Special Publication

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THREE DECADES
FOR MOUNTAINS AND PEOPLE

Research Insights on Climate and Water in the Hindu Kush Himalayas

SAWI SOUTH ASIA WATER INITIATIVE

About ICIMOD

The International Centre for Integrated Mountain Development, ICIMOD, is a regional knowledge development and learning centre serving the eight regional member countries of the Hindu Kush Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and based in Kathmandu, Nepal. Globalization and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. ICIMOD aims to assist mountain people to understand these changes, adapt to them, and make the most of new opportunities, while addressing upstream-downstream issues. We support regional transboundary programmes through partnership with regional partner institutions, facilitate the exchange of experience, and serve as a regional knowledge hub. We strengthen networking among regional and global centres of excellence. Overall, we are working to develop an economically and environmentally sound mountain ecosystem to improve the living standards of mountain populations and to sustain vital ecosystem services for the billions of people living downstream – now, and for the future.

ICIMOD gratefully acknowledges the support of its core donors: the Governments of Afghanistan, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland, and the United Kingdom.

Research Insights on Climate and Water in the Hindu Kush Himalayas

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Contents

Foreword

Managing water resources is one of the major challenges of our century. Nowhere could this be more so than for the waters emanating from the Hindu Kush Himalayas that serve over 1.3 billion people providing food, energy, household water supplies, and numerous other ecosystem services. The Hindu Kush Himalayan region is already characterized by a situation of 'too much and too little' water. Floods and droughts are already common, and the economic damage from these hazards is already high. Moreover, in some of the more arid areas, the situation of water scarcity is already being felt and is growing. In other areas, water in the rivers is seemingly abundant, but access to water for drinking, growing food, and obtaining energy is challenging for many rural people. Water access is a major concern for mountain and hill dwellers.

With a growing population, more urbanization, and increasing wealth, our demand for this resource is increasing. Yet with climate change, the situation of water supply remains uncertain with changing precipitation and snowmelt patterns. To adapt to this changing situation, well conceived investments are required, in addition to improvements in water governance and management. It is essential that more scientific results are generated and used to make more informed decisions about this crucial resource.

The water resources of the Hindu Kush Himalayas are a shared resource in many ways. They are shared between upstream and downstream users, between people and nature, and between countries. This shared nature of the resource brings the promise of multiple benefits, but also the threat of increased conflict . To realize the benefits of water resources, it is essential that there is a shared understanding of the resource. The South Asia Water Initiative Small Grants Program, whose results are reported here, was a particularly valuable exercise in that while it contributed to science and understanding, it also promoted a shared vision of water resource management by bringing researchers together from different countries in the region.

ICIMOD's mission is to enable sustainable and resilient mountain development for improved and equitable livelihoods through knowledge and regional cooperation. Over the past three decades, ICIMOD has provided a common platform for regional cooperation where policy makers, experts, planners, and practitioners exchange scientific data, information, ideas, and perspectives towards achieving common solutions at regional levels. Water issues, along with concerns of livelihoods and ecosystems, are integrated across ICIMOD's regional programmes addressing adaptation to change, transboundary landscapes, river basins, cryosphere and atmosphere, and regional information collection and sharing. ICIMOD also supports transboundary collaborative research among its regional member countries through its projects.

We would like to thank the World Bank for our involvement in the South Asia Water Initiative. Through its Small Grants Program, a new dimension has been added to ICIMOD's activities to promote new knowledge generation in the region. Through this programme we were able to mobilize partners to advance knowledge and regional cooperation to contribute to strategies that

will ultimately improve livelihoods. The programme has helped in promoting South-South cooperation in the HKH region for collaborative research among its knowledge institutions – a practice that helps to propagate regional research partnerships with multiplier effects. It has also helped in capacity building in those institutions on water resources research, especially in using climate and hydrological models for policy-relevant investigations. We hope such collaborative research between the institutions in different countries of the region will ultimately lead to 'goal congruence' among the different nations on issues concerning water resources development and management.

David Molden, PhD
Director General, ICIMOD

Preface

The great rivers of South Asia – including the Indus, Ganges, and Brahmaputra that traverse Afghanistan, Bangladesh, Bhutan, China, India, Nepal, and Pakistan – are critical to maintaining livelihoods and ecosystems and have a vast potential for producing food and clean energy. Regional water cooperation on these river systems has often been hindered by the lack of a sound knowledge base on the availability of resources and their distribution over space and time, and a lack of understanding of the impacts of various drivers of change on the supply and demand of resources – for example, the impacts of climate change on stream flow variability, sedimentation, and potential GLOF events.

The South Asia Water Initiative (SAWI) is a partnership established in 2009 between the World Bank and the governments of the United Kingdom, Australia, and Norway with the specific objective "to increase regional cooperation in the management of the Himalayan River systems to deliver sustainable, fair and inclusive development and climate resilience". It was established as a multi-donor trust fund financed by the three governments and administered by the World Bank. During 2009–2013, a Small Grants Programme was included as one of the activities, and administered by the International Centre for Integrated Mountain Development (ICIMOD). The idea for such a programme was conceived in 2008 at the first Abu Dhabi Dialogue Knowledge Forum (ADDKF) organized by the Abu Dhabi Dialogue Group, a partnership of senior members of government, academia, and civil society from the seven countries that share the rivers of the greater Himalayas, with technical support from ICIMOD. Participants at the Forum came from more than 50 knowledge institutions.

Following the deliberations and subsequent discussions during the Abu Dhabi Dialogue (ADD) meetings in 2009 and 2010, the Small Grants Programme was established to support knowledge generation and dissemination on the rivers of the greater Himalayas. The objectives of the Small Grants Programme were (a) to facilitate the quest to increase knowledge about water resource systems and their uses within the realm of the greater Himalayas, which are under particular stress from climate change and other drivers of change, including those arising from population and economic growth; (b) to facilitate collaboration among knowledge institutions from different countries sharing the rivers of the greater Himalayas; and (c) to support these institutions to work together in a collaborative manner. The priority topics of interest in the context of water resource systems and their uses were (a) vulnerability, adaptation and impacts of climate change, (b) integrated ecosystems and river basin management, including benefit sharing; (c) upstream-downstream impacts of water storage projects; and (d) the management of water for enhancing food security. The eligibility criteria required that the funded proposals include two or more knowledge institutions from two or more SAWI countries – Afghanistan, Bangladesh, Bhutan, China, India, Nepal, and Pakistan – had high relevance for river basin management and benefit sharing in the region, particularly in line with the priority topics of interest, and provided a spirit of regional cooperation and knowledge sharing.

The Small Grants Programme was officially launched in March 2011, when representatives of 40 research institutions from across the seven SAWI countries convened. The launch programme facilitated new partnerships between knowledge institutions from different countries, many of which had no prior history of formal interaction. Subsequently, a call for proposals was made. Twenty-three of the 39 proposals received met the SGP eligibility criteria, and they were reviewed and ranked by international technical experts and a Technical Assessment Panel comprised of representatives from ICIMOD and the World Bank and the SAWI donor representative. The Technical Assessment Panel recommended eight proposals for funding; these were shared with ADD members for comments and suggestions, and subsequently approved.

