water footprint in the basin is due to evaporation of irrigation water in agriculture, mostly for rice, wheat and sugar cane. These three crops together are responsible for 85% of the total blue water footprint in the basin. Overexploitation of the aquifers for irrigation is leading to depletion of the groundwater in the basin (Wada et al., 2010). According to Xu et al., on an annual basis the melted water from the glaciers accounts for only 9 percent of the river flow in the Ganges, but in the spring and autumn seasons the melted water from snow and ice comprises 70 percent of the Ganges' river flow. Although the stated 70 percent as exclusively snow and ice melt components is disputed, nevetheless the melt components are certainly quite significant during spring and autumn seasons. The melted water is similarly crucial for the water supply for agriculture during periods when the monsoons do not provide enough water for the crops.

It is not accurate to consider water scarcity by comparing *annual* values of water use and availability. In reality, water scarcity manifests itself at monthly rather than annual scale, due to the intra-annual variations of both water use and availability. Ignoring temporal variability in estimating blue water scarcity obscures the fact that scarcity occurs in certain periods of the year and not in others.

4.4.3.1.1 Contributions of Rivers from Nepal to Ganges

Alford et al., 2010 claimed that “Based on these methodologies, it is estimated that the contribution of glacier annual melt water to annual stream flow into the Ganges Basin from the glacierized catchments of the Nepal Himalaya represents approximately 4% of the total annual stream flow volume of the rivers of Nepal, and thus, is a minor component of the annual flow of the Ganges River. The models developed for this study indicate that neither stream flow timing nor volume of the rivers flowing into the Ganges Basin from Nepal will be affected materially by a continued retreat of the glaciers of the Nepal Himalaya.”

It is however misleading to regard the proportion of snow and glacilal melt as a minor component and thus insignificant merely by comparing it with respect to the total annual stream flow volume. In the case of Ganges river, for instance, the flow during the monsoon perid is almost ten times the flow during the dry period and during the dry period from February to May, the agricultural water withdrawls (blue water footprints) from the river are highest and the flow is even below the sustainable environmental requrements (Hoekstra et al., 2011).

It is actually during that lean flow period when the contributions of Himalayan snow and glacial melt water from the snow covered and glacierized catchments of the Nepal Himalaya provide invaluable flow of the Ganges river.

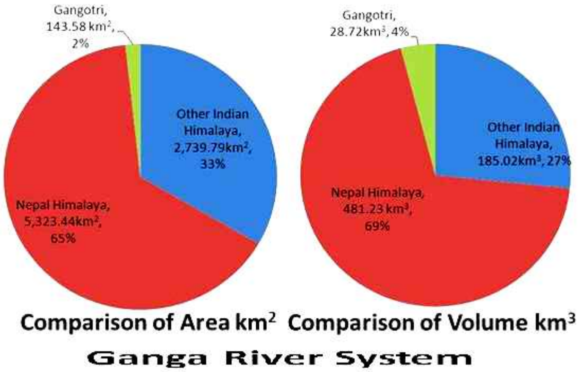


Fig. 4.3.2 Glacier Area and Volume from Nepal Himalaya and Indian Himalaya contributing to Ganges River System

In the Ganges river system, Nepal Himalayay carry about 65 percent of the glaciated area and 69 percent of the ice volume of the total glaciated area and ice volume in the whole Himalayan range covered by the Ganges river basin (Fig. 4.3.2). Three major tributaries originating in Nepal —the Karnali (Ghangra), Gandak, and Koshi—contribute significantly to water flow (approximately 70% of dry season flow and 40% of annual flows) and sediment discharge into the Ganges River (Alford 1992; Mirza 2004). As data for seasonal flow for Ganges river is not available, the contributions of the rivers from Nepal as percentage of annual flow at the Farakka dam is shown in Table 4.3.2.

Table 4.3.2 Contribution of Nepal Rivers to the Ganges River

Rivers from Nepal Joining Ganges	Annual Flow	Percentage of Fow at Farraka
Karnali (Ghagra)	94,400	20.6 %
Gandaki	52,200	11.4 %
Koshi	68,340	14.9 %
Total	**214,940**	**46.9 %**

4.3.3.2 Indus River Basin

The Indus River Basin is a densely populated basin (186 persons/km^2) facing severe water scarcity almost three quarters of the year (September-April). The peak flow of the Indus river as comapred to that of the Ganges river is lower by a factor of more than three. The basin receives around 70% of its precipitation during the months of June to October (Thenkabail et al., 2005). The low-water period in the Indus River Basin is from November through February. The Himalayan snow and glaciers melt enhances the river flow and the high waters begin in June and continue through October. Over 93% of the water requirements (blue water footprint) related to crop production in Pakistan occurs in the two major agricultural provinces of Punjab and Sindh which lie fully (Punjab) and mostly (Sindh) in the basin. Irrigation of wheat, rice and cotton crops account for 77% of the blue water footprint in the basin (Hoekstra et al., 2011).

4.3.4 Consequences to People's livlihood in the Highland and Downstream Regions

When water (or streamflow) flows from headwaters to floodplains, the water resources are widely utilised for many activities such as agriculture, drinking water, and hydropower. Changes in the temperature and precipitation pattern, shrinkage in snow cover and glacier and changes in the land cover in combination are likely to have impact on the hydrology of the river basins. The change in the water availability, seasonality, and quantity will have important implications for water resource management planning and can thus impact various sectors of development for example, hydropower, agriculture, drinking water supply and environmental flow.

The meltwater from snow covered and glacierised mountain catchments of the Himalayan region serve lives and livelihoods for millions of people living upstream and downstream. In the context of global change, the changes in snow and glacier melt seem to affect the spatial and temporal distribution of water resources in the region. Naturally the reduction in snow cover and the accelerated melting of glaciers in the Himalayas will adversely affect the water storage capacity of the mountains. On the whole, it will affect the water availability for both the upstream and downstream people. Decreased melt water contribution to the river flows particularly during non-monsoon season will have negative impact on run-of-river hydropower, irrigation and even municipal water supply during the periods when the demand of water is relatively higher.

The melting of snow and glaciers and subsequent changes in water system have multi-facet impacts on society and economy because of direct linkage of water with people, ecosystem, economy and society. The impact of changed runoff regime and widening gaps between water supply and demand disproportionately falls more on poor, marginalised, subsistent farmers and the economic units which are directly dependent on natural system.

4.3.4.1 Socio-economic consequences

The changes in meltwater from snow and glaciers resulting from the global change and subsequent changes in water system have multi-facet impacts on society and economy because of direct linkage of water with people, ecosystem, economy and society. Though the annual change in per capita water availability due to the change in meltwater may not be very much significant, their seasonal effect particularly during non-monsoon season seems substantial.

The impact of changed runoff regime and widening gaps between water supply and demand are disproportionately distributed within the region among different communities and sectors of society and it primarily falls more on poor, marginalised, subsistent farmers and the economic units which are directly dependent on natural system. The poorer, marginalised, people of the high mountains, subsistence farmers are likely to suffer the earliest and the most (Jianchu et al, 2007).

4.3.4.2 Tourism

The other direct impact of global change on snow ice, glaciers and rivers will be on tourism-based livelihood. The snow covered region of the Himalayan mountain system (HMS) is an abode of global attraction supporting tourism. Tourism for instance in Nepal is one of the major and reliable sources of national income and foreign currency earning. According to the Travel and Tourism Economic

Impact 2013 report published by the World Travel and Tourism Council (WTTC), Nepal's travel and tourism sector directly supported 504,000 jobs in 2013, which represents 3.2 percent of the total employment in the country, and the direct contribution of tourism to the country's Gross Domestic Product (GDP) was 3.9 percent of the total GDP. In the mountainous region the most popular destinations are Everest region, Annapurna region, Langtang region and Dolpo region. Annapurna region is recognized as the major tourist destination where about 70,000 tourist visit annually. Similar numbers of tourists visit the Everest region. Over 78% of Nepal's roughly $350 million a year tourism industry comes from trekkers looking to climb Mt. Everest (GoN, 2013). Melting of snow and glaciers may detrimentally affect the tourism sector. Rayamajhi (2012) has revealed that absence of snow on mountain caps may degrade the aesthetic view of the mountain and divert the tourists to other destinations. It would lead to a national economic loss and a loss of employment for people dependent on tourism in the medium and long term.

4.3.4.3 Hydropower

Hydropower is the one of the most promising renewable energy resources in the Himalayan region. Hydropower plants that are of the runoff river type are generally designed based on the dry season flows. Flood waters and river flows during monsoon seasons have relatively less meaning for runoff type hydropower generating plants. As this type of hydropower generation generally follows the pattern of dry season flows and as the melting of snow and glaciers contributes a major part in the dry season flows, changes in snow and glacier melts in the Himalayas as a result of global change will directly affect this type of hydropower generation in the region.

In the Nepalese context, for example, as it does not have any proven fossil fuel reserve, hydropower is its most promising energy resource. Out of the total electricity generated in 2012, only less than 1% was from thermal sources and about 80% was from domestic hydropower plants (NEA, 2013). Over 90% of the installed hydropower plants in Nepal are of the run-of-river type and are generally designed based on the dry season flows (Chaulagain, 2007). Because of the insufficient river flows during dry season, the existing hydropower plants could generate even at present just around 30% of the total installed capacity of the hydropower plants (ibid). An analysis of Marsyangdi Hydro Electricity Plant (HEP) (69 MW) by using the outputs of the glacier mass balance model (Kadota and Ageta, 1992; Naito, 2001) has revealed that about 27% of the present average annual electricity generation is contributed by snow and glacier melt water. Obviously, any decrease in the dry season river flows due to the decreased snow and glacier ice reserve as projected will further adversely affect the electricity generation. Any adverse impacts of glacier melt on the electricity generation from the hydropower plants may thus cause direct economic loss for Nepal.

As the glacier-melt water initially increases with increase in temperature, the hydropower potential also in general initially increase as it largely depends on the lean season flows. Acharya (2011) after analyzing the observed flows of 6 major tributaries of Narayani River (i.e. Marsyangdi, BudhiGandaki, Trisuli, Kali Gandaki, Madi and Seti) for the period of 20 to 40 years has reported a decreasing trend of the average flow during dry season (November to April). Further increase in temperature will adversely affect the projected future energy generation of the hydropower station.

The sensitivity analysis of annual electricity generation to atmospheric temperature revealed that the future impact of temperature change on the electricity generation by the hydropower plants largely depends on the rate of rise in temperature. Its results indicated that the electricity generation potential would increase in the initial decades (e.g. till 2030), and later would gradually go down. So the electricity generation potential of the hydropower plant will peak earlier, higher the rate of rise in temperature in the near future.

4.3.5 Strengthened Highland-Lowland Linkages

Highland-lowland relationships, whether formal or informal, have the potential to pay for investments in protection and sustainable use of mountain resources. When full costs are taken into account, stewardship of upland resources generally yields greater and more sustainable economic returns both to the people living in the mountain areas and to the immediate downstream economies when compared with extractive activities. In many cases, the focal point of such interactions has been based on providing a sustainable and clean supply of water, the most important and increasingly limiting mountain resource. In steep terrain, more than anywhere else, catchment quality is intimately linked to ecosystem integrity and functioning (MA, 2005). Thus environmental conservation and sustainable land use in the Himalayan mountains are not only a necessary condition for sustainable local livelihoods, they are also key to human well-being for nearly one-fifth of the world's population who live downstream and depend on fresh water from the Himalayan mountains.

4.3.6 Consequences to Water Resource Infrastructure Development in the Koshi Basin – A Case Study

4.3.6.0 General

The Koshi River is the main source of water for drinking water, irrigation and energy generation in the Eastern Nepal. Koshi basin is most comprehensive basin with respect to feasibility of irrigation, hydropower, and water supply, reservoirs and demand sites with all its components having equal priority or one component gaining higher priority. There exist large temporal and spatial variations of supply and demand throughout the river basin. The stream flow is lower in dry months and higher in wet months giving rise to a classic too much and too little syndrome every year. During the dry season, irrigated agriculture competes with domestic, livestock, aquaculture, hydropower and occasionally other sources of demand for available water resources. In contrast, the basin during the monsoon periods faces the disasters of landslides in the mountains and severe floods in the planes. In particular, the spatial and temporal variability of rainfall and runoff result in a situation in which water supply represents the binding constraint to improved agricultural productivity, household income, health and wellbeing in most of the lower part of the Koshi basin. The task of achieving efficient, sustainable water management within Koshi basin reflects the broader challenges of integrated water resources management. The situation becomes even more severe if the future climatic scenarios and their consequences are considered.

The traditional and conventional operational methods of the utilizing the river system have proved inefficient for a sustainable supply of water, resulting into a grave shortage of water for both irrigation and power supplies during the dry period and severe floods during monsoon periods. In order to meet the growing agriculture, domestic, industrial and power needs of the region, enhanced infrastructure and institutional support are called for to best utilize the river water resource.

This situation thus demands a comprehensive study to develop a robust and up-to-date methodology for the optimal operation of the Koshi River System. In addition to this, comprehensive management of water resources for water supply, irrigation, hydro-electric generation, navigation and inland fisheries is called for while mitigating and minimizing the problems of too little and too much water in different parts of the year, so that increasing challenges can be mitigated by sustainable development, allocation and monitoring of water resources use in the context of social, economic and environmental objectives with an approach of Integrated River Basin Management (IRBM).

4.3.6.1 JAICA Master Plan 1985 – A Classic Approach

Japan International Cooperation Agency (JAICA**)** after two years of rigorous exercise developed in 1985 a master plan on water resource development infrastucture in a classical hydrological approach with an objective towards the proper use of the water resources of Koshi river to meet the various irrigation, hydropower, and water supplies demands at different locations of the **K**oshi basin. The master plan framework (Fig. 4.3.3) included all the major confluences of the tributaries as well as all the major existing/planned demand points along the koshi river system. With the objectives of meeting the growing demands of irrigation, hydropower, and water supplies in the basin that exist at different locations during the dry periods, the potential for reservoir development was considered. Accordingly four reservoirs namely sunkoshi 1, sunkoshi 2, sunkoshi 3 and saptakoshi high dam were identified. Likewise, one major irrigation project (east & west koshi irrigation project) and one interbasin transfer to the Kamala basin were also taken into consideration. The master plan also idntified top thirteen hydropower schemes, among which hydropower from three schemes were meant for export and the rest ten schemes were considered as domestic priority schemes. The locations and layout of the projects as well as the capacities of hydropower schemes together with the anticipated water and energy demand data are all included in the provided Supplementary Materials.

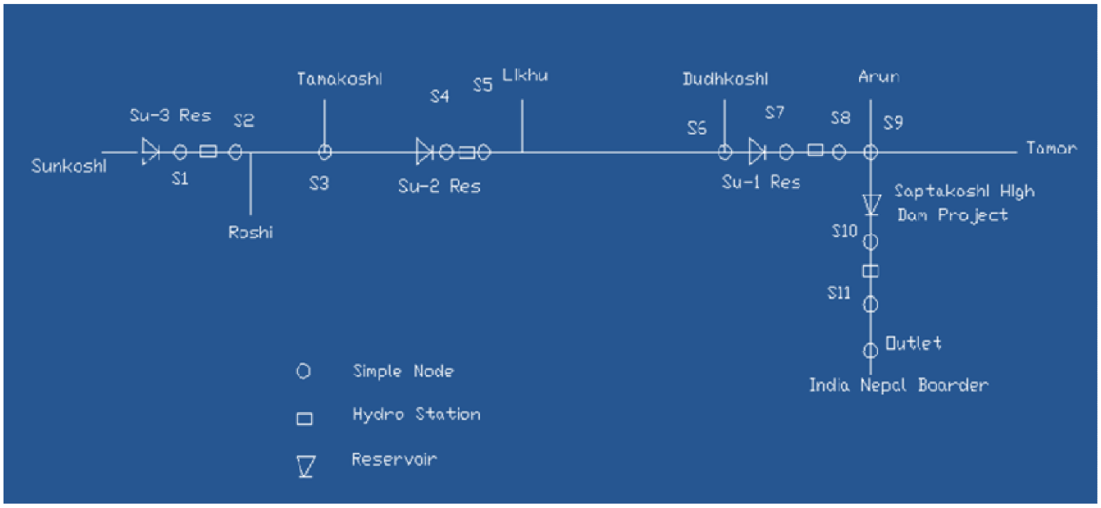


Fig. 4.3.3 Schematic Representation of Infrastructure Development Plan for Koshi Water Resources System

4.3.6.2 Economic Considerations

While hydrologic-based studies deal with hydrologic and system-control components, economic components are represented mainly by cost-benefit analyses and on the objective of optimization of net benefits. Integrated economic-hydrologic models consist of a hydrologic and an economic system. In such a model, the economic components are driven by the hydrologic system that is based on physical parameters and principles while the hydrologic components and their operation is driven by socio-economic (and environmental) objectives. A dynamic linkage of hydrologic and economic models is required because decisions concerning the quantity and timing of runoff and quantity of storage and extraction from dams act in turn to modify the hydrologic boundary conditions constraining such decisions. As the dynamics of hydrologic processes cannot be simulated accurately within the economic optimization model itself without a substantial increase in model complexity, it increases the burden on nonlinear optimization solvers.

Therefore in order to identify the integrated approach towards the use of the Water Resources of Koshi basin and also to find out the consequences of global change impact on the resources to upstream and downstream regions, General Algebraic Modeling System (GAMS) was adopted to integrate the basin hydrology with economic parameters and integrated Hydrologic-Economic models were developed with separate objective functions i) to minimize the sum of deficit in demand satisfaction; ii) to maximize the sum of net benefit for different purpose of water use without considering the climate change effect; and iii) to maximize the sum of net benefit for different purpose of water use considering the climate change effect as simulated by hydrological model using RCM.

A. Minimizing the Sum of Demand Deficit

This model, Model-A, optimizes water allocation in Koshi basin with objective function of minimizing the demand deficit giving equal priority to future irrigation demand diversion and hydropower generation with proposed four reservoirs in the Koshi Basin.

When the model is optimized with the demand data for 10 years (1993 -2003), only Koshi Irrigation Project could meet 100% of demand throughout the year, whereas Kamala Diversion could meet 100% demand only during the months of July and August. In case of energy generation from the SU-1, SU-2, SU-3 reservoirs, the targeted energy demand are hardly met fully. The satisfaction percentage in the different months of the year ranges from 14% to 92% for SU_3; from 27% to 73% for SU-2; from 29% to 100% for SU-1 and from 48% to 100 % for Saptakoshi reservoir. These are illustrated in Fig 4.3.4.

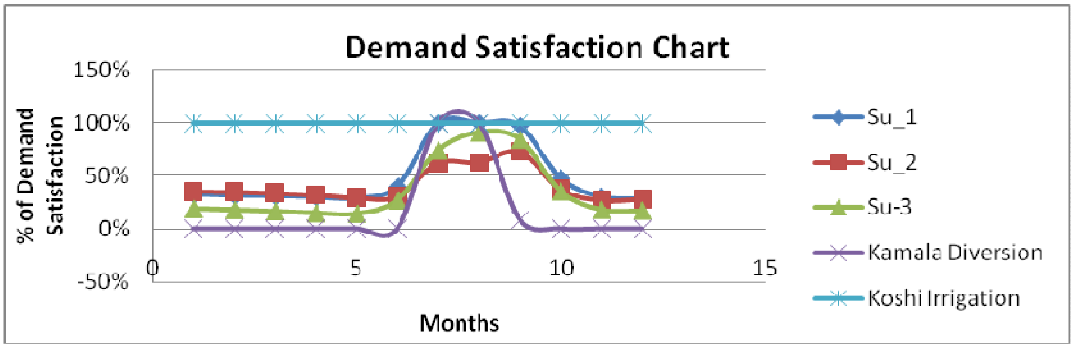


Fig. 4.3.4 Model A - Average Percentage Demand Satisfaction for 10 years (1993 -2003)

For this model, the optimal ten year average annual energy generation at proposed sunkoshi-3, Sunkoshi-2, Sunkoshi-1 and Saptakoshi reservoirs are 1,762.2 GWh, 4,118.7 GWh, 4,223.5 GWh & 22,000 GWh. The total annual generation from all schemes is 28,608 GWh. Figure 4.3.5 illustrates these results.

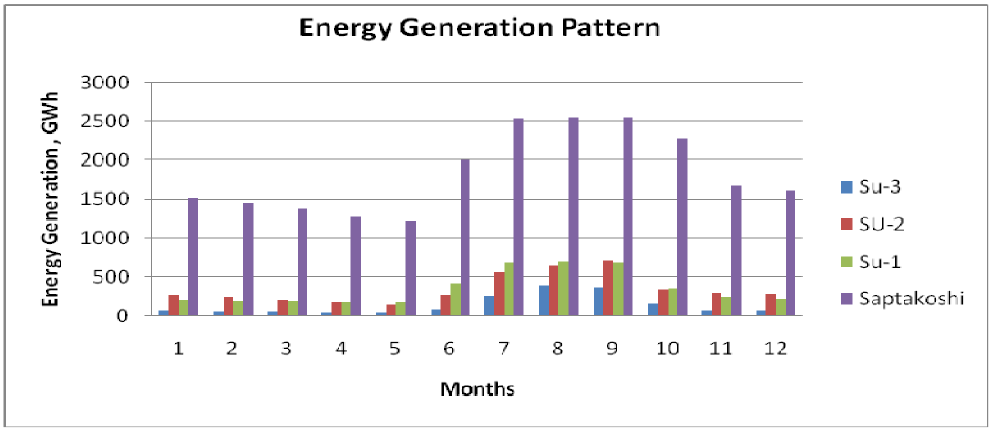


Fig. 4.3.5 Model-A Average Energy Generation (Gwh) at Reservoirs for 10 Years (1993 -2003)

B. Maximizing the Benefit

This model (Model-B) optimizes allocation of water in the Koshi basin with objective function of maximizing the benefit giving equal priority to future irrigation demand diversion (irrigating 175,000 ha of land by Kamala System and 1.522 million ha by Koshi System) and hydropower with proposed four reservoirs (res_1 : Su-3; res_2 : Su-2; res_3: Su-1; res_4: Saptakoshi High Dam) in the Koshi Basin.

When the model is optimized with the demand data for 10 years (1993 -2003), demand satisfaction for all irrigation and energy generation schemes are shown in Fig. 4.3.6. Demand satisfaction for the Kamala diversion is quite low (i.e. 8% to 46% for only July, Aug and Sep). The satisfaction percentage in the different months of the year ranges from 0% to 95% for the Koshi irrigation scheme, 7% to 92% for sunkoshi 3 reservoir, 8% to 85 % for sunkoshi 2, 8% to 100% for sunkoshi 1 and 25% to 100% for the Saptakoshi Reservoir schemes.

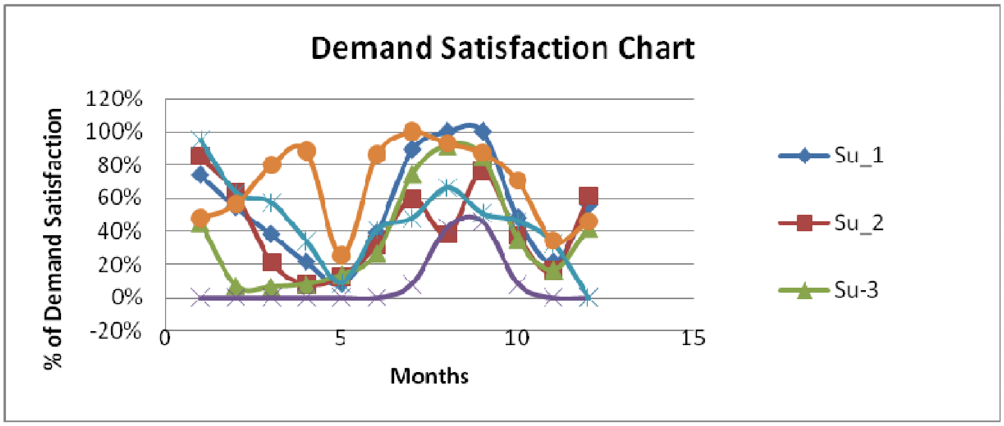


Fig. 4.3.6 Model B - Average Percentage demand satisfaction for 10 years (1993 -2003)

For this model ten year average annual energy generation at proposed sunkoshi-3, Sunkoshi-2, Sunkoshi-1 and Saptakoshi reservoirs are 1,767 GWh, 1,834 GWh, 4,129 GWh & 23,824 GWh and total average annual generation from all the proposed schemes will be 33,557 GWh. Fig. 4.3.7 illustrate these results.

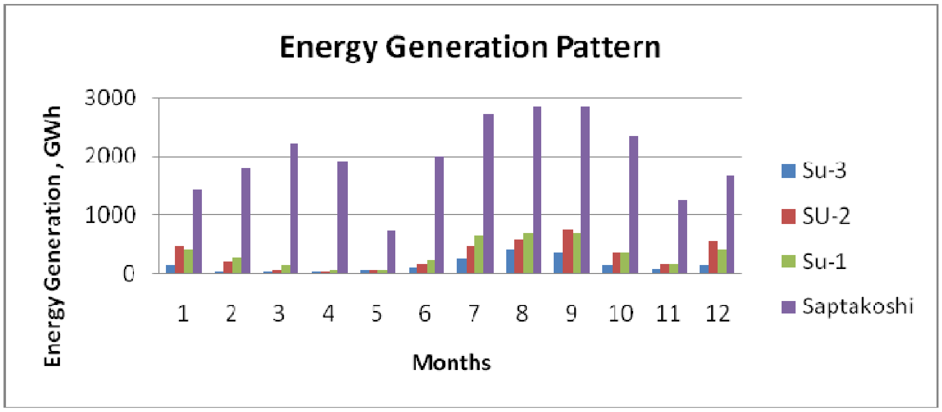


Fig. 4.3.7 Model B - 10 years (1993 -2003) Average Energy generation (GWh) at reservoirs

C. Consequences of Economic Considerations

Mere economic considerations of (a) minimizing summation of demand deficit (equity efficient model) and (b) maximizing the summation of total benefit (economic efficient model), without considering the future climate change impacts, indicated that while irrigation water demand of Koshi

Irrigation Project having gross command area of 1.522 million ha is satisfied for all the months over a year, the demand of Kamala diversion of 72 m^3/s is not satisfied throughout the year in equal priority model. Likewise, it also showed that for meeting the irrigation demand only, there is no need of development of sunkoshi 2 and sunkoshi 3 reservoirs and the development of Sunkoshi 3 reservoir is redundant because with and without sunkoshi 3 reservoir, energy generation and the irrigation demand satisfaction is nearly the same.

4.3.6.3 Consideration of Climate change

The consequence as a result of the likely variation in the discharge of the Koshi basin due to climate change has been taken up in the third model (Model C). The change in meteorological data as projected for 2040, 2050, 2060 by Regional Circulation Model (RCM) namely PRECIS under future scenarios of climate change has been used as input to comprehensive semi-distributed hydrological models (**HEC-HMS**) developed for the basin. The spatial and temporal distribution of flow in the Koshi basin thus simulated were used to further evaluate the impact of climate change on the planned water resources infrastructure development projects for their optimal uses as well as optimal benefits from them by using GAMS model.

This model thus optimizes allocation of water in the Koshi basin with objective function of maximizing the benefit while giving equal priority to irrigation demand and hydropower demand in future time (2041,2050,2060 and 2071 years) with consideration of climate change effect on future hydrology of basin . In this analysis, dam height of the Saptakoshi high dam has been taken as 269.0 m.

In the high altitude snow/glacier fed basins of the Himalayan region, the cryospheric melt runoff constitutes an important component in the total runoff. Thus generating better estimates of snow and glacier melt contribution to the Himalayan river flows and the likely change in this component due to global warming are two of the major driving concerns.

Demand satisfaction curves during the years 2041, 2050, 2060 and 2071 for all irrigation and energy generation schemes are shown in Fig.4.3.8 through Fig.4.3.13. The results indicate that the demand satisfaction by the different planned schemes in the Koshi basin will decrease sharply in the future and will be quite lower than the ten year average (1993 -2003). In case of the Kamala diversion project, the demand satisfaction will be nil in the year 2041 and the years beyond. And also, the demand for the Koshi irrigation will not be met fully in 2041, 2050, 2060 and will become nil in 2070.