In this volume, we present seven research papers and a note drawing on the final technical reports of the eight funded projects. These are preceded by a synthesis of the key findings of the research papers. We have three objectives in mind for publishing these papers. First, we felt that they will be of interest to scientists and policymakers in the SAWI countries to the extent that they reflect new knowledge on regional solutions to regional problems – generated by the knowledge institutions in the region itself. Second, it may be of interest to scientists and policymakers in the region to learn about the contribution the Small Grants Programme has made to capacity building of the knowledge institutions for scientific and policy-relevant research and to developing a regional network of those institutions for collaborative research. Third, such a participatory process of knowledge institutions from different countries working on common problems of regional concern may have important implications for promoting regional water cooperation in the Hindu Kush Himalayan region.

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The Small Grants Programme (SGP) was funded by the South Asia Water Initiative (SAWI), a programme of the World Bank with support from the governments of the United Kingdom, Australia, and Norway. We would like to acknowledge their support to this programme.

During the conception stage of the programme, we received valuable support from Dr David Grey and Dr Claudia Sadoff at the World Bank and Dr Andreas Schild and Dr Mats Eriksson at ICIMOD. During the proposal selection process, we received support from the chair and members of the SGP Technical Assessment Panel: Dr Madhav Karki (Chair) and Dr Hua Ouyang at ICIMOD, Dr Guy Howard at the Department for International Development, UK (DFID), and Ms Catherine Revels and Ms Stephanie Borsboom at the World Bank.

For the proposal selection process, we also received valuable support from international experts in reviewing the proposals: Professor AK Gosain at the Indian Institute of Technology, Delhi; Dr Walter Immerzeel at Futurewater, the Netherlands; Dr RPS Malik at the International Water Management Institute, Delhi; and Professor Peter Rogers at Harvard University, USA.

For the internal review of the proposals received and the quality assurance process of the funded proposals, we received support from our ICIMOD colleagues: Dr Bhaskar Karky; Dr Rajan Kotru; Mr Pradeep Mool; Dr Aditi Mukherji; Dr Hua Ouyang; Ms Neera Shrestha Pradhan; Dr Arun Shrestha; Dr Mandira Shrestha; Dr Rajendra Shrestha; and Dr Shahriar Wahid. We appreciate their continuous support and interest throughout the project period.

The SGP research output papers published in this volume were thoroughly reviewed by: Dr Richard Armstrong, University of Colorado, USA; Professor Mukand Babel, Asian Institute of Technology, Thailand; Professor Jack Ives, Carleton University, Canada; Dr Lisa Schipper, Stockholm Environment institute, USA; and Professor Jon Lovett, Leeds University, UK. We appreciate their valuable contributions in finalizing these papers.

We express deep gratitude to our research partners in the SAWI countries, whose valuable contributions are published in this volume: Bangladesh (Centre for Environmental and Geographic Information Services); China (Asian International Rivers Centre at Yunnan University, Chinese National Committee on Irrigation and Drainage, and Peking University); India (GB Pant Institute of Himalayan Environment and Development, Sharda University, and South Asia Consortium for Interdisciplinary Water Resources Studies); Nepal (Central Department of Geography at Tribhuvan University, Institute for Development and Innovation, International Network on Participatory Irrigation Management – Nepal, Jalsrot Vikas Sanstha, Kathmandu University, and The Small Earth – Nepal); and Pakistan (Centre for Excellence in Water Resources Engineering at the University of Engineering and Technology, and National University of Science and Technology).

We would also like to thank our consultant editor Dr A Beatrice Murray and the rest of the editorial and production team – Dharma R Maharajan, Asha Kaji Thaku, and Amy Sellmyer – and our administrative support team Sarita Joshi and Krisha Shrestha.

Acronyms and Abbreviations

ADD	Abu Dhabi Dialogue
ADDKF	Abu Dhabi Dialogue Knowledge Forum (ADDKF)
AET	actual evapotranspiration
AMT	average monthly temperature
BC	bias correction
BHIWA	basin-wide holistic integrated water assessment
BP	back propagation
CBO	community-based organizations
CFUG	community forest user group
DDC	District Development Committee
DDF	positive degree day factor
DSSAT	Decision Support System for Agro-technology Transfer tool
EMC	Environmental Monitoring Committee
ETO	reference evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FGD	focus group discussion
FO	farmer organizations
GBM	Ganges-Brahmaputra-Meghna basin
GCM	general circulation models
GDEM	Global Digital Elevation Model
GIS	geographical information system
GLOF	glacial lake outburst flood
HKH	Hindu Kush Himalayas
ICID	International Commission on Irrigation and Drainage
ICIMOD	International Centre for Integrated Mountain Development (ICIMOD)
IPCC	Intergovernmental Panel on Climate Change
IWRM	integrated water resources management
KHEP	Kulekhani Hydro Electricity Project
KII	key informant interviews
LANCO	Lagadapati Amarappa Naidu Company
LDOF	landslide dam outburst flood
LSGR	Local Self Governance Rules
NAPA	National Adaptation Programme of Action
NEA	Nepal Electricity Authority
NGO	non-governmental organizations
NHPC	National Hydroelectric Power Corporation, Government of India
PCA	principal component analysis

PDD	positive degree day
PES	payments for ecosystem services
PET	potential evapotranspiration
PIPIPP	Punjab Irrigated Agriculture Productivity Improvement Programme Project
PRECIS	Providing Regional Climates for Impact Studies model
R&R	resettlement and rehabilitation
RCM	regional climate model
RCP	representative concentration pathway
REA	reliability ensemble averaging
SAWI	South Asia Water Initiative
SDSM	statistical downscaling model
SGP	Small Grants Programme
SWAT	soil and water assessment tool
TAR	Tibet Autonomous Region
VDC	village development committee
WRF	Weather Research and Forecasting model

1

Synthesis

Research Insights on Climate Change and Water Resources Management in the Hindu Kush Himalayas

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Introduction

The Hindu Kush Himalayan (HKH) region has one of the largest bodies of ice outside the polar caps, covering an area of more than 60,000 km^2 (Bajracharya and Shrestha 2011). The glaciers, ice fields, and snow packs provide important intra- and inter-annual water storage facilities, and the mountains are often referred to as the 'water towers' of Asia. The HKH mountain systems are a vital resource for the 1.3 billion people living in the basins of the ten rivers that have their origins in the region. They are the major source of water in the region, both surface and groundwater, during the dry season. They play a significant role in agriculture and food security and also have the potential to play a vital role in energy security; if properly harnessed, hydropower could play a crucial role in transforming the lives of the people living in the river basins. But in the wet monsoon season, the contributions of meltwater and rainfall coincide, creating a situation of too much water in the wet season and too little water in the dry season, which is exacerbated by the lack of water storage facilities. The increasing gap between water availability and demand in months other than the monsoon season is already posing a serious threat to livelihoods and economic development in the region. Climate change is projected to result in further adverse effects on overall water availability, while the incidence and intensity of floods in the river basins is expected to increase as a result of an increase in precipitation during the monsoon season.

Knowledge gaps with respect to present and future hydrology pose a real constraint to water resource management. There is increasing evidence that glaciers are receding; less clear, however, is the impact on downstream water sources from the changes in the cryosphere and monsoon patterns. There is little information about the role and changing nature of monsoons, snow cover, permafrost, glacial lakes, wetlands, and groundwater – all essential if we are to understand how much water will be available in the future and in which months of the year. In addition, transboundary river basin governance and management arrangements are essential to reap the potential benefits and to manage the hazards, but these are difficult given the geopolitical environment. However, important steps can be made in the direction of regional cooperation on water. These include knowledge-sharing efforts between research and management communities and encouraging dialogue between scientists and policy makers in the region (Molden et al. 2014).