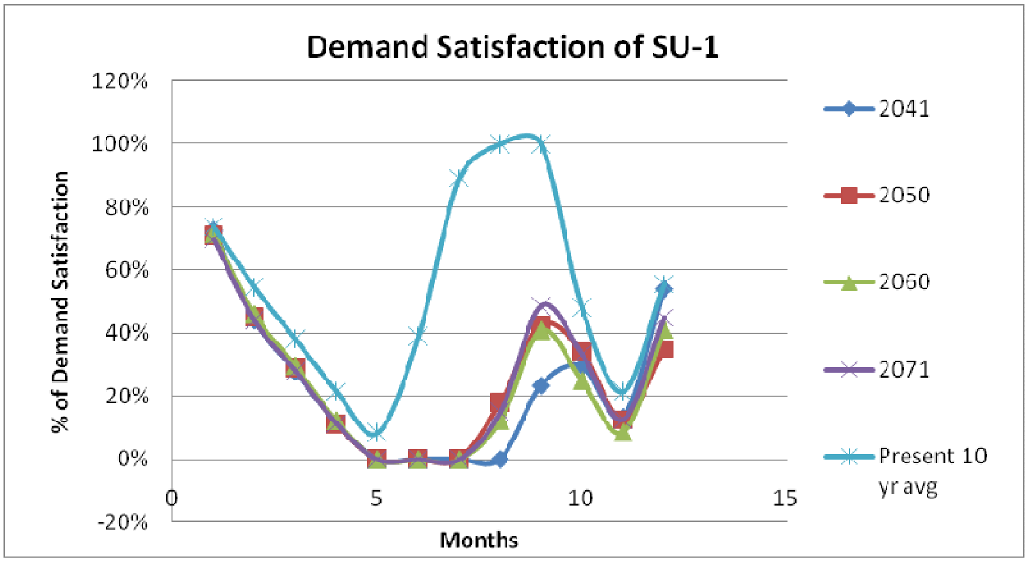


Fig. 4.3.8: Model C - Demand Satisfaction Pattern Of Sunkoshi 1 Reservoir

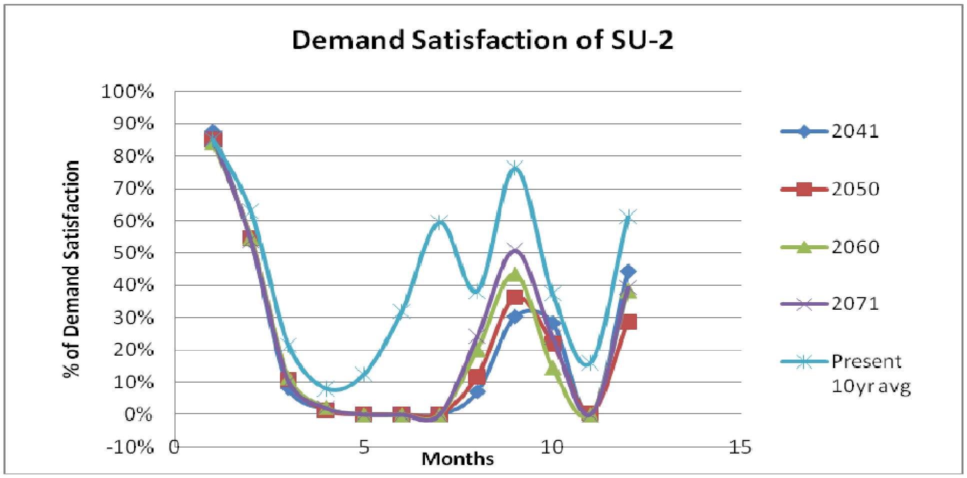


Fig. 4.3.9 Model C - Demand Satisfaction Pattern of Sunkoshi 2 reservoir

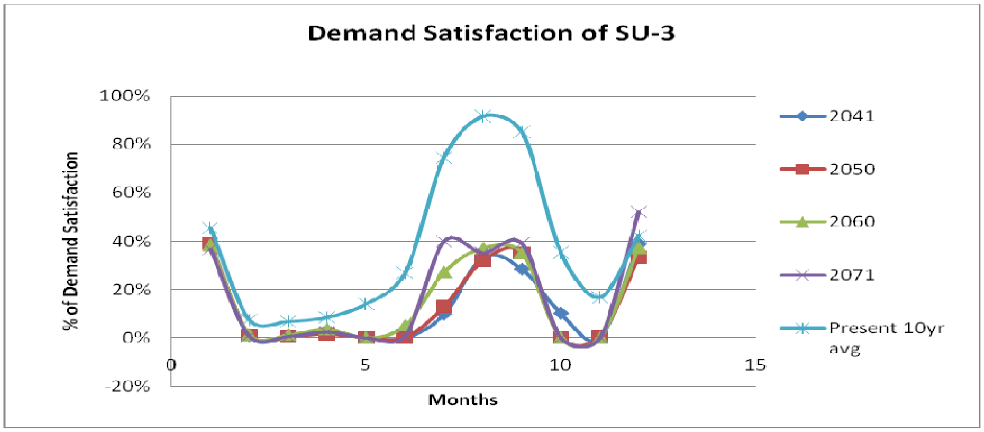


Fig. 4.3.10 Model C - Demand Satisfaction Pattern of Sunkoshi 3 reservoir

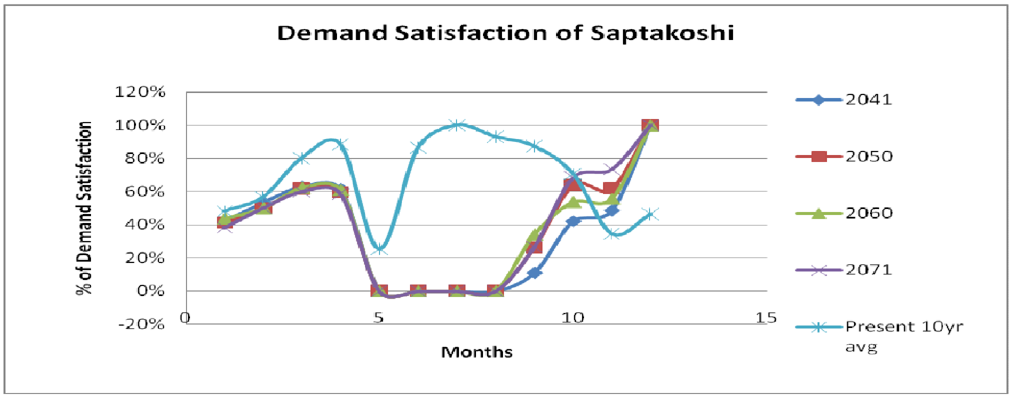


Fig. 4.3.11 Model C - Demand Satisfaction Pattern of Saptakoshi reservoir

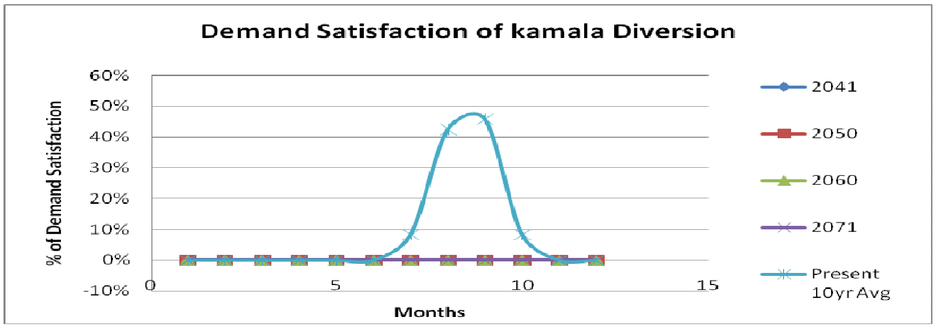


Fig. 4.3.12 Model C - Demand Satisfaction Pattern of Kamala Diversion

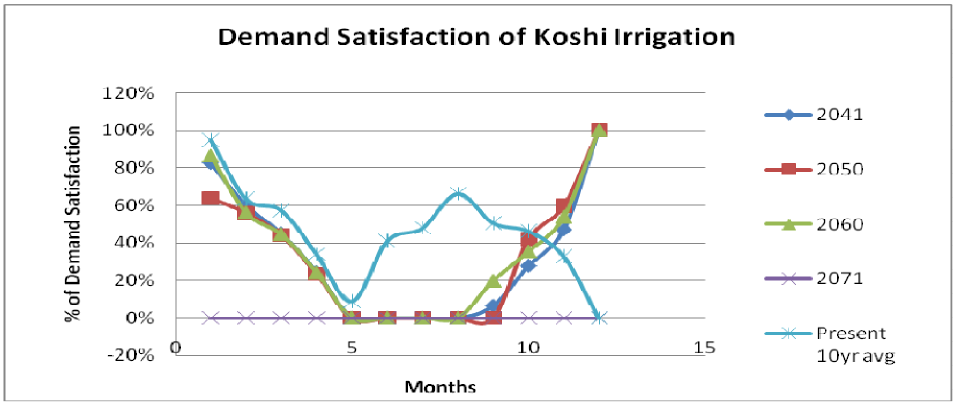


Fig. 4.3.13 Model C - Demand Satisfaction Pattern of Koshi Irrigation

The comparison among the energy generation pattern by the schemes in Koshi basin during different years in future and present energy generation trend are presented in fig. 4.3.14. The energy generation from the reservoirs will reduce significantly in 2041, 2050, 2060 and 2071. The total annual energy generation from all planned reservoirs will be 15047.44 GWh in 2041, 16,786.29GWh in 2050, 16,758.51 GWh in 2060 and 17,523.73 GWh in 2071 which are quite low (about 50 % less) in comparison to the planned annual generation of 33,556.59 GWh.

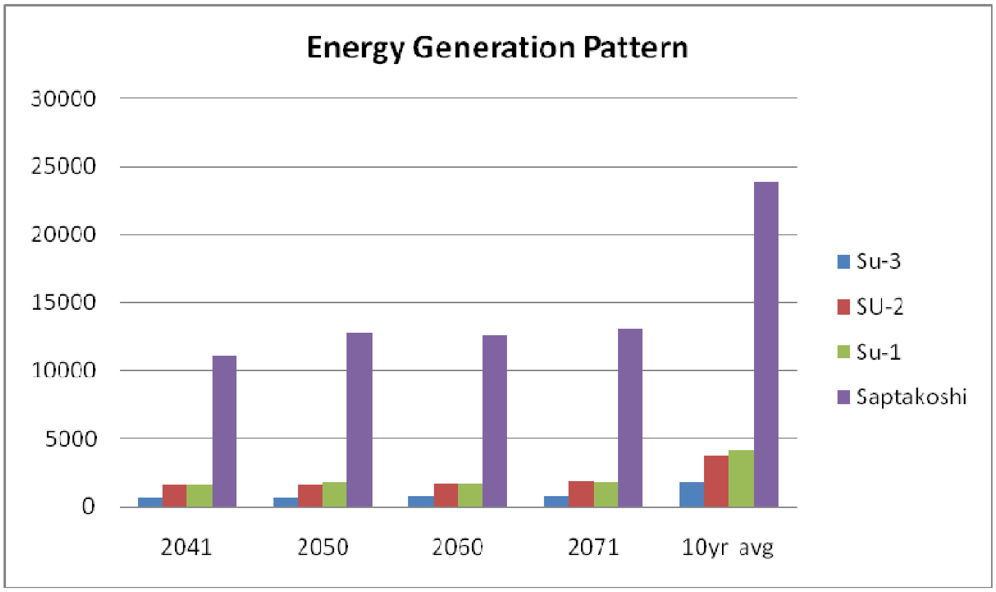


Fig. 4.3.14: Model C - Comparison of Energy Generation Pattern

Consequences of Climate Change Considerations

While considering the future runoff within the basin in response to predicted climate by Regional Circulation model (RCM), percentage of demand satisfaction will decrease considerably for years 2041, 2050, 2060 and 2071 as compared to the present satisfaction.

- The demand satisfaction will be quite low for year 2041, 2050, 2060 and 2071 as compared to the present satisfaction i.e. almost half for energy generation and also very low for irrigation supply.
- Result shows that the deficit will occur in all the Koshi Basin water resources development schemes designed in conventional ways using historical parameters without taking into account the impacts of global change in the future.
- the study simulated the impacts of CC on water infrastructure development in the Koshi basin
- All these results are very relevant to future water management in the basin.
- The combined impact of future water infrastructure development and climate on river flow in the Koshi basin and the availability of water for agriculture and other uses, as well as the impacts of CC on operation of infrastructure itself, should be a subject of a subsequent study.
- It could be argued that precipitation scenarios used to anticipate hydrological change under CC are not reliable as they originate only from one climate model: PRECIS RCM forced by HadCM3. It is now accepted that climate models are not able to accurately simulate precipitation, mostly because of their inability to simulate actual climate dynamics. For instance, Kingston et al. (2011) showed that uncertainty in precipitation is the main source of error in hydrological projections. Even the use of averaged precipitations projected by several climate models cannot reduce this uncertainty as the variability between different climate projections from different models is high.

4.4 Discussion

As per the project research strategy, downscaled climate models were developed and applied to study the global change impacts on snow, glaciers and runoff in the three selected river basins and then consider consequences of the impacts to the highland and lowland regions in the himalayan range.

The UBC model applied in Hunza basin and the SMR model applied in Upper Bhagirathi River Basin required relatively less field data inputs and the results based on them have to be considered with their limitations.. In the Koshi basin, models like energy and mass balance model, Tank model and HEC-HMS model were applied at various appropriate locations of the runoff flow chain to overcome the limitations to the extent possible. All the approaches have however helped to provide a general picture on the climate change impacts on snow, glaciers and runoff in the studied basins.

While projecting future runoff, no change in the extent and mass of the glaciers were considered. Likewise, in the absence of high altitude meteorological stations, meteorological parameters were derived from theoretical temperature lapse rate or those from the nearby low altitude stations as precipitation lapse rates in the regions are unknown/not available in general. Good satellite data at high resolutios are not readily accessible. The subsurface flow, which is currently found to be an important component in mountain river runoff, has so far been overlooked. Little is known regarding global change impacts on the subsurface flow in the region.

So, all the above results have to be considered in the context of the above limitations.

5.0 Conclusions

It is apparent that the impact of global changes on snow and glaciers in the Himalayas would result into significant changes in nature of hydrological processes in time and space, which would result into uneven distribution of availability of melt water in the upstream and downstream of the Himalayas. All these would thus pose immense challenge to Himalayan water resources management due to high spatial and temporal variation of resource endowment, and upstream-downstream linkages as a result of high degree of interrelationship among water sources, uses and users as well as their transboundary nature. In particular, since the contributions from snow and glacier melt in the Himalayn river runoff are significant during the dry periods and directly and indirectly affect livelihood of billions living in the upstream and downstream regions, therefore, estimation of snow and glacier melt and their roles in the context of global change turn out to be quite important.

A review of earlier publications on global change impact on snow, glaciers and their melts on the basins of the three major Himalayan rivers namely Indus, Ganges and Brahmaputra revealed a clearly declining trend in the snow cover and glacial ice in the basins and as a result a reduction in the water storage capacity of the basins in the form of snow and ice. Although a marked spatial and temporal variations are noted in the scale of such changes in the different parts of the Himalaya, a declining trend has been noted all over the Himalayan range.

As a result of climate change, a rise in temperature would further cause more precipitation in the high altitude regions as rain instead of snow with the snowline eventually shifting to high-altitude areas. Meanwhile, the Equlibrium Line Altitudes (ELAs), the altitude wherein accumulation and depletion of glaciers are in equilibrium, would also shift to higher altitudes resulting into the overall loss in glacial ice volume. All these on the whole would in future lead to a decrease in the water storage capacity of the basins in the form of snow and ice. The current ‘melt-dominated rivers’ are thus likely to turn ultimately to a ‘rain-dominated rivers’ on the long run.

In the selected Himalayan river basins, e.g. Koshi, Upper Bhagirathi and Hunza basins, various hydrological models have been applied in the present study to find the roles of snowmelt and glacial-melt in the hydrological system in the respective regimes and also to assess impacts of global change on them by applying the hydrological models forced by climate parameters from the RCMs . The results of such studies in the selected study basins suggest that maximum snow and glacier melt contributions to the total runoff varies, for instance, from over four-fifth in the Hunza basin to nearly one-third of the streamflow in the Koshi basin. Similarly, the melt runoff is a seasonal phenomena and costitutes in general quite significant components during the pre-monsoon and post-monsoon periods. In the Kosh basin for example, melt component is found as high as three-fourth of the total flow in one of the high altitude station during dry period. Hydrological models forced by climate parameters from the RCMs tend to project significant change in the hydrographs of these rivers originating from snow and glacier dominated highlands. It is also found that infrastructures for water resource development in such basins designed using the historical flow trends and without considering the potential impacts of global change can get highly over estimated or under estimated to stand the brunt of extreme events resulting from the global change. Hence for the sustainable development and use of the Himalayan water resource, the considerations of global change impacts on the resource itself become a mandatory concern.

The model results from present study have several incorporated uncertainty arising from different sources. This uncertainty is not only caused by inherent uncertainty of climate scenarios and predictions, but also because of to start with a lack of reliable data on changes in glacier volumes and melting rates. A large part of the currently reported estimated glacier decline is based on changes in area; there are however many unknowns in the relationship between Himalayan glacier volume and area. The hydro-meteorological input data are the other primary source of uncertainty. The input data, such as precipitation, are less representative due to the low station network density in the Himalyan regions in general and at the higher altitudes in particular. Similarly, the validation data, i.e. discharge, are another source of uncertainty as the measurement process of discharge during flood periods is less representative. Likewise, the model parameters are also a source of uncertainty in the model results.

For reducing such current scientific uncertainty, long-term scientific programmes are hence essential for monitoring and assessing cryospheric changes in the Himalayas in the context of ongoing and projected global change.

As there is severe deficit of field observations on hydro-climatic and cryospheric records in Himalaya, more so in the higher reions, studies under such programes need to include both ground-based and satellite-based monitoring. Remote Sensing, for example, could be utilized for regular and repeated monitoring of cryospheric regions in the harsh and remote areas for assesing on an a continuous basis the state of snow and glaciers in the Himalayan regions. Selection of bench mark study areas and baseline studies on glaciers, snowpack, and permafrost particularly in areas above 4000 m amsl and long-term monitoring through well equipped stations together with their networking and cooperation within and outside the region would greatly help in understanding the snow and glacier changes as well as complex hydrodrological dynamics in the Himalayan regions. Participatory methods of assessing and monitoring climate and cryospheric changes as well as stream flow and river runoff and making the most of local perceptions, and practices can play a vital role in determining best adaptation practices including those based on local information and knowledge.

Likewise, further modelling exercises at finer resolutions are essential to improve the knowledge and understanding of the impacts of global change on hydrological dynamics of the of the Himalayan rivers discharge in greater details including changes in water storage in the form of snow and glaciers and effect of evapotranspiration as well as to quantify to the extent feasible the changes in runoff components of snow and glacier melts. With the quantitative projections of changes in water flow in the Himalayan rivers and their consequent upstream and downstream impacts in the context of socio-economic future and considering the change in water demands as well, it would greatly facilitate the decision makers to identify practical strategies to mitigate or adapt to global change for a sustainable development and management of the Himalayan water resources.

Meanwhile expressions of melt flow as percentage of mean annual flow (MAF) can be quite misleading, because the high flow during monsoon period, when almost 80% of the annual precipitation takes place, leads to a high value of MAF and the melt flow that is prominent during dry period figures as a trivial componet when expressed in terms of percentage of MAF. As melt flow is a seasonal phenomenon, it needs to be expressed in terms of percentage of mean seasonal flow (MSF) in each season or as percentage of mean monthly flow (MMF) in each month. Only then the relative significance of the melt flow can be ascertained.

Furthermore the consequences of global change impacts on Himalayan snow, glaciers and runoff to livelihood and socio-economic development are altitude dependent as well as region specific and hence these should be considered carefully while developimg necessary adaptation strategies.

6.0 Future Directions

It is apparent that the impact of global changes would result into significant changes in nature of hydrological processes in time and space which would result into uneven distribution of availability of melt water in the upstream and downstream of the Himalayas. All these would thus pose immense challenge to Himalayan water resources management due to high spatial and temporal variation of resource endowment, and upstream-downstream linkages as a result of high degree of interrelationship among water sources, uses and users as well as their transboundary nature. In particular, since the contributions from snow and glacier melt in the Himalayn river runoff are significant in the arid regions and during the dry periods in other monsoon dominant regions as well and hence directly and indirectly affect livelihood of billions living in the upstream and downstream regions, the estimation of snow and glacier melt and their roles in the context of global change is therefore critically important.

In order to provide best possible science based information regarding future changes in the hydrological dynamics in the Himalyas in such a way as to enable all responsible decision makers to find practical strategies to mitigate or adapt to global change for a sustainable development and management of the Himalayan water resources and to mitigate flash flood and other flood hazards, it is essential to reduce existing scientific uncertainities in the estimations of snow and glacial melts and identify potential GLOF areas in space and time along the Himalayan range.

For reducing such current scientific uncertainty, long term scientific programmes are hence essential for monitoring and assessing cryospheric changes in the Himalayas in the context of ongoing and projected global change.

As there is a severe deficit of field observations on hydro-climatic and cryospheric records in Himalaya, more so in the higher regions, studies under such programes need to include both ground-based and satellite-based monitoring. Remote Sensing, for example, could be utilized for regular and repeated monitoring of cryospheric regions in the harsh and remote areas for assesing on an a continuous basis the state of snow and glaciers in the Himalayan regions. Selection of bench mark study areas and baseline studies on glaciers, snowpack, and permafrost particularly in areas above 4000 m amsl and long-term monitoring through well equipped stations together with their networking and cooperation within the region would greatly help in understanding the snow and glacier changes as well as complex hydrodrological dynamics in the Himalayan regions. Participatory methods of assessing and monitoring climate and cryospheric changes as well as stream flow and river runoff and making the most of of local perceptions, and practices can play a crucial role in determining best adaptation practices including those based on local information and knowledge. Studies on altitudinal variations of water demand and use as well as available sources of water can help in identify site specific adaptation strategies that vary greatly in the Himalayan basins. Similarly, assessments of hazards due to GLOFs, permafrost change induced land slides and other floods can help greatly reduce loss of life and property of many in the Himalayan river basins.

Likewise, further modelling exercises at finer resolutions are essential to improve the knowledge and understanding of the impacts of global change on hydrological dynamics of the of the Himalayan rivers discharges in greater details including changes in water storage in the form of snow and glaciers and effect of evapotranspiration as well as to quantify the changes in runoff components of snow and glacier melts. Further model exercises using various hydrological-climatological coupled models would help in reducing uncertainities in projected changes. With the quantitative projections of changes in water flow in the Himalayan rivers and their consequent upstream and downstream impacts considering the change in water demands as well as potential socio-economic changes would greatly facilitate all concerned decision makers to identify practical strategies to adapt to global change for a sustainable development and management of the Himalayan water resources and mitigate potential flash flood and other flood hazards.

Recent studies have moreover revealed the important role of southern mountains in the Himalayan ranges, which have no snow cover and glaciers, but yet have been providing valuable water supply even during dry seasons through ground water and springs and even several perinnial rivers originating from these mountain ranges. Studies on these matters, it seems, could further help in understanding the complex hydrology of the Himalayan river systems.

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Appendix

Conferences/Symposia/Workshops

Appendix A.1

The glimps of the synopsis of the Meeting, Joint Workshops, International Workshop and Seminar held during the periods of Year I & II the Project are presented below.

Initial Meeting: 13 – 14 November 2008

Joint Workshop: 17 – 19 February 2010

International Workshop: 13 – 15 September 2010

Scoping Workshop: 21 – 22 February 2011

Country Workshop held in India on
27-28 February 2012

Country Workshop held in Nepal on
10 April 2012

Seminar: 11 November 2012

Joint Workshop: 29 30 April 2013

Note: Agenda/Programme (including title, date and venue) and Participants list (comprising contact details of each participant, including organisation, address, phone number, fax number, and email address) of the events are provided separately.

Funding sources outside the APN

Uttarakhand State Council for Science and Technology (UCOST), Dehradun, India, cosponsored the Workshop on "Impacts of global change on the dynamics of snow, glaciers and runoff over the Himalayan Mountains with particular reference to Uttarakhand" held on 27-28 February, 2012 at G. B. Pant Institute of Himalayan Environment & Development (GBPIHED), Kosi-Katarmal, Almora, India.

Other significant achievements of the project:

- Organized one national level workshop in India on "Impacts of global change on the dynamics of snow, glaciers and runoff over the Himalayan Mountains with particular reference to Uttarakhand" (27-28February, 2012) under the auspices of the APN project ARCP2009-04CMY-Shrestha.
- Organized one national and two regional level workshops in Nepal on "Impacts of global change on the dynamics of snow, glaciers and runoff over the Himalayan Mountains" under the auspices of the APN project ARCP2009-04CMY-Shrestha.
- Published report of the workshop held in India, in an International quarterly e-Journal "***Earth Science India*** (Volume 63(1), August, 2012)", jointly with the Society of Earth Scientists and Springer-Verlag**.**
- One book, entitled "Impacts of global change on snow, glacier and runoff un North-Western Himalaya (Tentative Title), is under the process of publication as proceedings of the workshop held in India.
- Three research papers from the ARCP2009-04CMY-Shrestha project work have been submitted for publication and are under process.
- Three papers on the ARCP2008-16NMY-Shrestha and ARCP2009-CMY-Shrestha project works have already been published.
- A number of researcher/manpower working in the participating institutions in their different capacities and a number of project fellows under the project have been trained.

Acronyms & Abbreviations

ADPC	Asian Disaster Preparedness Center
amsl	above mean sea level
APN	Asia Pacific Network for Global Change Research, Japan
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
DEM	Digital Elevation Model
ELA	Equilibrium Line Altitude
DHM	Department of Hydrology and Meteorology, Govt. of Nepal, Nepal
DST	Department of Science and Technology, Govt. of India, India
EC	European Commission
GCISC	Global Change Impact Study Centre, Pakistan
GCM	General Circulation Model
GBPIHED	G. B. Pant Institute of Himalayan Environment & Development, India
GHG	Green House Gas
GIS	Geographic Information System
GLIMS	Global Land Ice Measurements from Space
GLOF	Glacier Lake Outburst Flood
GoI	Government of India
GoN	Government of Nepal
GRACE	Gravity Recovery and Climate Experiment
HKH	Himalaya-Karakoram-Hindu-Kush
ICESat	Ice, Cloud, and land Elevation Satellite
ICIMOD	International Center for Integrated Mountain Development
IDI	Institute for Development and Innovation, Nepal
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute
JAICA	Japan International Cooperation Agency
Landsat	Land Resources Satellite
MAF	Mean Annual Flow
MODIS	Moderate Resolution Imaging Spectroradiometer
NDSI	Normalized Difference Snow Index
NAPA	National Adaptation Programmes of Action
NGO	Non-Governmental Organization
NIH	National Institute of Hydrology, Roorkee, India
OECD	Organization for Economic Co-operation and Development
PRECIS	Providing Regional Climates for Impacts Studies
RCM	Regional Circulation model
RIMES	Regional Integrated Multi-Hazard Early Warning System
RS	Remote Sensing
SAC	Space Application Centre, Ahmedabad, India
SASE	Snow Avalanche Study Establishment, Chandigarh, India
SPOT5	Satellite Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
TERI	The Energy and Resources Institute
TM	Thematic Mapper (Landsat)
TMI	The Mountain Institute
TP	Tibetan Plateau
UCOST	Uttarakhand State Council for Science and Technology, India
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme

UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
WAPDA	Water and Power Development Authority (Pakistan)
WGMS	World Glacier Monitoring Service
WGI	World Glacier Inventory
WIHG	Wadia Institute of Himalayan Geology, Dehradun, India
WRF	Weather Research and Forecasting
WWF	World Wildlife Fund
WRI	World Resource Institute

Appendix

Conferences/Symposia/Workshops **Appenxix A**

Appendix A.1

The glimps of the synopsis of the Meeting, Joint Workshops, International Workshop and Seminar held during the periods of Year I & II the Project are presented below.

Initial Meeting: 13 – 14 November 2008

Joint Workshop: 17 – 19 February 2010

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Country Workshop held in India on
27-28 February 2012

Country Workshop held in Nepal on
10 April 2012

Seminar: 11 November 2012

Joint Workshop: 29 30 April 2013

The following Appendices present the Country Workshops, Seminar and Joint Workshop held during the periods of Year II of the Project together with the corresponding programme schedule and list of participants of the individual events.

Appendix A.2

Report on Country Workshop in India on "Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains with Particular Reference to Uttarakhand"

G. B. Pant Institute of Himalayan Environment & Development (GBPIHED)
Kosi-Katarmal, Almora, India

27-28 February, 2012

Introduction

Himalaya, often referenced as the water tower of Asia, stores a significant quantity of fresh water in the form of seasonal snow cover and glaciers. It is a serious concern that the Himalayan glaciers, largest outside of the polar region, are showing a decrease in snow cover and glacial retreat. The recession and overall decrease in the volume of glaciers is adding to the total area of erosion every year. Focusing on these aspects, a two days workshop ''*Impacts of global change on the dynamics of snow, glaciers and runoff over the Himalayan Mountains with particular reference to Uttarakhand*", was organized by G. B. Pant Institute of Himalayan Environment & Development (GBPIHED), Kosi-Katarmal, Almora during 27-28 February, 2012 in collaboration with the Asia Pacific Network for Global Change Research (APN), Japan, under the project ARCP2009-04CMY-Shrestha, and Uttarakhand State Council for Science and Technology (UCOST), Dehradun. Main aim of the workshop was to bring together leading experts working in the area to (i) discuss changes in the dynamics of Himalayan snow, glacier & runoff *vis-a-vis* climate change, (ii) address issues related to the impacts of changes in hydrological regimes on livelihood of people inhabiting upstream/ downstream areas, and (iii) provide much needed science based information for identifying and implementing adaptation and mitigation strategies for sustainable development of the region. About 45 delegates, including distinguished scientists, academicians, and research students from various organizations of India and from Nepal participated in the workshop (as listed below).

Inaugural Session

The inaugural session of the workshop started with welcome address by Dr. Rajesh Joshi, scientist, GBPIHED. Addressing to the gathering, Dr. L.M.S. Palni, Director, GBPIHED, highlighted R&D activities of the institute in entire Indian Himalayan Region (IHR). He specifically elaborated about the national/international programs of the Institute and expressed need for further developments in the field of glacier studies in the country and also shared few important documents prepared by the Institute such as Governance for Sustaining Himalayan Ecosystem (G-SHE): *Practices & Guidelines* and Compendium of Statistics for the Sates of IHR. Briefing about background and objectives of the workshop, Er. K. Kumar, scientist, GBPIHED advocated on more scientific information on climate change impacts on water resources in the Himalaya. Later, Dr. K.L. Shrestha, Institute for Development and Innovation (IDI), Kathmandu, Nepal, in his inaugural speech emphasized on necessity for dedicated efforts to study Himalayan climate and cryosphere. Dr. P.S. Rao, Adviser, DST, Govt. of India, New Delhi, and Guest of Honor of the occasion, stressed upon need of comprehensive studies for climate change and glacier in Himalaya. He advocated for making a system of data sharing at institutional level so that research can be benefited and coordinated & multi-disciplinary team work approach for high altitude-low altitude research in Himalaya. Presiding over the function, Dr. Rajendra Dobhal, Director General, UCOST, pointed out about scantiness of empirical database on climate change and glacier studies in Himalaya and expressed need for making single knowledge repository for all kinds of such database for the entire IHR. During the workshop, presentations and deliberations were held under following technical sessions: (i) Dynamics of Snow & Glacier, (ii) Climate Change Patterns, (iii) Climate Change and Flow Regime, and (iv) Consequences of Changes: Upstream-Downstream Linkages.

Session on Dynamics of Snow and Glacier

In the keynote address, a systematic overview of glaciers of Uttarakhand was presented by Dr. Deepak Srivastava, (Centre for Glaciology, Dehradun). He mentioned that average annual retreat of the majority of the glaciers is about 0.30% of the total length and average annual recession, in terms of area vacated by the glacier, is about 0.11 % of the total area. He further mentioned that, the small size glaciers (length wise) are retreating fast as compared to large glaciers. Rainfall and moraine mass/debris deposition is causing more glacier retreat, and changes in climate and mass balance leads to glacial fluctuations. He stressed on taking up new glaciers, irrespective of the ease of accessibility, for glaciological studies which will help in strengthening databases and filling up the research gaps. Dr. I. M.