The Abu Dhabi Dialogue Group is a partnership of senior members of government, academia, and civil society from the seven countries that share the rivers of the greater Himalayas, namely Afghanistan, Bangladesh, Bhutan, China, India, Nepal, and Pakistan. The ten year vision of the Dialogue Group is a cooperative and knowledge-based partnership of states for fairly managing and developing the Himalayan river systems to bring economic prosperity, peace and social harmony, and environmental sustainability from the source to the sea. The Small Grants Programme (SGP) was set up as a part of the plan of action to achieve this vision. Its specific objectives were to facilitate the quest to increase knowledge about water resource systems and their uses within the realm of the greater Himalayas, which is under particular stress from climate change and other drivers of change, and to facilitate collaboration among knowledge institutions from the different countries sharing the region's rivers. To this end, a call for proposals was announced for research in four priority topics of interest: (1) vulnerability, adaptation, and impacts of climate change, (2) integrated ecosystem and river basin management, including benefit sharing, (3) upstream-downstream impacts of water storage projects, and (4) the management of water for enhancing food security. Eight proposals were funded.

The purpose of this chapter is to present a summary of the key findings of the research output papers prepared by the grantees. The challenges of water availability and demand and water-related hazards in the HKH region are first discussed to set the stage for the discussions of the key findings. The findings are then summarized in terms of their contribution to the key themes of climate change impacts, adaptation and resilience, and holistic approaches to management at the basin level. The chapter concludes with a discussion of the policy implications of the key findings, recommendations, and a look at the way forward. The detailed research results are presented in the second part of the book.

Water-Related Challenges in the Hindu Kush Himalayas

The major challenges for water resources in the Hindu Kush Himalayan region are the gap between water availability and demand and the need for resilience in the face of water-related hazards.

Water availability and demand

Although the HKH mountain system plays a vital role in the region in providing food security and potential energy security and maintaining environmental flow requirements, water availability in the dry season is a serious problem. This is primarily due to the high intra-annual rainfall variability, with more than 80% of annual precipitation in much of the region falling during the monsoon season. Six of the countries in the region (Afghanistan, Bangladesh, Bhutan, India, Myanmar, and Nepal) have a relative variability, as measured by the coefficient of variation (the ratio between the standard deviation and the mean of monthly amount), of about 100%. Mongolia and North Korea are the only other countries in Asia with such high intra-annual rainfall variability (Figure 1). Thus a critical issue in many of the countries in the region is how to store the massive quantities of rain that fall in a very short period for use over the entire year.

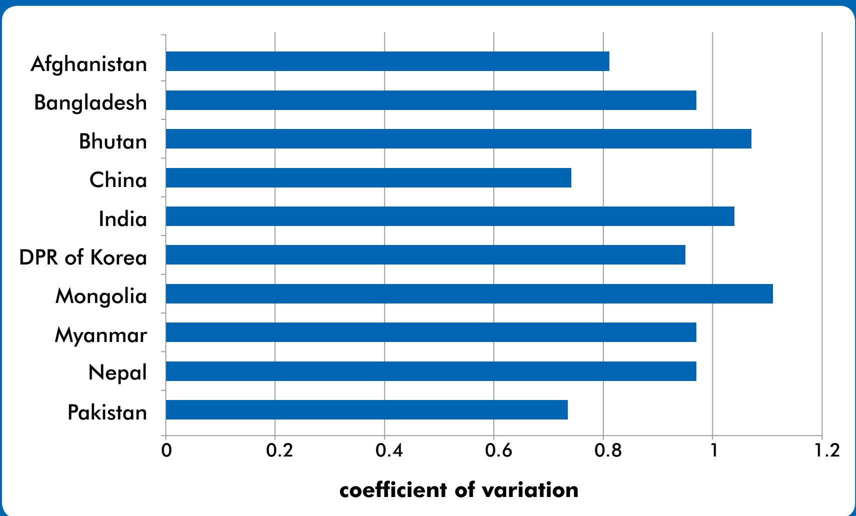
Increasing the capacity to store water and reduce seasonal differences in availability may help to reduce the gap between the supply and demand of water. The current water storage capacity for countries in the HKH region is limited, however, and much below the estimated need for food security. Estimates of seasonal storage requirements are based on the food demand of the population, the area of cultivated land, and the rainfall distribution pattern over the year. According to the estimates, only 33% of the seasonal storage requirements are met in Bangladesh, while 76% is met in India (Table 1). Fortunately, except for

Table 1: **The gap between water storage capacity and needs**

Country	Seasonal storage index (km^3)	Current storage as a percentage of seasonal storage index
Bangladesh	62.28	33
Bhutan	0.40	0
India	356.60	76
Nepal	29.86	0

Source: Brown and Lall (2006)
Note: The seasonal storage index indicates the volume of storage needed to satisfy annual water demand based on the average seasonal rainfall cycle. The study identified 23 of 163 countries studied as having a positive storage requirement, that is, a need to reduce the impact of rainfall variability on food and livelihoods by transferring water availability from wet months to dry months. China and Pakistan were not among the 23; Afghanistan and Myanmar may not have been studied.

Figure 1: **Monthly rainfall variability, coefficient of variation, in Asian countries**



Data source: Tyndall Centre for Climate Change Research (Mitchell et al. 2002)

Afghanistan, the countries of the HKH region have relatively high mean annual rainfall and low inter-annual rainfall variability, as shown by the Tyndall Centre data. As a result, it may be possible to meet the seasonal storage requirements by developing water storage facilities.

In some countries of the region, water scarcity is no longer just a seasonal problem. For example, although water withdrawal (demand) greater than one-third of the annual water resources available (supply) is considered risky, the level of water withdrawal in Pakistan is already about three-quarters of its annual level of available water and in excess of environmental flow requirements. The ratio of withdrawal to supply is also above 33% in India and Afghanistan (Table 2). Moreover, in spite of a seemingly abundant supply of water in the mountain areas, water access is quite difficult in the hills as water flows in deep valleys, and rainfall quickly runs off steep hill slopes. Water access is a major issue for people in hills.

Table 2: **Percentage of water in excess of environmental flow requirements in the HKH countries**

Country	Annual renewable water resources (RWR), 1998-2002 (km^3)	Total water withdrawal, 1998-2002 (billion m^3/yr)	Withdrawal rate %	Environmental flow requirement as % of RWR[a]	% in excess of environmental flow requirement and withdrawals
Afghanistan	65	23.26	36	28.9	35
Bangladesh	1,211	79.4	7	22.8	71
Bhutan	81	0.425	1	23.0	76
China	2,830	630.4	22	28.8	49
India	1,880	645.9	34	23.9	42
Myanmar	1,046	33.23	3	23.2	74
Nepal	210.2	10.18	5	22.9	72
Pakistan	225.3	169.4	75	27.5	-3

Source: FAO AQUASTAT data, various years
[a] Converted from Smakhtin et al. 2004

With increasing population and wealth, the demand for water for irrigation, domestic uses and energy is increasing. In addition, there is a recognized need for environmental flows. In some basins like the Indus this supply and demand balance is already troublesome and is arising concern in other river basins. The changing water supply and demand balance may have serious consequences in the future in those countries where a large proportion of the water supply originates outside the national borders. Both Bangladesh and Pakistan receive more than three-quarters of their surface water supply from across their borders, mainly from India (Table 3). Furthermore, although only about one-third of water supply to India originates outside its borders, almost three-quarters of the surface water during the dry season in the fertile and densely populated Ganges basin flows from Nepal (Eriksson et al. 2009).