Bahuguna (SAC, Ahmedabad) deliberated on progress in snow and glacier studies of Himalaya using RS and ground data and underlined effective use of these tools for snow cover & glacier monitoring and mass balance studies. Dr. K. L. Shrestha presented a case study of Koshi river basin (Nepal), wherein, PRECIS and WRF RCM simulations results shows increasing trends of discharge with rise in temperature. The study was an outcome of a project (funded by APN, Japan) being implemented in China, India, Nepal, and Pakistan. Dr. Rajesh Joshi (GBPIHED, Almora) presented the work being carried out in Indian part under the same project. Reporting to the findings, he presented seasonal snow cover variation in Upper Bhagirathi basin using MODIS satellite data. Based on past 10 years data (2000-2010), shift in accumulation & ablation duration and decrease in winter & spring seasonal snow cover was prominently mentioned. Such changes in seasonal snow cover affects stream flow and water availability in downstream areas.

Session on Climate Change Patterns

Deliberating on patterns of climate change in North-West Himalaya, Dr. M. R. Bhutiyani (SASE, Chandigarh) mentioned that Himalayas are warming at higher rate than the global rate; particularly warming in winter season is significant due to which snow and glacial cover of the region is declining. Indicating on perceptible evidences of human induced climatic change, he provided insights on (i) significant increase in population and urbanization, (ii) increase in per capita consumption of petroleum products, (iii) decrease in waste lands, fallow lands and increase in concentration of PM greenhouse gases in the NWH. He stressed upon need to restore glacial health and snow cover for which following methods were suggested to salvage the situation: (i) identifying river basins/areas where ‘Mountain-Spring-Heat-Island effect’ can have dangerous effects, (ii) highly reflective roofing material may be used for households in urban areas to alter the energy balance, (iii) snow harvesting techniques using snow pits, snow fences and check walls to retain snow cover for longer duration, (iv) formation of zone avalanche control structures, catchment dams in the avalanche tracks, and (v) artificial increase in concentration of aerosol particles in higher reaches to ensure lower shortwave radiation. Dr. J. S. Rawat (Kumaun University, SSJ Campus, Almora) presented progress of development of Uttarakhand climate change portal and demonstrated use of web GIS for data management. Dr. J. C. Kuniyal (GBPIHED, Kullu Unit) dwelt on distribution of aerosol, gaseous pollutants such as SO_2, NO_2, O_{310} particles, and in Kullu valley. He mentioned that, fine size aerosols are increasing at the rate of 0.7% per year and elaborated that the region has both local sources (biomass burning and vehicular emissions) and external sources (episodic sources mainly from the NW countries) of aerosols. Dr. Varun Joshi (GGSIP University, Delhi) mentioned that the mean $CO{-}4SO_2$ concentration at Dokriani (383 ppm) glacier is higher than the global mean atmospheric CO_2 value (380 ppm). Since, troposphere baseline data of CO_2 concentration has not been measured over the IHR, therefore, precise measurement of atmospheric CO_2 under diverse environmental settings of IHR is suggested.

Session on Climate Change and Flow Regime

An important issue in global warming is its impact on the environment, and water resources in particular. The quantity and timing of river flow are critical components to water supply, water quality, and the ecological integrity of river systems and thus changes in river flow regimes reflect the climate conditions and, naturally, are bound to respond to climatic changes. Dr. S.K. Jain (NIH, Roorkee) focused of glacial lake outburst flows (GLOFs). On the basis of findings of hydrological studies carried out by NIH in Beas, Chenab and Satluj basins of NW Himalaya, he revealed that, stream flow and snowmelt runoff is more sensitive to temperature change rather than changes in precipitation. Speaking on GLOFs, he provided insight on effect of warming climate on frequency of GLOFs and emphasized on (i) regular mapping and monitoring of lakes, (ii) identification and prioritization of potentially dangerous glacial lakes, (iii) monitoring of potentially dangerous lakes on a continuous basis using high resolution time series satellite imageries, and (iv) need for appropriate measures to reduce the potential risks from these lakes. Dr. A. K. Lohani (NIH, Roorkee) deliberated on assessment and simulation of glacier lake outburst to estimate the flood due to GLOF. He mentioned that, since GLOF has the possibility of flood hazard therefore, in the quest of development, due consideration to GLOF should be given while planning for dam break analysis. While discussing variable response of glacier melt to climate change, an overview of annual retreat of glaciers of Uttarakhand was presented by Dr. D. P. Dobhal (WIHG, Dehradun) for the period 1965-2010. He stated that, glacier retreat rates are not only controlled by changes in climate but topographic and morphologic features also play important role. He further stated that, over the years, retreating trends of glaciers are largely same; however, the magnitude of retreat has changed. The annual fluctuations in the retreat of any glacier may be due to variable winter snowfall therefore, volume loss is more important than the snout retreat. Prof. R. Shankar (Institute of Mathematical Sciences, Chennai) shared the progress of development of flow line model for flow and retreat measurements of Satopanth glacier which can capture the response of debris covered glacier to the climate. Mr. Pradeep Rawat (Kumaun University, Nainital) presented spring hydrology of non-glacial river basin wherein need for protecting the spring by creating spring sanctuaries was highlighted.

Session on Consequences of Changes: Upstream-Downstream Linkages

The major glacier-fed Himalayan rivers along with glaciated catchments have regional importance; water from the melting of glacier sustains stream flow in these rivers during the dry season and sustains livelihood of people inhabiting upstream & downstream areas. Pointing to these issues, Er. Kireet Kamar (GBPIHED, Almora) described hydrological response of glacial and non-glacial river systems of Himalaya. He indicated that, in glaciated catchments, response to seasonal climate variability is predominant in flow pattern as winter snow plays major role in controlling flow conditions and summer precipitation & lowering of temperature affects diurnal variations. But, in case of non-glacial catchments, inter-annual variations are more predominant under the influence on rainfall pattern; therefore the hydrological response time in such catchments is much shorter (1-3 days). He underlined the need for considering watershed as a unit for conservation & management of water. Dr. M. Arora (NIH, Roorkee) mentioned that statistical downscaling technique may be adopted for using GCM output for regional climate impact studies. In his presentation, Dr. N.P. Chaulagain (AEPC, Kathmandu, Nepal) presented socioeconomic dimension of glacier melt in Nepal; wherein, he mentioned adverse affects of rise in glacier melt with the rise in temperature. Dr. S.C.R. Vishvakarma (GBPIHED, Almora) deliberated on Climate change and its impact on water resources in the Kullu Valley; the rise is particularly higher during winter months thereby affecting snow and ice caps of NW Himalaya. Dr. Ravindra Kaur (SES, JNU, Delhi) spoke on ‘Uttarakhand developmental policies, IEL compliance in climate change perspective’ and debated for promotion of meticulously enforced eco-friendly infrastructure and technology in the state.

Concluding Session

In his concluding remarks, Dr. L.M.S. Palni emphasized on the need of collaborative and coordinated approach for glaciological studies and stressed for provision of high altitude incentives for research in this field. He further stressed upon need for human resource development in this area. Dr. K.L. Shrestha called for trans-boundary collaboration and long term research in glaciology. Further, it was suggested that, proper attention needs to be given to the socio-economic issues of the people inhabiting in the areas upstream and downstream and fresh water issues needs to be addressed adequately. Dr. P.S. Rao shared valuable information about new proposal/initiatives of DST, Government of India such as extra incentives for researchers working in high altitude areas, and initiation of integrated programmes for long term glaciers research.

G. B. Pant Institute of Himalayan Environment & Development
Kosi-Katarmal, Almora-263643, Uttarakhand
Workshop On
"Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains with Particular Reference to Uttarakhand"
(27-28 February, 2012)

Programme Schedule

DAY 1

09:30-10:00 **Registration**

10:00 -10:50 **Inaugural Session**

Welcome Address	Dr. L M S Palni, Director, GBPIHED
Workshop Introduction	Er. Kireet Kumar, GBPIHED
Inaugural Address	Dr. K.L. Shrestha, IDI, Kathmandu, Nepal
Address by Guest of Honour	Dr. P.S. Rao, Adviser, DST, New Delhi
Presidential Address	Dr. Rajendra Dobhal, DG, UCOST, Dehradun
Vote of thanks	Dr. Rajesh Joshi, GBPIHED

10:50-11:10 **Inaugural Tea**

11:10-13:30 Hrs **TECHNICAL SESSION–I**

Dynamics of Snow and Glacier

Session Chair: Dr. P. S. Rao

S. No.	Title	Speaker	Time
1	**Glaciers of Uttarakhand Himalaya : An overview**	**Dr. Deepak Srivastava**	**11:10-11:40**
2	Progress in Snow and Glacier Studies of Himalaya: Using Remote Sensing and ground data.	Dr. I.M. Bahuguna	11:40-12:00
3	Investigating the Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains	Dr. K. L. Shrestha	12:00-12:20
4	Changes in seasonal snow cover in Upper Bhagirathi Basin	Dr. Rajesh Joshi	12:20-12:40

12:40-13:30 **Panel Discussion**

13:30-14:30 **Lunch Break**

14:30-16:10 Hrs **TECHNICAL SESSION–II**

Climate Change Patterns

Session Chair: Dr. Deepak Srivastava

S. No.	Title	Speaker	Time
1	**Patterns of climate change in North-West Himalaya**	**Dr. M. R. Bhutiyani**	**14:30-14:50**
2	Towards Development of Uttarakhand Climate Change Portal	Dr. J. S. Rawat	14:50-15:00
3	Aerosols and temperature rise in the northwestern IndianHimalaya	Dr. J.C. Kuniyal	15:00-15:10
4	Measurement of atmospheric Carbon Dioxide Levels at Dokriani Bamak Garhwal Himalaya, India: Climate change study	Dr. Varun Joshi	15:10-15:20

15:20-16:00 **Panel Discussion**

16:00-16:15 **Tea Break**

16:15- 18:00 Hrs **TECHNICAL SESSION – III**

Climate Change and Flow Regime

Session Chair: Dr. K L Shrestha

S. No.	Title	Speaker	Time
1	**Identification of Glacial lake and the potentially dangerous glacial lake in the Himalaya basin**	**Dr. Sanjay K Jain**	**16:15-16:25**
2	Assessment and simulation of glacier lake outburst floods for a basin in Himalayan region	Dr. A K Lohani	16:25-16:35
3	Variable Response of Glaciers Melt to Climate change; Study from Uttarakhand	Dr. D.P. Dobhal	16:35-16:45
4	Spatial and temporal trends in glacier fluctuations in Uttarakhand	Dr. Milap Chand Sharma	16:45-16:55
5	Retreat and Flow Measurements of the Satopanth Glacier	Dr.Ramachandran Shankar	16:55-17:05
6	Spring Hydrology of non-glacial river basins in Himalaya: A case study of Dabka Catchment	Dr. C.C. Pant	17:05-17:15

17:15-18:00 **Panel Discussion**

19:00-21:00 **Inaugural Dinner**

DAY2

09:30-11:45 Hrs TECHNICAL SESSION–IV

Consequences of Changes: Upstream-Downstream Linkages

Session Chair: Dr. M. R. Bhutiyani

S. No.	Title	Speaker	Time
1	**Hydrological behaviour of glacial and non-glacial watershed**	**Er. Kireet Kumar**	**09:30-10:00**
2	Impact of Climate Change on water resources	Dr. Manohar Arora	10:00-10:10
3	Socioeconomic Dimension of Glacier Melt in Nepal	Dr. Narayan Prasad Chaulagain	10:10-10:20
4	Climate change and its impact on water resources in the Kullu Valley, North Western Himalaya	Dr. S.C.R. Vishvakarma	10:20-10:30
5	Uttarakhand Developmental Policies, IEL Compliance And Climate Change: A Perspective	Dr. Ravindra Kaur	10:30-10:40
6	Current Tree/Vegetation line status of Garhwal region of Uttarakhand	Ms. Asha Thapliyal	10:40-10:50

10:50-11:30 Discussion

11:30-11:45 Tea Break

11:45-13:00 Hrs POSTER SESSION &

Visit to Poster and Photo Exhibition of GBPIHED

Valedictory Function

Closing Remarks

13:00-13:30 Vote of Thanks

13:30-14:30 LUNCH

15:00 onwards Site Viewing: Visit to Kausani

19:30-21:00 Dinner

List of Participants

S. No.	Name of Delegate	Institute/ Organization and Email	Presenting paper (Oral/Poster)
Invited Resource Person			
1	Dr. P.S. Rao	DST, Delhi, psrao@nic.in	Talk
2	Dr. R. Dobhal	DG, UCOST, Dehradun, ucost@ucost.in	Talk
3	Dr. Deepak Srivastava	Centre for Glaciology, Dehradun, deepaksrivas@yahoo.com	Talk
4	Dr. D.P. Dobhal	WIGH, Dehradun, dpdobhal@wihg.res.in	Paper (O)
5	Dr. Sanjay K. Jain	NIH, Roorkee, sjain@nih.ernet.in	Paper (O)
6	Dr. Manohar Arora	NIH, Roorkee, arora@nih.ernet.in	Paper (O)
7	Dr. I.M. Bahugua	SAC, Ahmedabad, imbahuguna@sac.isro.gov.in	Paper (O)
8	Dr. Varun Joshi	IP University, Delhi, varunj63@gmail.com	Paper(O)
9	Dr. M.R. Bhutiyani	Joint Director, SASE, Chandigarh, mahendra_bhutiyani@yahoo.co.in	Paper (O)
10	Dr. J.S. Rawat	Kumaun University, Almora, jsrawat1955@gmail.com	Paper(O)
11	Dr. C.C. Pant	Kumaun University, Nainital, ccpgeol@yahoo.com	----
GBPIHED Participants			
12	Dr. L.M.S. Palni	Director, GBPIHED, Almora, lmspalni@rediffmail.com	
13	Er. Kireet Kumar	GBPIHED, Almora, kireet@gbpihed.nic.in	Paper (O)
14	Dr. S.C.R. Vishvakarma	GBPIHED, Almora, scrv@gbpihed.nic.in	Paper (O)
15	Dr. J.C.Kuniyal	GBPIHED, Mohal, Kullu, jckuniyal@rediffmail.com	Paper (O)
16	Dr. Subrat Sharma	GBPIHED, Almora, subrats@rediffmail.com	NO
17	Dr. Rajesh Joshi	GBPIHED, Almora, dr.rajeshjoshi@gmail.com	Paper (O)
18	Er. M.S. Lodhi	GBPIHED, Itanagar, mahen29.mail@gmail.com	NO
19	Er. S. Tarafdar	GBPIHED, Srinagar, Garhwal, soukhin1974@yahoo.co.in	NO
Other Participants			
20	Dr. K.L. Shrestha	IDI, Kathmandu, Nepal, klshrestha1@ntc.net.np	Paper (O)
21	Dr. Narayan Prasad Chaulagain	Alternative Energy Promotion Centre, Nepal narayanchaulagain@gmail.com	Paper(O)
22	Dr. A. K. Lohani	NIH, Roorkee, lohani@nih.ernet.in	Paper(O)
23	Dr. Nathaniel B Dkhar	TERI, Delhi, Nathaniel.Dkhar@teri.res.in	Paper(P)
24	Dr. Deepak Kholiya	Deptt. of Env. Sc., GEH, University, Bhimtal, deepak151176@gmail.com	Paper(P)
25	Dr. Ravindra Kaur	School of Environmental Sciences JNU, New Delhi, ravindrakaur@yahoo.co.in	Paper(O)
26	Mr. Argha Banerjee	The Institute of Mathematical Sciences, Chennai, argha.k@gmail.com	Paper (P)
27	Dr. Neeraj Tiwari	Kumaun University, S.S.J.Campus, ALmora, kumarn_amo@yahoo.com	----
28	Mr. Anil Sharma	IIT, Roorkee anil123456@gmail.com	----
29	Mr. Malay Goel	IIT, Roorkee, goel.malay@gmail.com	----
30	Mr. Ashutosh Kumar	IIT, Roorkee, ak10907030@gmail.com	----
31	Mr. Amit Kumar	IIT, Roorkee, amit.kr64@gmail.com	----
32	Mr. Raj Kumar	IIT, Roorkee	----
33	Mr. Pradeep Rawat	Kumaun Uni., Nainital	Poster(P)
34	Dr. Ramachandran Shankar	The Institute of Mathematical Sciences, Chennai	Paper (O)

35	Mrs. Umang	Kumaun University, Almora, anilumang@yahoo.co.in	Paper (P)
36	Ms. A Sirohi	Kumaun University, Almora	Paper (P)
37	Mr. Jagdish Pande	GBPIHED, Almora	----
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39	Dr. Prashant	UCOST, Dehradun	
40	Mr. Sandeep Soni	GBPIHED, Almora	
41	Ms. Gunjan Joshi	GBPIHED, Almora	
42	Ms. Sapna Bisht	GBPIHED, Almora	

Report on Country Workshop in Nepal on

“Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains with Particular Reference to Koshi Basin”

Godavari Village Resort, Lalitpur
Tuesday, 10th April 2012

The national workshop was participated by experts from ICIMOD, WWF, IWMI and various concerned institutions relating the theme of the Workshop. The presentations by the concerned experts shed light on the ongoing reearch in their institutions and also indicated the new research trends. All these proved very useful in carrying out the second year activities of the APN project.