The annual water withdrawals for agriculture are projected to increase, under IWMI's comprehensive assessment scenario, by 9% in South Asia and 16% in East Asia from 2000 to 2050, compared to a global average of 13% (de Fraiture et al. 2007). For non-agricultural uses, the withdrawals have been projected to increase much more quickly – at an average annual rate of 3.3% for South Asia and 2.9% for East Asia, compared to the global rate of 1.6% (de Fraiture et al. 2007)

Table 3: Dependence on imported surface water

Country	Incoming waters as a percentage of the total annual renewable water resources
Afghanistan	15
Bangladesh	91
Bhutan	0.4
China	1
India	34
Nepal	6
Pakistan	76

Source: WWAP 2006

The HKH mountain systems play a significant role in agriculture and food security in the region. They are the major sources of water in the dry season, both surface and groundwater. More than one-third of arable land in the HKH countries (excluding Bhutan and Myanmar) is irrigated (Table 4), mainly from rivers originating in the HKH mountains. Pakistan has the highest proportion of irrigated land (82%) and the most extensive irrigation system in the world. Irrigated area as a percentage of total area is among the highest in the world in the Indus and Ganges basins (Siebert et al. 2000). Two issues are of major concern here. First, what will be the impact of climate change on irrigation water demand in terms of the net effect of the changes in precipitation and evapotranspiration, which is discussed in one of the SGP studies (Mu et al., this volume). Second, what will be the impact on groundwater extraction, as farmers pump up water from wells to supplement surface water irrigation needs. The current situation of overextraction of groundwater in the Indus and western Ganges basins may become further aggravated and eventually unsustainable.

Table 4: Agricultural GDP and water withdrawals by agriculture in the HKH countries

Country	Value added in agriculture in 2000 (million USD[a])	Value added in agriculture as % of GDP in 2000	Arable land, 1998–2002[b] ('000 ha)	Proportion of arable land irrigated (%)	Annual agricultural water withdrawal, 1998–2002[b] (billion m^3)
Afghanistan	1,547	45[c]	7,379	43	23
Bangladesh	13,900	25	7,997	47	76
Bhutan	126	28	125	31	0.4
China	152,354	15	130,667	41	427
India	112,374	23	159,934	36	558
Myanmar	5,226	57	9,862	16	33
Nepal	2,340	41	2,357	50	10
Pakistan	18,303	26	21,606	82	163

Sources: World Bank, World Development Indicators, various years; FAO AQUASTAT data, various years; UNESCAP data, 2009
[a] Expressed in real terms as constant 1990 USD
[b] Average annual data
[c] Data for 2002

When the impacts of climate change are superimposed on those of other drivers of change such as population growth and accelerating rates of economic growth, it becomes clear that the threat of water scarcity – seasonal in some other countries and total in others – pose a serious challenge to the 1.3 billion people living in the ten river basins of the region. There is thus a growing need to study the potential impacts of climate change on water availability in the region – and to identify effective measures for adaptation and building resilience.

Water-Related Hazards

Recurrent floods in the rivers of the HKH region are a major hazard for the vulnerable population and often lead to disasters. During the four months of the monsoon from June through September, the whole environment of the region changes. In the mountains, tiny rivulets and streams become raging torrents. What are known as marginal rivers – rivers that exist as seasonal streams – suddenly assume threatening proportions and erode banks, flooding fields and areas of habitation. The big rivers rise and overtop their banks, inundating large areas, often for long periods, and causing tremendous destruction to lives and livelihoods (Table 5), with a resultant marked impact on the economy of the countries of the region (Table 6).

Table 5: **Deaths and affected population in some recent flood events in the HKH countries**

Country	Period	Number of deaths	Number of people affected
Afghanistan	March 2005	100	11,000
Bangladesh	July 2007	1,230	13,851,380
Bhutan	August 2000	200	1,000
China	June 2005	138	16,700,000
India	July 2007	2,051	38,143,000
Myanmar	August 1997	68	137,418
Nepal	July 2007	214	640,658
Pakistan	August 2010	2,000	20,000,000

Source: EM-DAT (www.cred.be/emdat)

Table 6: **Economic and social costs of natural disasters in the countries of the Ganges, Brahmaputra, Meghna basin**

		People affected per annum on average			Economic loss (annual average from 1971-2008)		
	Mortality 1971-2008 (Average no. of people dying annually)	Drought ('000)	Floods and storms ('000)	Share of population (%)	Droughts (million US$)	Floods and storms (million US$)	Largest loss per event (% of GDP)
Bangladesh	5,673	658	8,751	9.1	0	445.6	9.8
India	2,497	25,294	22,314	7.2	61.6	1,055.4	2.5
Nepal	137	121	87	2.0	0.3	25.8	24.6

Source: Rasul 2014; Data obtained from World Bank 2010

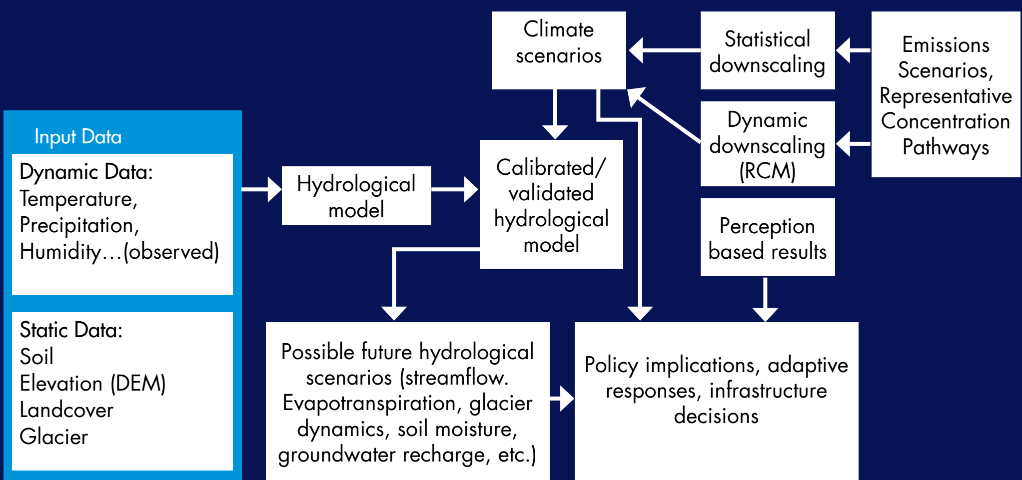
Over the last 25 years, the frequency of reported flood hazard events has increased in the HKH countries of Afghanistan, Bangladesh, Bhutan, India, Nepal, and Pakistan (National Research Council 2012). A large number of the events affected more than one country. In addition to the increase in frequency of events, the flood-related disaster risk has also increased because of increases in exposure to potential hazards and in vulnerability.

The frequency and intensity of water-related hazards are expected to increase further in the HKH region as a result of climate change, with more frequent and more damaging cycles of floods and droughts. The resultant increase in risk to the population of the Hindu Kush Himalayas needs to be better understood and addressed. Furthermore, there is a concrete risk evolving as a result of the rapid retreat of glaciers in the form of the growing number and increasing size of moraine-dammed pro-glacial lakes (Ives et al. 2010). These lakes pose a real threat to communities and infrastructure immediately downstream, and this risk needs to be better understood (Ives et al. 2010; ICIMOD 2011).