Country Workshop on
"Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains with Particular Reference to Koshi Basin"

Godavari Village Resort, Lalitpur
Tuesday, 10th April 2012

Programme

Arrival at Godavari Resort			**09:00**
Registration			**09:00-09:30**
Welcome & TECHNICAL SESSION–I [09:30-11:00 Hrs] **Dynamics of Snow and Glacier** **Session Chair: Dr. Madan Lal Shrestha**			
	Title	**Speaker**	**Time**
1	Welcome Address	Dr. Kedar Lal Shrestha	09:30-09:35
2	Participants' self introduction	Participants	09:35-09:45
3	"Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains with Particular Reference to Koshi Basin"	Dr. Kedar Lal Shrestha	09:45-10:00
4	"Monitoring and Assessment of Snow – Cover in HKH"	Mr. Deo Raj Gurung	10:00-10:15
5	"Status of Glaciers in Nepal"	Mr. Samjwol Bajracharya	10:15-10:30
6	**Floor Discussion**		10:30-11:00
Tea Break			11:00-11:30
TECHNICAL SESSION–II [11:30-13:00 Hrs] **Climate Change Scenarios and Glacial Changes** **Session Chair: Mr. Pradeep Mool**			
	Title	**Speaker**	**Time**
1	"Development of Climate Scenarios for Koshi Basin"	Dr. Madan Lal Shrestha	11:30-11:45
2	"Summer Monsoon Rainfall Over Nepal and Atmospheric Circulations "	Dr. Madan Sigdel	11:45-12:00
3	"Recent activities of Kathmandu University on glacier mass balance and glacio-hydrological modeling in Nepal."	Dr. Rijan Bhakta Kayastha	12:00-12:15
4	"Investigating the applicability of WRF mesoscale meteorological model for hydroclimate projections in Dudh Koshi basin".	Dr. Kundan Shrestha	12:15-12:30
5	**Floor Discussion**		12:30-13:00
Lunch Break			13:00-14:00

TECHNICAL SESSION–III [14:00-16:00 Hrs]

Runoff Modeling, Consequences and Adaptation

Session Chair: Dr. Bal Krishna Sapkota

	Title	Speaker	Time
1	“Socio-economic Dimension of Snow & Glacier Melt in the Nepal Himalayas”	Dr. Narayan Chaulagain	14:00-14:15
2	“Climatic pattern, hazard and land degradation in the Jaladh watershed in the Siwaliks hills and Terai, East Nepal.”	Dr. Moti Ghimire	14:15-14:30
3	"Global change and resulted glacier retreat, changes in surface morphology, and glacial lake development of Imja and Chamlang South glaciers in Dudh Koshi Basin, eastern part of Nepal Himalaya".	Dr. Damodar Lamsal	14:30-14:45
4	“Changing Climate-Melting Glaciers: Vulnerability of Glacial Lakes in Eastern Himalaya, Nepal.”	Mr. Jeeban Panthi	14:45-15:00
5	“Adaptation and Resilience to Climate Change in Koshi Basin”	Mr. Ajaya Dixit	15:00-15:15
6	Runoff Modelling of Glacierized Sub-basins of Koshi Basin	Dr. Narendra Sakya	15:15-15:30
7	**Floor Discussion**		15:30-16:00
Tea Break			16:00-16:30

CONCLUDING SESSION–III [16:30-17:05 Hrs]

Session Chair: Dr. Kedar Lal Shrestha

Title	Speaker	Time
Summary Technical Session I	Mr. Pradeep Mool	16:30-16:40
Summary Technical Session II	Dr. Madan Lal Shrestha	16:40-16:50
Summary Technical Session III	Dr. narayan Chaulagain	16:50-17:00
Concluding Remarks		17:00-17:05
Departure for Kathmandu		**17:15**

Country Workshop on
"Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains with Particular Reference to Koshi Basin"

Monday, 9th April 2012

Godavari Village Resort, Lalitpur

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Appendix A.4

Seminar on

Himalayan Mountain Headwaters and Recharge of Groundwater and Natural Reservoirs

11 November, 2012

Hotel Himalaya, Lalitpur, Nepal

Background

In the high Himalaya, rain, ice and snow are thought to control discharge of the large rivers. Almost eighty percent of the precipitation in the eastern Himalayan regions falls within four months of the year during summer monsoon. While the high mountains store some of the precipitation in the form of snow and ice and then provide melt water during the dry period, the mountains without such snow and ice cover supply water during the dry period only through the storage in the form of groundwater and other natural reservoirs. The water resource system in Kathmandu valley is a typical example.

Andermann et al. (2012) discusses the impact of transient groundwater on river flows from Nepal, finding that the volume of water through these stores is approximately six times higher than the glacier melt contribution.

In the above context, a one-day seminar with the participation of relevant experts was organized on Sunday, 11th November 2012 at Hotel Himalaya in Lalitpur to deliberate on integrated mountain hydrology while focusing on the following:

- Mountain System Recharge: Process & Estimation
- Headwater Areas & Global Change Impacts
- MSR around Kathmandu valley

Seminar on

Himalayan Mountain Headwaters and Recharge of Groundwater and Natural Reservoirs

11 November, 2012

Hotel Himalaya, Lalitpur, Nepal

Tentative Programme

Nov. 11 (Sunday)	**OPENING AND TECHNICAL SESSION 1** **Chairperson: Dr. Madan Lal Shrestha**		
Morning / Afternoon	Registration of Participants	09:00-09:30	
	Welcome and Introduction to the Objectives and expected outcome of the Seminar	09:30-09:40	Dr. Kedar Lal Shrestha
	Drinking Water Demand and Supply in Kathmandu Valley	09:40-10:00	Mr. Prayag Lal Joshi
	Status of Groundwater Usages in Kathmandu Valley	10:00-10:20	Mr. Surendra Raj Shrestha
	Kathmandu Valley Groundwater Outlook	10:20-10:40	Mr. Dhiraj Pradhananga
	Floor Discussion	10:40-11:00	
	Tea Break	11:00-11:30	
	TECHNICAL SESSION 2 **Chairperson: Dr. Bal Krishna Sapkota**		
	Water Quality along the Bagmati River in Kathmandu Valley	11:30-11:50	Ms. Indra Kumari Manandhar
	Hydrological Study on Augmentation of Groundwater in Kathmandu Valley	11:50-12:10	Mr. Kiran Shankar Yogacharya
	Field Visit to Groundwater & Natural Storage Recharge Study at Garhwal in India	12:10-12:30	Dr. Kundan Lal Shrestha
	Floor Discussion	12:30-13:00	
	Lunch	13:00-14:00	
Afternoon	**TECHNICAL SESSION 3** **Chairperson: Mr. Kiran Shankar Yogacharya**		
	Spatial Hydrological Modeling for Groundwater Recharge	14:00-14:20	Dr. Madhav Narayan Shrestha
	Water environmental model in the Yodo-Biwako basin, Japan	14:20-14:40	Dr. A. Kondo
	Himalayan Mountain System Recharge	14:40-15:00	Dr. Kedar Lal Shrestha
	Floor Discussion	15:00-15:30	
	Tea	15:30:16:00	

Seminar on

Himalayan Mountain Headwaters and Recharge of Groundwater and Natural Reservoirs

11 November, 2012

Hotel Himalaya, Lalitpur, Nepal

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Appendix A.4

Joint Workshop on
“Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains”

Hotel Himalaya, Lalitpur

29th – 30th April 2013

The joint workshop was the last event under the APN project ARCP2009-04CMY-Shrestha organized between the researchers from participating countries to share obtained results and exchange knowledge and experince gained in course of the project execution. Prof. Dr. Kedar Lal Shrestha initited the workshop with his welcome address and he followed it with a synopsis of the activities taken up so far to attain the objectves of the project. He highlighted the importance of the workshop stating that it provides the last opportunity for personal interactions between the researchers from the participating institutions for discussing their experiences and results. It was then followed by the presentation of research results and broad discussions on them amongst the participants.

Appendix A.4 (Contd.)

Joint Workshop on
“Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains”

Hotel Himalaya, Lalitpur

29th – 30th April 2013

Programme

Day 1: Monday, 29th April 2013			
Registration			**09:00-09:30**
Welcome & TECHNICAL SESSION–I [09:30-11:00 Hrs] **Impacts of Global Change on Water Resource in the Himalayan Mountains** **Session Chair: Mr. Kiran Shankar Yogacharya**			
	Title	**Speaker**	**Time**
1	Welcome Address	Dr. Kedar Lal Shrestha	09:30-09:35
2	Participants’ self introduction	Participants	09:35-09:45
3	“Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains”	Dr. Kedar Lal Shrestha	09:45-10:15
4	"Impacts of Climate Change on Dynamics of Snow Glacier and runoff in Upper Bhagirathi Basin (India)"	Dr. Rajesh Joshi	10:15-10:45
5	Floor Discussion	Participants	10:45-11:00
6	Chairman’s Remarks and Closing of the session		11:00-11:10
Tea Break			11:10-11:30
TECHNICAL SESSION–II [11:30-12:30 Hrs] **Climate Change and Water Resource Management** **Session Chair: Dr. Balkrishna Sapkota**			
	Title	**Speaker**	**Time**
1	"Impacts of Climate Change on water resources of Himalaya : Issues and Policy Planning for future Environmental Flows"	Er. Mahendra Lodhi	11:30-11:50
2	“Climate Change Impact Assessment-A Case Study of Koshi River Basin	Mr. Rocky Talchabhadel	11:50-12:10
3	Floor Discussion & Group Formation	Participants	12:10-12:25

4	Chairman's Remarks and Closing of the Session		12:25-12:30
Lunch Break			12:30-13:30

Appendix A.4 (Contd.)

Group Discussion [13:30-15:00 Hrs]

Group	Theme	Group Members	Time
I	Theme I Climate and Hydrological Modelling		13:30-15:00
II	Theme II Snow and glacial melt and total runoff		
III	Theme III Socio-economic consequences		

GROUP PRESENTATION SESSION–I [15:00-16:00 Hrs]

Session Chair: Dr. Kedar Lal Shrestha

Presentation on	Time
Group I Climate and Hydrological Modelling	15:00-15:15
Group II Snow and glacial melt and total runoff	15:15-15:30
Group III Socio-economic consequences	15:30-15:45
Comments, Remarks and Guidelines for further exercise	15:45-16:00
Tea Break	16: 00-16:30

Day 2: Tuesday, 30th April 2013

TECHNICAL SESSION–III [09:30-11:00 Hrs]

Hydrological Modelling and Climate Change Impacts

Session Chair: Er. Mahendra Lodhi

	Title	Speaker	Time
1	"Impact of climate Change on Potential Water Resources of Koshi basin"	Dr. Narendra Shakya	09:30-09:50
2	"Vulnerability and adaption to water availability in the Mountain and Downstream regions with special reference to Sikkim Himalaya, India"	Dr. Varun Joshi	09:50-10:20

	" Hydrological Modelling and Climate Change Impact Analysis of Indrawati Basin"	Ms. Laxmi D. Maharjan	10:20-10:40
5	Floor Discussion	Participants	10:40-11:00
Tea Break			11:00-11:30

Appendix A.4 (Contd.)

Group Discussion (Continuel) [11:30-12:30 Hrs]			
Group	**Theme**	**Group Members**	**Time**
I	Theme I Climate and Hydrological Modelling		11:30-12:30
II	Theme II Snow and glacial melt and total runoff		
III	Theme III Socio-economic consequences		
Lunch Break			12:30-13:30

GROUP PRESENTATION SESSION–II [13:30-16:00 Hrs]

Session Chair: Dr. Kedar Lal Shrestha

Presentation by	**Time**
Group I Er. Mahendra Lodhi	13:30-14:00
Group II Dr. Rajesh Joshi	14:00-14:30
Group III Prof. Dr. Balkrishna Sapkota	14:30-15:00
Comments, Remarks and Conclusions	15:45-16:00
Tea Break	16:00-16:30

Joint Workshop on Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains

29 – 30 April 2013
Hotel Himalaya, Lalitpur, Nepal

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Impacts of Global Change on the Dynamics of Snow, Glaciers and Run-Off over the Himalayan Mountains and their Consequences for Highland and Downstream Regions

INITIAL MEETING

13 and 14 November 2008

Hotel Himalaya in Lalitpur

An Initial Meeting of the APN Project ARCP208-16NMY-Shrestha was held on 13 and 14 November 2008 at Hotel Himalaya in Lalitpur to discuss among the project collaborators and the local stakeholder for discussing the project implementation strategies and charting out detailed work plan. The Programme of the Meeting and the list of Participants are attached herewith (Attachments 1 & 2).

Project leader Dr. K. L. Shrestha briefly presented the objectives of the project together with anticipated activities in the year I and the roles of the collaborators in attaining the objectives. It was followed by presentations from Dr. Yao Tandong, Director, Institute of Tibetan Plateau Research, China, and Mr. Ghazanfar Ali, Head, Water Section, Climate Change Impact Study Centre, Pakistan made their presentations highlighting the activities of their respective institutions and the roles they as collaborating institutions, would be playing in the project implementation.

Dr. Narayan Chaulagain then made a brief presentation based on the work he conducted for his Ph. D. thesis on the impact of climate change on the snow, glaciers and runoff in the Langtang Himalaya and their consequences to the hydropower development and livelihood of people in the region.