A Framework for Studying Climate Change Impacts on Water Availability and Adaptation Practices

The SGP studies looked at the impact of climate change on water availability in a number of selected basins and catchments in the Hindu Kush Himalayan region. Many of the studies selected a number of emissions scenarios and projected temperature and precipitation patterns using a large number of climate models. Figure 2 shows the process schematically. Climate scenarios are developed by statistical downscaling from general circulation models or dynamic downscaling from regional climate models. Hydrological models are developed and calibrated using observed climate data together with land use, land cover, geographic, and socioeconomic data, often from secondary sources. The outputs from the climate models are

Figure 2: **Process for climate change impact analysis**



fed into the hydrological models to project future hydrological scenarios which can be used in policy development, recommendations for adaptation, and different types of planning. Other SGP studies looked at present day perceptions of climate change, adaptation strategies, problems of spatial distribution in measurements, and mechanisms for basin management to address climate-related issues. Table 7 summarizes the research papers prepared from the studies and referred to in this section (presented in full in Part 2 of this publication), including the emissions scenarios, climate models, hydrological models, and projection horizons used. Measures for adaptation and building resilience to water availability can be envisaged in three ways: a) developing water storage facilities, including natural and artificial, surface and groundwater, and blue and green, for example, soil moisture management; b) adopting techniques that help improve water productivity in terms of crop per drop through water saving practices, pressurized irrigation, and water reuse, among others (Molden et al. 2010); and c) changing the structure of economic activities, say from farming high water-intensive crops to farming low water-intensive crops (De Fraiture et al. 2004).

Table 7: **Summary of the research papers from the SGP studies**

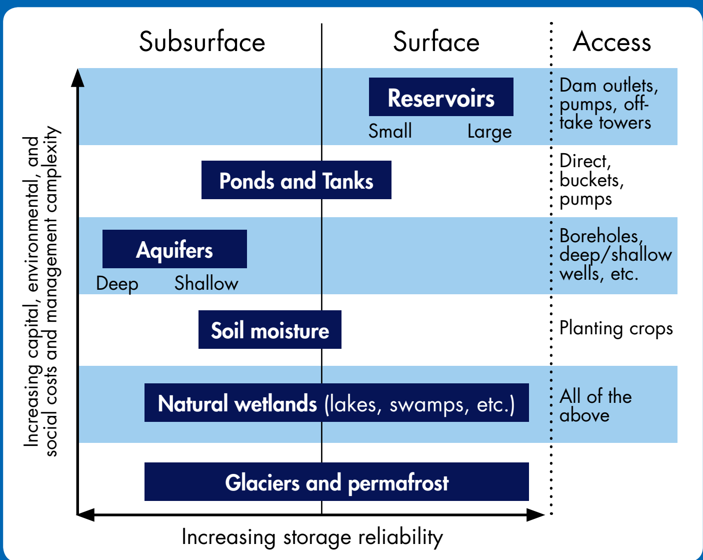
Paper (first author)	Page[a]	Study site (basin/ sub-basin)	Major basin	Method details/Topic			
Studies focusing on future projections							
				Emission scenario	Climate model	Hydrological model	Climate projection
Kayastha et al.	41	Langtang River	Ganges	RCP 4.5	WRF	PDD	2010–2050
		Kafni River	Ganges	RCP 4.5	PRECIS	PDD	2010–2050
Khanal et al.	54	Poiqu/ Bhotekoshi River	Ganges	A2; A1B; B1	ECHAM5	HBV-Light	2046–2065
Mu et al.	76	Yellow River	Yellow	A2; A1B; B1	20 GCMs	BHIWA	2010–2050
Hassan et al.	97	Ganges, Brahmaputra, Meghna (GBM)	GBM	A2; A1B; B1	16 GCMs	SWAT	2050s
Sijapati et al.	109	Indrawati River	Ganges	A2	HADCM3	SWAT	2020s, 2055s, 2080s
		Hakra Branch Canal/Sutlej River	Indus	A2	HADCM3	SWAT	2020s, 2055s, 2080s
Studies focusing on present day observations							
				Main focus			
Yang et al.	129	Koshi River	Ganges	Perceptions of and adaptation strategies to climate change			
Pant et al.	145	Bagmati River	Ganges	Benefit sharing mechanisms in hydropower projects			
		Teesta River	Brahmaputra				
Tarafdar et al.	161	Microwatershed, Uttarakhand	Ganges	Spatial variability and isotope content of monsoon rain			

[a] in this volume

Water storage is increasingly important in the Hindu Kush Himalayas. It can be used to even out supply in areas where the intra-annual precipitation is uneven, it can be used as a buffer to reduce risk from high precipitation events, and it can be used to store water at times of low requirement for use at times of high requirement. This is especially true in hilly areas where water storage can improve access to water in dry periods. All of these are relevant in the Hindu Kush Himalayan region. Future scenarios of water availability suggest that water storage may also become a key strategy for climate change adaptation. The need to develop natural and artificial systems to increase water storage capacity was stressed by the participants in the 5th World Water Forum in Istanbul in March 2009. There are a wide range of options available for water storage, small scale to large scale, natural and artificial, surface and subsurface (Figure 3). Approaches relevant to the Hindu Kush Himalayas in the context of climate change have been discussed in detail (ICIMOD 2009).

At the same time, it is important to note that water storage is not straightforward, and there are a number of issues that need to be taken into account when considering storage approaches. Sedimentation may be the greatest challenge for both large and small surface water storage reservoirs in the HKH region, while seismic risks and GLOF risks (Ives et al. 2010) are also important. Above all, an important issue facing large dams is their social and environmental impact, mainly land submergence and population resettlement (Wang et al. 2013), and the consequences for terrestrial biological diversity (Pandit and Grumbine 2012). The success of reservoir projects lies in well-conceived and implemented rehabilitation and resettlement plans (World Commission on Dams 2000). It has been suggested that a participatory approach should be adopted involving the stakeholders, and that the basic rules of the game be set and agreed upon right at the outset of the project (Gopalakrishnan 2012). Institutional mechanisms may have to be developed for benefit-sharing, and sometimes cost-sharing, between the upstream and downstream communities affected by storage projects, often across national borders.

Figure 3: **Water storage options**



Source: Adapted from McCartney and Smakhtin (2010)

In the context of natural systems of water storage, watershed management through integrated land and water management practices can help maintain soil moisture and support water harvesting, improve infiltration for groundwater recharge, and keep mountain springs flowing. For example, in the zabo ('impounding water') system practised in Kukuma village in Nagaland, India, which is a holistic approach to watershed management, the catchment area at the top of the hill slope is kept under natural vegetation (Agarwal and Narain 1997). Scientific studies have also supported such practices: a hydrological study carried out in an agrarian watershed in the Sikkim Himalaya has recommended that dense mixed forest cover should be maintained in the higher elevation catchment areas in the watershed to regulate and ensure stream flows downstream (Rai and Sharma 1998). More recently, in the context of climate change induced precipitation patterns, the application of geohydrological techniques for identifying recharge areas of unconfined aquifers in the mountains has been suggested to support watershed management (Tambe et al. 2012). The SGP studies have also discussed such measures.

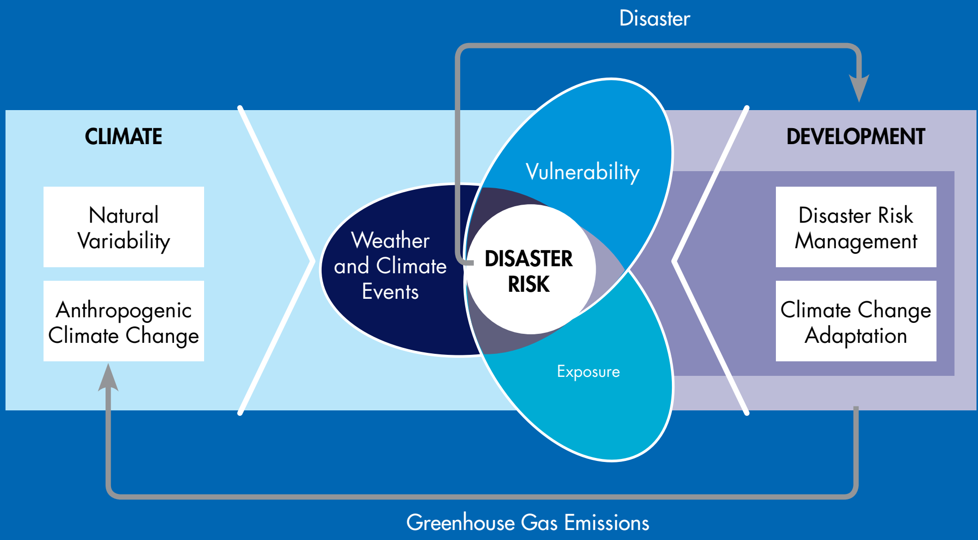
Measures for adaptation and building resilience to water demand can be envisaged in terms of pursuing measures to reduce irrigation water demand, which would focus on ways of reducing evapotranspiration. The SGP studies have discussed measures such as shifting the sowing period by planting early in the season, and developing a seasonal weather forecasting system that would help communities adjust the sowing period, among others.

Measures for adaptation and building resilience to water-related hazards can be envisaged in terms of pursuing measures to reduce exposure and vulnerability. The concepts, goals, and processes of adaptation share much in common with disaster risk management (Figure 4). It may, therefore, be possible to conceptualize climate change adaptation starting from disaster risk management, in which best practice cases already exist in the literature – of course, with an understanding of the differences between the two, for example, the relevant time horizon.

HKH countries are less resilient to water-related disasters than other Asia-Pacific countries, and resilience building is a major challenge that needs to be addressed, especially in the context of climate change adaptation. For example, while Bangladesh ranks eleventh among the Asia-Pacific countries for potential flood-related hazards, after accounting for vulnerability – which is interpreted mathematically as a reciprocal of resilience – it ranks fourth for flood-related risk, reflecting its low resilience (Asian Development Bank 2013). Fortunately, there are low-hanging fruit available to expedite resilience building at the community level through measures such as reducing exposure (e.g., through zoning regulations), reducing vulnerability (e.g., by awareness building), enhancing soft coping capacities (e.g., by establishing early warning systems), and enhancing hard coping capacities (e.g., by investing in appropriate infrastructure facilities). Active local participation will, of course, be essential while arriving at all these decisions.

The key to solving flood risk management problems may lie partly in having modern hydromet stations to collect and store data, terrestrial and satellite communication systems to transmit

Figure 4: **Climate change, disaster risk, and adaptation**



Source: Lavell et al. 2012

data in real-time, and mechanisms for sending flood alerts to the last mile – all to help develop a better system for information management and dissemination. A regional flood outlook system is being designed under the HKH-HYCOS initiative at ICIMOD (www.icimod.org/?q=264) to demonstrate the utility of real-time data collected through the project using a hydrological and hydrodynamic model; the idea is to provide to national hydro-meteorological agencies the products needed to support the development and refinement of national flood forecast and warning systems (ICIMOD 2012). However, it could prove difficult to find sufficient resources in government budgets for implementing non-structural measures, such as flood early warning systems, in the absence of an economic analysis to justify the value of reducing the disaster risk (IPCC SREX 2012). Flood risk management projects may be able to negotiate for more resources in the annual budget if the benefits of such projects could be valued more precisely to prepare feasibility studies (Vaidya 2008). Equally, if national governments could clearly show a link between key disaster management activities and those for climate change adaptation, such projects might qualify for funding under the many climate resilience initiatives in the process of being launched. Finally, in terms of the value of information, the question is how much would a national government be willing to invest in information systems, such as early warning systems at the community level, in order to detect the hazards with sufficient lead time to take action to reduce their potential adverse effects on life and property. The value of information depends on the cost of evacuation, potential loss of life and property, mental trauma (communities losing sleep over potential flood events and trauma after the events), and the probability of floods. The SGP studies have also discussed measures aimed at reducing exposure and vulnerability and enhancing coping capacities at the study sites.

The findings of the studies in terms of potential climate change impacts (on water availability and hazards); adaptation and resilience (related to water management, agricultural practices, and hazards); and supporting mechanisms for adaptation (through a basin-wide approach and incentive-based mechanisms) are summarized in more detail below. The SGP papers are referred to by the name of the first author; the pages where they appear in this volume are given in Table 6.

Results on Climate Change Impacts

Climate change and water availability and demand

Water scarcity is already a problem in the countries of the HKH region, whether seasonal or year round, and poses a potential threat to food and energy security, environmental quality, and livelihoods and quality of life in general. Climate change is expected to have a further impact on water availability. In order to address the problems of water availability, it is important first to understand the present situation and how the hydrological system of the HKH region is likely to respond to climate changes and variability. In the HKH region, the hydrological regime is likely to be affected both by direct impacts on precipitation and evapotranspiration and indirect impacts through changes in the cryosphere.

The recession of the region's glaciers has already become a matter of great concern, particularly since the release of AR4 by the Intergovernmental Panel on Climate Change (IPCC), which prompted significant interest in the subject and led to a marked increase in studies of the Himalayan glaciers. Several recent studies (e.g., Armstrong 2010; Immerzeel et al. 2010; Miller and Rees 2011; Bolch et al. 2012; Cogley et al. 2010) indicate that, although glacial retreat in the HKH region is occurring, the rates of retreat are less than those originally suggested by AR4. Information on changes in snow cover and permafrost is scanty or absent for the region.

In the rivers of the eastern part of the region, glacial melt coincides with monsoon precipitation, and by comparison, the large volume of rainwater dwarfs the contribution of meltwater. Even in monsoon-dominated areas, however, glacial melt is still an important source of water for both agriculture and vegetation in the upper reaches, especially during dry periods. Glacial melt contributes significantly to the water discharge of the Indus in the western part of the region because in this area the summer monsoon is weak and the contribution is more obvious in the arid areas downstream. The HKH region is likely to suffer significant changes in its cryosphere regime because of climate change, although it will manifest differently in different parts since the wide range in latitude, longitude, and topography will influence the amount of monsoon precipitation and contribution of snowfall. The changes that will take place on the high Tibetan plateau are also likely to differ from the changes that will be experienced in the rugged mountain ranges to the south.