Discussion sessions followed on ‘Climate modeling, Validation and Projection’, ‘Climate Change Impacts on Himalayan Snow and Glacier Dynamics’, ‘Snow and Glacial Melt Run-Off and Hydrology’, and ‘Availability and Access to the Required Data and Support Services, each one led by Dr. Madan Lal Shrestha, Dr. Narayan Chaulagain, Dr. Narendra Sakya and Mr Promod Pradhan respectively. Finally conclusions and recommendations resulting from the floor discussions were presented and approved with necessary adjustments.

Discussion was held on those subjects with Dr. L.M.S. Palni, Director Incharge, G B Pant Institute of Himalayan Environment and Development (GBPIHED), India, who arrived Kathmandu later and similar arrangements were agreed on regarding the role of GBPIHED in the project implementation.

Impacts of Global Change on the Dynamics of Snow, Glaciers and Run-Off over the Himalayan Mountains and their Consequences for Highland and Downstream Regions

2.1 INITIAL MEETING

13th to 14th November 2008

Hotel Himalaya, Lalitpur, Nepal

2.2 SCHEDULE

Thursday 13 November 2008

09:00 – 09:15 **Registration**

09:15 – 11:00 am: **INTRODUCTORY SESSION**

MC – Mr. J. Karmacharya

09:15 – 09:30	Welcome and Self Introduction
09:30 – 10:00	Presentation on the APN Project on Climate Change Impacts on Himalayan Snow, Glaciers and Run-Off Dynamics: Research Plan and Strategies - Prof. Dr. Kedar Lal Shrestha
10:00 – 10:20	Envisaged Project Activities in China - Prof. Dr. Yao Tandong
10:20 – 10:40	Envisaged Project Activities in Pakistan - Mr. Ghazanfar Ali
10:40 – 11:00	Responses from Participants

11:00 – 11:15 Tea/Coffee

11:15 am – 12:30 pm: **PRESENTATION SESSION**

Chair: Dr. Madan Lal Shrestha

11:15 – 11:45	Impacts of Climate Change on water Resources of Nepal - Dr. Narayan Chaulagain
11:45 – 12:30	Discussion on Impacts of Climate Change on Himalayan Snow and Glaciers and Their Consequences

12:30 – 13:30 **Lunch**

13:30 – 16:00 pm **TECHNICAL SESSIONS**

Chair: Prof. Dr. Yao Tandong

13:30 – 14:15 Discussion on Climate modeling, Validation and Projection

- Alternative Models and Their Selection
- Validation Procedures and Usage of
    - Field Data
    - EO Data
- Projection Strategies
    - IPCC Scenarios

\- *Dr. Madan Lal Shrestha will lead the Discussion*

14:15 – 15:00 Discussion on Climate Change Impacts on Himalayan Snow and Glacier Dynamics

- Energy Balance Models
- Validation Procedures and Usage of
    - Field Data
    - EO Data
- Projection Strategies
    - IPCC Scenarios

\- *Dr. Narayan Chaulagain will Lead the Discussion*

15:00 – 15:15 Tea/Coffee

15: 15 – 16:00 Discussion on Snow and Glacial Melt Run-Off and Hydrology

- Melt Run-Off and Routing
- Temporal and Spatial Distribution of Total Run-Off

\- *Dr. Narendra Shakya will Lead the Discussion*

Friday 14 November 2008

09:00 – 11:00 am: **TECHNICAL SESSIONS (CONTD.)**

Chair: Prof. Dr. Hua Ouyang

09:00 – 09:45 Discussion on Availability and Access to the Required Data and Support Services

- Field Data
- EO Data
- Computing Facility

\- *Mr. Pramod S. Pradhan will Lead the Discussion*

09:45 – 10::30 Selection of Study Basins

- Selection Criteria
- Selection of Basins
    - China
    - India
    - Nepal
    - Pakistan

\- *Mr. Ghazanfar Ali will Lead the Discussion*

10:30 – 11:00 Discussion on Reporting Formats and Schedules

11:00 – 11:15 Tea/Coffee

11:15 – 12:30 Prepare Write-Ups on Discussion Summaries

12:30 – 13:30 Lunch

13:30 – 16:00 pm SUMMARY PRESENTATIONS SESSION

Chair: Prof. Dr. Kedar Lal Shrestha

13:30 – 13:45 Presentation of Discussion Summary on Climate Modeling and Forecasting

13:45 – 14:00 Presentation of Discussion Summary on Snow and Ice Dynamics

14:00 – 14:15 Presentation of Discussion Summary on Melt Run-Off and Hydrology

14:15 - !4:30 Presentation of Discussion Summary on Data Availability and Access

14:30 – 14:45 Tea/Coffee

14:45 – 16:00 pm CONCLUDING SESSION

Impacts of Global Change on the Dynamics of Snow, Glaciers and Run-Off over the Himalayan Mountains and their Consequences for Highland and Downstream Regions.

INITIAL MEETING

Date: 13 – 14 November 2008 **Venue: Hotel Himalaya**

List of Participants

1. Prof. Dr. Yao Tandong, RITP, China
2. Prof. Dr. Kedar Lal Shrestha, IDI, Nepal
3. Mr. Shrestha, NAST, Nepal
4. Prof. Dr. Balkrishna Sapkota, IOE, TU, Nepal
5. Prof. Dr. Narendra Shakya, IOE, TU, Nepal
6. Dr. Narayan Chaulagain, PEEDA, Nepal
7. Mr. Pramod Sagar Pradhan, SAIT, Nepal
8. Mr. Om Bajracharya, DHM, Nepal
9. Mr. Jagadishwor Karmacharya, DHM
10. Mr. Jayandra Shrestha, IOE, TU, Nepal
11. Dr. Lochan Devkota, CDoM, TU, Nepal
12. Dr. Rijan Bhakta Kayastha, KU, Nepal
13. Mr. Rupak Rajbhandari, DHM, Nepal
14. Mr. Sarju Vaidya, DHM, Nepal
15. Prof. Dr. Hua Ouyang, ICIMOD
16. Dr. Arun Bhakta Shrestha, ICIMOD
17. Mr. Pradeep Mool, ICIMOD
18. Mr. Anil Manandhar, WWF/Nepal
19. Mr. Narayan Belbase, IUCN/Nepal
20. Dr. Sita Ram Joshi, IDI, Nepal
21. Dr. Kanti Shrestha, IDI, Nepal
22. Mr. Kedar Jung Thapa, IDI, Nepal

Impacts of Global Change on the Dynamics of Snow, Glaciers and Run-Off over the Himalayan Mountains and their Consequences for Highland and Downstream Regions

JOINT WORKSHOP

A three days joint workshop of the project partners of the APN Project ARCP2008-16NMY-Shrestha entitled **"Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains and Their Consequences for Highland and Downstream Regions"** was held in Kathmandu, Nepal on 17 – 19 February 2010. Participants from the project collaborator Institutions in India, Nepal and Pakistan together with those from the other local partner Institutions and stakeholders exchanged and shared their research studies results and experiences. The conspicuous absence of the team from China was regretfully noted. The Programme of the Workshop and the list of Participants are attached herewith as Attachments 3 & 4..

The workshop started with the Introductory Session wherein Project leader Dr. K. L. Shrestha welcomed the participants and briefly presented the objectives of the workshop together with strategy and activities undertaken in the year one in attaining the project objectives. It was followed by presentations summarizing the activities undertaken in India, Nepal and Pakistan by the representatives from the respective countries.

Supplementary presentations on similar project relevant works carried out by various other institutions in the following Session provide an opportunity for the exchange of views and experiences amongst the participants representing a broader circle.

Detailed presentations were made by respective researchers on exercises carried out on the Regional Climate Model, Snow and Glacial Melt Runoff and Hydrology in the selected study areas in the Himalayan range in the three subsequent Technical Sessions. Each presentation was followed by discussions trying to compare results and share knowledge and experience amongst the country study teams. Except for the part to be undertaken by Chinese collaborating institution, the set targets for the year-1 project activities seemed to have been fulfilled.

Likewise, discussions were also held on various methods for impact assessment of the hydrological changes on the water availability and food security, on the hydropower generation potentials and on the society & economy in the upland and downstream regions.

The workshop concluded with accords on using similar RCMs in all the selected basins as well as on the methods to be adopted for bias corrections before using the RCM results for projecting hydrological changes. It was stressed that the hydrological projections have to reflect the average for a period of a decade or so such that the projected hydrological changes could be considered to be due to change in climate rather than those caused by erratic weather changes. In addition, concurrence was reached on selection of methodologies and working procedures to conduct, in accordance, the impact assessment in the second year for attaining the key objectives of the above APN project.

At the end, it was also agreed to prepare and publish joint papers in suitable peer reviewed international journals by integrating the relevant works of all the country study teams carried out during the first year period..

Impacts of Global Change on the Dynamics of Snow, Glaciers and Run-Off over the Himalayan Mountains and their Consequences for Highland and Downstream Regions

JOINT WORKSHOP

17th to 19th February 2010 **Hotel Manaslu, Kathmandu, Nepal**

TENTATIVE PROGRAM

Wednesday 17 February 2010

09:00 – 09:30 **Registration**

09:30 – 11:30 am: **INTRODUCTORY SESSION**

MC – Mr. J. Karmacharya

09:30 – 10:00	Welcome Address and Introductory Presentation on the APN Project on Climate Change Impacts on Himalayan Snow, Glaciers and Run-Off Dynamics: Research Plan and Progress - Prof. Dr. Kedar Lal Shrestha
10:00 – 10:15	Synopsis of Project Studies on Northern Koshi Basin - Prof. Dr. Yao Tandong
10:15 – 10:30	Synopsis of Project Studies on Upper Bhagirathi Basin - Er. Kireet Kumar
10:30 – 10:45	Synopsis of Project Studies on Southern Koshi Basin - Dr. Madan Lal Shrestha
10:45 – 11:00	Synopsis of Project Studies on Hunza Basin - Mr. Ghazanfar Ali
11:00 – 11:30	Responses from Participants

11:30 – 11:45 **Tea/Coffee**

11:30 – 13:00 **SUPPLEMENTARY PRESENTATION SESSION**

Chair: Prof. Dr. Hua Ouyang

11:30 – 11:50	Climate Change Impact Assessment for Water Dependant Economic Sectors in the Himalayan Regions - Dr. Narayan Chaulagain

11:50 – 12:20 Validation of satellite rainfall estimation (cpc_rfe_v2.0) over Nepal region in the central Himalaya

- Mr.Rupak Rajbhandari

12:20 – 12:30 Living with Stress in the Koshi Basin, Nepal

- Ajaya Dixit

12:30 – 13:00 Floor Discussion on the Presentations

13:00 – 14:00 **Lunch**

14:00 – 16:30 **TECHNICAL SESSION I**

Chair: Dr. Madan Lal Shrestha

14:00 – 15:30 Presentations Discussions on Regional Climate modeling, Validation and Projection in

- Upper Bhagirathi Basin – Dr. Rajesh Joshi
- Northern Koshi Basin – To be confirmed
- Southern Koshi Basin – Mr. Jagadiswor Karmacharya
- Hunza Basin - Mr. Shahbaz Mahmood

15:30 – 15:45 **Tea/Coffee**

15:45 – 16:30 Discussions on Regional Climate modeling, Validation and Projection (Contd.)

Thursday 18 February 2010

10:00 – 11:30 **TECHNICAL SESSION II**

Chair: Mr. Ghazanfar Ali

10:00 – 11:10 Presentations and Discussions on snow and glacial runoff modeling and validation in the Selected Basins

- Upper Bhagirathi Basin - To be confirmed
- Northern Koshi Basin – To be confirmed
- Tamakoshi Basin – Mr. Bhai Raja Silpakar
- Hunza Basin - Ms. Abeer Mazhar

11:10 – 11:30 Presentations and Discussions on Koshi Basin Project Preparatory Phase – Dr. Arun Shrestha

11:30 – 11:45 **Tea/Coffee**

11:45 – 13:00 **TECHNICAL SESSIONS III**

Chair: Mr. Ajaya Dixit

11:45 – 13:00 Presentations and Discussion on Hydrological Modeling, Caliberation and Validation for the Selected Basins

- Upper Bhagirathi Basin – Er. Kireet Kumar
- Northern Koshi Basin – To be confirmed
- Southern Koshi Basin – Dr. Narendra Shakya
- Hunza Basin - Mr. Ghazanfar Ali

13:00 – 14:00 **Lunch**

14:00 – 15:30 **TECHNICAL SESSION IV**

Chair: Prof. Dr. Narendra Shakya

14:00 – 15:30 Discussion on Project Activities in the Next Year and Identification of Methodologies and Reporting Formats

- Development of Runoff Scenarios
- Impacts on
    - Water Availability
    - Hydropower Development
    - Food Security
    - Socio-economic Consequences in the high land and downstream regions and highland Lowland Linkages

15:30 – 15:45 **Tea/Coffee**

15:45 – 16:30 pm **DISCUSSION SESSION**

Discussion on Joint Paper Publication based on Year – 1 activities in Peer Reviewed Journals

Friday 19 February 2010

10:00 – 12:30 **CONCLUDING SESSION**

Chair: Prof. Dr. Kedar Lal Shrestha

- **Brief Reporting on Outcomes of the Discussions during the Technical Sessions**
- **Development of Strategies and Work Plan for Next Year with Timeline**
- **Plan with Timeline for**
    - **Production of Year I Final Report**
    - **Production of Joint Paper for Publication**

12:30 – 13:30 **Lunch**

13:30 – 17:00 **Field visit**

Project Title: **Impacts of Global Change on the Dynamics of Snow, Glaciers and Run-Off over the Himalayan Mountains and their Consequences for Highland and Downstream Regions.**

JOINT WORKSHOP

Date: 17 – 19 February 2010

Venue: Hotel Manaslu,
Kathmandu

List of Participants

India

1. Er. Kireet Kumar, GBPIHED
2. Dr. Rajesh Joshi GBPIHED

Pakistan

3. Mr. Ghazanfar Ali, GCISC
4. Mr. Shahbaz Mahmood, GCISC
5. Ms. Abeer Mazhar, GCISC

Nepal

6. Dr. Kedar Lal Shrestha. IDI
7. Dr. Madan Lal Shrestha, IDI
8. Dr. Narendra Shakya, IoE
9. Mr. Jagadishwor Karmacharya,DHM
10. Dr. Narayan Chaulagain, AEPC

Other Institutions

11. Dr. Rijan Bhakta Kayastha, KU
12. Mr. Om Bajracharya, DHM
13. Prof. Dr. Balkrishna Sapkota, IDI
14. Prof. Hua Ouyang, ICIMOD
15. Dr. Arun Bhakta Shrestha, ICIMOD
16. Mr. Pradeep Mool, ICIMOD
17. Mr. Prabin Raj Aryal, MoE
18. Mr. Nirmal Hari Rajbhandari, DHM
19. Dr. Keshav Prasad Sharma, DHM
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21. Ms. Meena Khanal, MoEnv.
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23. Mr. Tek Gurung, UNDP
24. Ms. Mandira Shrestha, ICIMOD
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26. Mr. Ajaya Dixit, ISET-N
27. Mr. Gehendra Gurung, Practical Action
28. Ms. Neera Shrestha Pradhan, WWF/Nepal
29. Ms. Emma Sundam, IUCN/Nepal
30. Mr. Saroj Yakami, NGO
31. Mr. Pitambar Aryal, Red Cross/Nepal
32. Mr. Dhiraj Pradhanang, SEN
33. Mr. Pramod Sagar Pradhan, SAIT
34. Mr. Jayandra Shrestha, IoE
35. Mr. Kedar Jung Thapa, IDI
36. Dr. Sita Ram Joshi, IDI
37. Dr. Kanti Shrestha, IDI
38. Mr. Bhai Raja Silpakar, IoE

Workshop on Integrated Studies of Environmental Changes and Climate Adaptation Responses in the Tibet-Himalayan Region

Soaltee Crowne Plaza

Kathmandu, Nepal

13th – 15th September 2010

Report of proceedings

Backgrounds and Workshop Organization

The Himalaya-Tibetan Plateau (HTP) region is of great importance to the global climate system, and it is the source of much of the water used by millions of people from the major rivers that rise in the region. Many climate change research pointed out temperatures have been warming in the Himalayas, with acceleration in recent years, particularly at high elevations. Along with climate warming, the environmental components and natural resources in the region are leading to large scale and rapid land use changes. So-called glacial lake outburst flooding, basically the collapse of a permafrost moraine bridge freeing up meltwater is an increasing risk in some areas. Thus, to grab the whole picture of global warming impact on HTP region is an urgent target for mountain environment study.