Overall, studies indicate that the mean upstream water supply will decrease between the two time slices 2000–2007 and 2046–2065 at rates of -8.4% for the upper Indus, -17.6% for the Ganges, -19.6% for the Brahmaputra, and -5.6% for the Yangtze (Immerzeel et al. 2010). These decreases are less than the reduction in the release of meltwater would indicate, as they are compensated to varying extents by an increase in upstream rainfall of +25% for the Indus, +8% for the Ganges, +25% for the Brahmaputra, +5% for the Yangtze, and +14% for the Yellow River. A 9.5% increase in upstream water yield was projected for the Yellow River because this basin depends only marginally on glacial melt. However, Immerzeel et al. (2010) emphasize that results should be treated with caution because of difficulties associated with monsoon simulation and inter-annual variations in precipitation. In a study at intermediate spatial scale in the Hunza, Gilgit, and Astore river basins, Akhtar et al. (2008) considered three hypothetical glacial depletion scenarios: total disappearance of glaciers, 50% disappearance, and no disappearance. The timescale slice was 2071–2100 at a spatial resolution of 25 km. This study found that both temperature and precipitation tended to increase towards the end of the twenty-first century. The models showed an increase in discharge with both a 100% and a 50% reduction in glaciers, whereas with a 0% reduction in glaciers, less water was available. In a study that compared the drier, western Himalayas with the monsoon-dominated eastern part, Rees and Collins (2006) suggest that climate warming would not have a uniform effect on river flow in the region. Some older studies, for example on the Sutlej river basin by Singh and Bengtsson (2004, 2005), indicate that climate change will impact seasonal water supplies more than annual water supplies. Reduction of water supplies during the summer months is likely to affect agriculture and tourism adversely in many areas. However, in general the older models are not fully distributed, are not forced by a wide range of new climate scenarios, and are weak in parameterization of glacial extent and processes. Immerzeel et al. (2012) used fully distributed models that forced taking these shortcomings into account to investigate how glaciers and runoff would respond to an ensemble of downscaled climate model data in the Langtang catchment in Nepal. These projections show both an increase in temperature and precipitation and a concomitant steady decline in glacial area which would lead to a significant increase in river flows in the shorter term. A number of the SGP studies looked at the projected impacts of climate change on water availability in different sub-basins in the region.

Langtang and Kafni catchments (Ganges River basin)

Kayastha et al. used a positive degree day (PDD) model to simulate the flow from two glacierized sub-basins, the Langtang catchment in Nepal and the Kafni catchment in India, and to assess the future impact of climate change on the flow regime in the Ganges River basin. The results essentially agree with the findings of other authors as outlined above, but with some regional differences.

The positive degree day model is able to reproduce hydrological processes fairly well. For the Langtang River basin, the model outputs showed an increasing trend in discharge from 2010 to 2050, with pronounced interannual variability. The increasing trend was confined to the wet season (June–September); there was a slightly decreasing trend in the dry season (October–May). In the Kafni basin, the river discharge was projected to increase up to 2040 and then decrease gradually, in both the wet and dry seasons. The changes in flow regime in both Langtang and Kafni seem to be more strongly related to the changes in precipitation than to the changes in snow/ice cover area projected by the climate models.

The study also assessed the relative contributions of snow and ice melt to the total flow. In the Langtang River basin, the average contribution of snow and ice to the annual discharge during 2010-2050 was projected to be 47% (with a slight decrease over the period), similar to the contribution of 49% in the baseline period (1995–2003), and similar to the estimate by Racoviteanu et al. (2013). The projected relative contribution of snow/ice melt was about 12% in the winter season (October–February), 38% in the pre-monsoon season (March–May), and 57% in the monsoon season (June–September). In contrast, in the Kafni River basin, river discharge is mainly dominated by precipitation throughout the year, with rainfall contributing 81% of annual average discharge over the period 2010–2050. The average contribution of snow/ice melt was 19%, with 20% contributed by snow/ice melt during the monsoon season (June–September); 31% during the pre-monsoon season; and very little in the winter.

Yellow River basin

The study by Mu et al. on the Yellow River basin analysed the impact of climate change on future water demand and water stress situations, focusing on irrigation water demand. A marked decrease in outflow to the sea from the basin was observed between 1956 and 2006, which was considerably more prominent than the slight reduction in mean annual precipitation observed during the same period. A part of the reduction is attributed to increased irrigation water consumption, but the increase in temperature and reduction in precipitation (both of which influence evapotranspiration) observed over the same time period could also be drivers for the decrease in runoff. The study used statistically downscaled temperature and precipitation scenarios produced by the National Climate Centre of China using a back-propagation neural network. The downscaled data were input into a basin-wide holistic integrated water assessment (BHIWA) model to analyse the irrigation water demand and water stress situations in terms of both water quantity and water quality in the basin and to assess the effect of changes in evapotranspiration (compared to the reference period 1980-2000) and precipitation (compared to the reference period 1956-2000).

Four indicators were used to assess the water situation in 2030 and 2050 under three different climate change scenarios (A1B, A2 and B1), two indicators measured the ratio of withdrawals and returns to total input to surface water, and two measured the ratio of withdrawals and returns to total input to groundwater. Three additional scenarios were developed to test the potential extent of climate change impact on water stress: precipitation decreasing by 5 and 10% and evapotranspiration increasing by 10 and 15%; precipitation increasing by 5 and 10% and evapotranspiration decreasing by 10 and 15%; and precipitation decreasing by 5 and 10% and evapotranspiration decreasing by 5 and 10%, all by 2030 and 2050, respectively. The results suggest that irrigation water demand will increase and the water situation will become more stressed in 2030 and 2050, even though there is some increase in precipitation in most of the sub-basins under the General Circulation Models (GCM) scenarios. With the same variation range of precipitation and reference evapotranspiration, the evapotranspiration will have a bigger impact than precipitation on irrigation water demand and water stress situations. A slight increase in evapotranspiration will result in a big increase in irrigation water demand. In other words, a small change in climate could result in a big change in irrigation water demand, and water surplus/deficit conditions. The study also found that groundwater quality was more vulnerable to climate change than surface water quality.

Ganges-Brahmaputra-Meghna River basin

The study by Hassan et al. focused on the potential impact of climate change on water availability and crop yield in the Ganges-Brahmaputra-Meghna (GBM) basin. The GBM basin covers an area of 1.7 million km^2 and is home to 630 million people. Changes in the climate and in water availability are likely to influence agricultural production and food security, ecology, biodiversity, river flows, floods and droughts, water security, and human and animal health. The impact of climate change on the components of water balance in the GBM basin in the 2050s were simulated using a semi-distributed hydrological model with projections of climate factors from 16 general circulation models using different emissions scenarios (A2, A1B, B1). This information was then used to project the local seasonal surface and ground water availability in two districts, one in Bangladesh and one in Nepal, and estimate the yield of major crops under the changed climate and water situation.

Annual average precipitation in the three basins during the baseline period (1981–2012) was 981 mm, 1,981 mm, and 3,816 mm. In the Ganges basin, 59% of precipitation evaporated, and in the Brahmaputra and Meghna basins around 33%. Snowmelt contributed 10% of annual flow to the Ganges and 17% to the Brahmaputra. The results showed an overall increase in average annual precipitation and surface runoff in all three basins under all scenarios in the 2050s, but with marked changes in seasonality. In the Ganges basin, dry season, monsoon, and post-monsoon flows were projected to increase by up to 20%, and pre-monsoon flow to decrease by up to 15%; in the Brahmaputra and Meghna basins, flow was projected to increase in all seasons, with a marked increase in the Brahmaputra basin in the dry season (17%), and in the Meghna basin in pre-monsoon (20%). More than 60% of annual flow occurs during the monsoon, and this may increase by the 2050s.