From economic-social perspective, the high mountains of Himalayas are tectonically unstable, ecologically sensitive, and economically under-developed. They also represent the most densely populated mountain ecosystems of the planet. They are particularly vulnerable to various types of environmental changes because of their highly fragile environment and tectonic instability. Moreover, the intensification of human activities and rapid urbanization, with increasing energy use, in the Himalayas are bringing about widespread and long-term environmental changes in the region. The vulnerability of HTP ecosystem services and regional sustainability are the key issues for future HTP development.

As a sequel of the activities of the APN-supported project entitled ‘Impacts of Global Change on the Dynamics of Snow, Glaciers and Runoff over the Himalayan Mountains and their Consequences for Highland and Downstream Regions”, the Workshop on “Integrated Studies of Environmental Change and Climate Adaptation Responses in the Tibet-Himalayan Region” was held jointly by the Institute for Development and Innovation (IDI), Nepal, the Australian National University (ANU), Australian Government Overseas Aid Program (AusAID), and Monsoon Asia Integrated Regional Study (MAIRS), China, on 13-15 September 2010, in Kathmandu, Nepal. The Workshop was attended by 40 delegates from over 20 organizations from the region

The primary aim of the workshop was to bring together regional knowledge and research findings under the auspices of a truly multinational, interdisciplinary research framework programme for the Himalaya-Tibetan Plateau (HTP) region. Specific workshop objectives included:

1. Assess and document the current research status and projects from each country/region.
2. Identify knowledge gaps.
3. Establish a set of research priorities for the region.
4. Determine an effective mechanism to enhance knowledge sharing in the region

Executive Summary of the Proceedings

During the three day workshop, the delegates provided an overview of their research. Scientific data collected from across the region over a long time period has shown (unequivocally) that temperatures are warming in the Himalayas, with acceleration in recent years. Along with warming, changes in precipitation across the region have also been observed with a notable difference in rainfall between arid and non-arid regions. Changes in the Asia Monsoon System have also been observed, but the reasons for these observed changes are not clear. Without doubt, water security (supply, storage and access) was identified as a major issue facing the region.

In terms of land use change, land use activities such as rapid urbanization, increased resource utilization, large-scale infrastructure development, the overgrazing of livestock, as well as climate change have led to rapid change on a large scale. Research has shown that higher temperatures are contributing to permafrost melt and landslides as well as the rapid retreat of small glaciers at lower elevations. With further increases in global emissions, temperatures will continue to rise in the future leading to further social disruption for many vulnerable communities. Forced migration and increased population growth and urbanization will ensue and the region's unique biodiversity will face an ever greater threat of extinction from climate change and anthropogenic influences.

Delegates identified areas where further research is urgently required and ways knowledge sharing and collaboration could be further strengthened and enhanced for the benefit of all. In summary the workshop proceedings identified the following needs:

- Environmental monitoring in the region must be scaled-up and refined to improve or enhance predictive capabilities and decision making processes.
- There is a need to improve adaptive response strategies through better integration of knowledge and experiences amongst stakeholders. However, lack of monitoring, data availability and accessibility remains a major problem for researchers working in the region. It was agreed that a knowledge management system for researchers be developed with the capacity to provide, in the first instance, basic metadata on research activities and data/results (who is doing what and why) in the region.

- The quantification of social hardship originating from extreme events such as landslides, floods, long-term drought and desertification is lacking. Natural risk assessments and early warning systems should be adopted where possible.
- There is a strong demand in the region for hydrological models that adequately incorporate social- economic parameters (integrative models).
- It was agreed that a steering committee be established to encourage cross-cutting collaborative research opportunities.

Workshop on Integrated Studies of Environmental Changes and Climate Adaptation Responses in the Tibet-Himalayan Region

Soaltee Crowne Plaza
Kathmandu, Nepal
13th – 15th September 2010 Date

	Session	Activities & Outcomes
Mon 13th		
All day	**Session 1: State of current Knowledge and Research** **Four panels:** ▪ *Changes of Water resources* ▪ *Changes of land/ecosystem* ▪ *Climate governance* ▪ *Regional network*	Assess and document the current research status and projects from each country/region. Speakers from various institutions will provide a 15 minute overview of their research and knowledge gaps followed by 5-min question time. Develop questions and points for further discussion in sessions 2 & 3).
18:30 ~	**Reception hosted by MAIRS**	Solatee Crown Plaza
A small group meeting to prepare the discussion next day		
Tues 14th		
09:30-10:15 (each talk 10-15 minutes)		**Talk 1:** Tibet-Himalaya Ecosystem: A Generic View and Sustainable Governance of Its Resources and Services **by Kedar Shrestha** **Talk 2:** Reprot of land use and land cover changes in Tibetan Plateau **by Yili ZHANG** **Talk 3:** MRI mountain activities **by K. Morton**
10:15-13:00 **Coffee break: 11:30-11:50**	**Session 2: Overview of Current Research** (4 reports by each panel rapporteur) **Summary**	1) Summarise the current research from session 1. 2) Identify synergies.

Workshop on Integrated Studies of Environmental Changes in Tibet-Himalayan region

13-15 Sep. 2010, Khatmandu, Nepal

List of Participants

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Scoping Workshop on Enhancing Science - Policy Dialogue on Himalayan Water Resources in the Global Change Context

21-22 February 2011, Kathmandu, Nepal

Backgrounds

The Himalaya with its high significance in the regional climate system is also the water tower for several millions living in the northern part of the South Asian subcontinent. Many climate change research studies have clearly pointed out that temperatures have been warming in the Himalayas, at an increasing rate in recent years particularly at high elevations, with significant impacts on the hydrology of the Himalayan region.

Water is the primary medium through which climate change influences the ecosystems and therefore people's livelihoods and well-being. Already, water-related climate change impacts are being experienced in the form of more severe and more frequent droughts and floods. Higher average temperatures and changes in precipitation and temperature extremes are projected to affect the availability of water resources through changes in rainfall distribution, soil moisture, glacier and ice/snow melt, and river and groundwater flows. These factors are also expected to lead to further deterioration of water quality as well.

Along with climate variability and change, the rapidly growing population coupled with changes in their life styles and the ongoing higher economic activities, water stress is already increasing in the Himalayan highlands and downstream regions. The poor, who are the most vulnerable, are also likely to be affected the most.

Water resources and how they are managed impact almost all aspects of society and the economy, in particular food production and security, domestic water supply and sanitation, health, energy, industry, and the functioning of ecosystems. Climate change adds even more urgency for action. Without improved water resources management, the progress towards poverty reduction targets, the Millennium Development Goals, and sustainable development in all its economic, social and environmental dimensions, will be jeopardized.

While science relates as such with all the various aspects of water resources, the governance and management of the resource come mostly under the purview of external drivers like political, civil society, business and economic actors. Major decision process concerning water is made in general outside the domain of water managers and full incorporation of major external drivers' articulation, which at times can even be vague, becomes essential to move towards sustainable development and use of water resources.

The sense of urgency for climate change adaptation and the recognition of the centrality of water therein, have not yet permeated the political world and are not systematically reflected in national plans or international investment portfolios for adaptation.

It is thus imperative for the parties to the policy making and planning processes to recognize the pivotal role of water in adapting to climate change in order to increase resilience and achieve sustainable development.

Better water governance and management including the adaptation to increasing climate variability and change would require policy shifts, institutional development and significant investments that would need to be guided by well considered principles. Science based information would be valuable inputs in charting out and implementing the thus required policy shift and investment plans and programme.

Continuous effective and meaningful dialogue between science and policy making process including effective linkage of research results to policy and practices would be essential to deal with the new challenges in Himalayan water governance and management resulting from socio-economic and climate changes.

In the above context, IDI under the sponsorship of APN has organized a two day scoping workshop on 21-22 February 2011 in Kathmandu with the following objectives:

- Providing a platform for system-wide discussions to identify challenges in national and regional water governance and management, analyze options for meeting these challenges and ensuring that science based reliable information and sound analysis informs the national and regional policy debate on Himalayan water.
- Considering measures for providing information, policy briefs and other communication materials for policymakers and managers who work directly with Himalayan water issues, other decision-makers that have an influence on how Himalayan water is used, as well as the general public.
- Recognizing actions for furthering the science knowledge base on Himalayan water issues and facilitating easy access to this knowledge.

A Group of the Scoping Workshop Participants

Scoping Workshop on

Enhancing Science - Policy Dialogue on Himalayan Water Resources in the Global Change Context

21-22 February 2011, Kathmandu, Nepal

Hotel Greenwich Village, Kupondole Height, Lalitpur

2.3 PROGRAM SCHEDULE

Monday 21 February 2011

09:00 – 09:15	**Registration**	
09:15 – 11:00	**FIRST SESSION**	
	Chair: Dr. Rameshananda Vaidya	
09:15 – 09:30	Welcome and Introductory Remarks	- K L Shrestha
	Self Introduction by Participants	
09:30 – 10:00	"Integrated Headwater Management for Conservation of Water Resources in Himalaya"	- P C Tiwari
10:00 – 10:30	"Climate change and water linkages taking systemic perspective"	- Ajaya Dixit
10:30 – 11:00	"Koshi Basin Transboundary Programme"	- Hua Ouyang
11:00 – 11:30	**Tea/Coffee**	
11:30 – 13:00	**SECOND SESSION**	
	Chair: Prof. Prakash C Tiwari	
11:30 – 12:00	"Science and Policy Development on Himalayan Water Resources in the Global Change Context"	- K L Shrestha
12:00 – 12:30	"Sustainable Hydropower Development and Adaptation to Climate Change Impacts"	- R. N Vaidya
12:30 – 13:30	**Lunch**	
13:30 – 14:30	**THIRD SESSION**	
	Chair: Dr. Narendra Shakya	
13:30 – :14:00	Major Climate Change Activities Initiated by the Ministry of Environment	- Batuk Uprety
14:00 – 14:30	"Securing Water Resources of Nepal: A Policy Aspect"	- T N Bhattarai
14:30 – 17:00	**FOURTH SESSION**	
	Chair: Dr. Madan Lal Shrestha	
	Co-Chair: Dr. Narayan Chaulagain	
14:30 – 15:30	Discussion on Theme I	
15:30 – 16:00	**Tea/Coffee**	
16: 00 – 17:00	Discussion on Theme II	

18:00-20:00 **Dinner at Hotel Greenwich Village**
(All the participants are cordially invited)

2.3.1.1.1.1.1.1 Tuesday 22 February 2011

2.3.1.2

09:30 – 11:00	**FIFTH SESSION** **Chair: Er. Iswer Raj Onta**	
09:30 – 10:00	"Emerging Challenges for Water Resources of Pakistan"	-S Hasson
10:00 – 10:30	"Hydrological Modeling for Koshi Basin In Nepal"	- N, Shakya
10:30 – 11:30	Discussion on Theme III	
11:30 – 12:00	**Tea/Coffee**	
12:00 – 13:00	**REPORING ON THEME DISCUSSIONS**	
13:00 – 14:00	**Lunch**	
14:00 – 15:00	**FLOOR DISCUSSION & CONCLUDING SESSION** **Chair: Dr. Kedar Lal Shrestha**	

Theme I Recognizing actions for furthering the science knowledge base on Himalayan water issues and facilitating easy access to this knowledge.

Theme II Considering measures for providing information, policy briefs and other communication materials for policymakers and managers who work directly with Himalayan water issues, other decision-makers that have an influence on how Himalayan water is used, as well as the general public.

Theme III Identify challenges in national and regional water governance and management, analyze options for meeting these challenges and measures for ensuring that science based reliable information and sound analysis informs the national and regional policy debate on Himalayan water.

Scoping Workshop on
Enhancing Science - Policy Dialogue on
Himalayan Water Resources in the Global Change Context

Venue: Hotel Greenwich

Date: 21 – 22 February 2011

Kupandole Height Lalitpur

List of Participants

India

1. Prof. Prakash C. Tiwari, Kumaon University

Pakistan

2. Mr. Shabeh ul Hasson, GCISC

Nepal

3. Dr. Kedar Lal Shrestha. IDI
4. Dr. Madan Lal Shrestha, IDI
5. Dr. Narendra Shakya, IoE

Other Institutions

6. Dr. Narayan Prasad Chaulagain, AEPC
7. Dr. Keshav Prasad Sharma, DH
8. Mr. Ajaya Dixit, NWCF/ISET-N
9. Prof. Hua Ouyang, ICIMOD
10. Dr. Rameshananda Vaidya, ICIMOD
11. Ms. Mandira Shrestha, ICIMOD
12. Dr. Arun Bhakta Shrestha, ICIMOD
13. Mr. Pradeep Mool, ICIMOD
14. Dr. Rijan Bhakta Kayastha, KU
15. Mr. Om Bajracharya, DHM
16. Dr. Balkrishna Sapkota, IDI
17. Mr. Prabin Raj Aryal, MoE
18. Mr. Nirmal Hari Rajbhandari, DHM
19. Mr. Gautam Rajkarnikar, WECS
20. Mr. Saraju Kumar Baidya, DHM
21. Mr. Tek Gurung, UNDP
22. Mr. Gehendra Gurung, Practical Action
23. Ms. Neera Shrestha Pradhan, WWF/Nepal
24. Mr.Rupak Rajbhandari, TC, TU
25. Mr. Saroj Yakami, NGO
26. Mr. Pitambar Aryal, Red Cross/Nepal
27. Mr. Dhiraj Pradhanang, SEN
28. Mr. Pramod Sagar Pradhan, SAIT
29. Mr. Rajendra Kishor Chhetry, MoEnergy
30. Mr. Batuk Krishna Uprety, MoEnv.
31. Ms. Meena Khanal, MoEnv.
32. Mr. Anup Upadhaya, WECS
33. Mr. Sanjaya Dhungel, WECS
34. Dr. Govinda Nepal, MoEnv.
35. Dr. Tara Nidhi Bhattarai,
36. Mr. Madhukar Upadhyaya
37. Mr. Kedar Jung Thapa, IDI
38. Dr. Sita Ram Joshi, NBS&M
39. Dr. Kanti Shrestha, IDI
40. Mr. Jayandra Shrestha, IoE
41. Ms. Beena Shrestha, MAN
42. Er. Iswer Raj Onta, JBS