The impact of climate change on groundwater recharge was analysed using simulated monthly percolation rates. In the Ganges basin, groundwater recharge remained confined mainly to the monsoon period, whereas in the Brahmaputra and Meghna basins recharge starts in pre-monsoon and continues well into the post-monsoon. Recharge was projected to increase in all three basins by the 2050s.

The impact of climate change on local water availability was analysed in two districts: Nachole in the drought prone area of northwest Bangladesh (average annual precipitation during the base period 1,413 mm) and Rasuwa in north-central Nepal (average annual precipitation during the base period 2,808 mm), both in the Ganges basin. Simulated surface runoff showed available annual surface water of 525 mm and 646 mm, respectively, in the baseline period. This was projected to increase at both sites by the 2050s under all emission scenarios, and in all seasons except the dry season. However, the change was more pronounced during the pre-monsoon season in Nachole (greatest percentage increase) and during the dry season in Rasuwa (greatest percentage decrease). This is in line with recent observations of increased flooding in the Bangladeshi floodplain in the monsoon, and increased dry season water scarcity in the mountain districts of Nepal, and also underlines the differences in climate change impacts at the local level. Annual groundwater recharge in the baseline period was 217 mm in Nachole and 1,040 mm in Rasuwa, with most taking place during the monsoon season. Recharge amounts were projected to increase by the 2050s under all emission scenarios, and especially under the A1B scenario (by 8% in Nachole and 5% in Rasuwa).

Indrawati sub-basin and Hakra Branch Canal (Sutlej River basin)

Sijapati et al. used a case study approach to assess, project, and compare the impacts of climate change on water availability in a predominantly rain-fed agricultural area in the Indrawati sub-basin in Nepal, and a predominantly irrigated agricultural area along the Hakra Branch Canal (which is drawn from the Sutlej River) in Pakistan. The study compared and contrasted the results of model simulations from downscaled climate scenarios with farmers' perceptions, collected using questionnaires at community level. The study focused on the potential impact of climate change on water availability and crop yield at the local level, and identification of existing response strategies and potential adaptation strategies.

The study used a soil and water assessment tool (SWAT), calibrated against observed discharge, and forced by a climate scenario based on a statistical downscaling model (SDSM) to compare present and future water and climate scenarios. The SDSM was used to generate future high-resolution monthly climate information for the A2 emission scenarios for different periods (2020s, 2050s/2055s, 2080s) from coarse-resolution global circulation model simulations (HadCM3 for the Indrawati and CSM, CanESM2, and NorESM for the Hakra Branch Canal).

The simulation for the Indrawati basin showed no significant trend in average annual precipitation or water availability, or in seasonal water availability, in the reference period from 1980 to 2008. However, the majority of farmers reported a decline in annual precipitation, and many had observed a change in precipitation patterns. The annual contribution of snowmelt in stream flow was not significant. Similarly, rainfall records showed no clear trend in precipitation in the Hakra Branch Canal area between 1980 and 2004, although there were wetter and drier periods, and more than half of the farmers considered that rainfall had decreased.

Average annual precipitation in the Indrawati basin was projected to decrease slightly by 0.9, 1.4, and 3.0% of baseline by the 2020s, 2055s, and 2080s, respectively, with a marked increase in early winter, a small increase in spring and early summer, and a decrease in late winter, mid-to late summer, and autumn. In the Hakra Branch Canal area, average annual precipitation was projected to decrease by 7.8% by the 2020s, with decreases in early summer, autumn, and early winter, but then to increase by 49% and 36% of baseline by the 2050s and 2080s, respectively, with the most marked increase in late winter and spring in the 2055s and in autumn and early winter in the 2080s. Overall flows in the canal were also projected to decrease slightly under all three time segments in future climate scenarios, except the 2050s scenario during the monsoon season. The seasonal changes have considerable implications for the crop calendar.

Almost all farmers in the Indrawati basin considered that overall temperatures had become slightly higher over the previous decade, with close to a third saying that the hot season had become hotter, and more than a third experiencing less frost. The majority of farmers in the Hakra Branch Canal area also thought that summer temperatures had increased, but not winter temperatures. The observed data during the baseline period showed that both summer and winter maximum temperatures had increased slightly over the previous three decades

Uttarakhand microwatershed

The study by Tarafdar et al. looked at a different aspect of water availability, the spatial variability of rainfall and surface temperature patterns at the finer watershed scale, which has marked implications both for the local water supply, and for the extrapolation of data from sparsely located hydromet stations.

Springs and spring-fed streams are the most assured sources of freshwater for the rural population in the remote microwatersheds of the Himalayas. Most have been traditionally managed and preserved as they are of major significance for all domestic requirements including cattle. Although piped water from groundwater sources or pumped from local rivers is becoming increasingly common in the Indian Himalayan region, the supplies remain unreliable and often of poor quality, and springs remain an essential source of water. Proper identification of the recharge areas for these key water resources is vital for their protection and for implementation of groundwater augmenting interventions. It is also important to analyse the distribution of precipitation within the microwatershed containing the springs.

In the study, rain gauges and temperature and humidity loggers were installed to measure the microclimate at three elevations representing the major topographic divisions in the watershed, and an automated weather station was installed at a central point to record air temperature, humidity, wind speed, wind direction, rainfall, and solar radiation. The preliminary results indicated a large spatial variability in rainfall over small distances, with a strong ridge to valley gradient. There was also a variation in temperature; the temperature lapse rate with elevation in the monsoon months was 0.6°C (100 m^{-1}), very similar to values reported by others for the Himalayas. Changes in isotope patterns are also being investigated to help in identification of recharge areas. The preliminary results show that water recharge in a microwatershed is a complex phenomenon affected, among others, by dominating weather patterns, topography, and altitude. The findings also indicate that in Himalayan basins, the sparse distribution of rain gauges might lead to under or over representation of rainfall as a result of the high spatial variability.

Climate Change and Water-Related Hazards

The Himalayan mountain ranges have a characteristically variable climate marked by extreme weather events, intense seasonal precipitation, and long periods of drought. Thus water-related hazards – riverine floods, flash floods, landslides, debris flows, and droughts – are a common feature of life, with impacts that extend from the high mountains to the plains. The countries of the HKH region have been affected by a number of extreme disasters over the past thirty years. The most common type of disaster in the region is flooding, and the increasing frequency of floods is causing greater and longer-lasting damage to infrastructure and livelihoods. The high levels of hazard and disaster in the region are holding back socioeconomic development and hamper progress in poverty reduction.

Climate change is thought to be increasing the frequency and potential of hazards as a result of increasing average temperature, changes in average annual precipitation, irregular rainfall patterns, and increasing number of extreme weather events, especially intense rainfall events (Shrestha 2009). In the HKH region, shifts in monsoon precipitation patterns may lead to episodes of intense precipitation, which may in turn lead to increases in floods, landslides, and erosion, as well as an increase in the frequency and intensity of droughts, with a resultant lowering of the water table, drying of natural springs, and reduced stream discharge. Moreover, the Himalayan glaciers have experienced rapid retreat in recent decades, which has resulted in the formation and growth of many glacial lakes. These lakes are held back by unstable moraine materials and can burst out, leading to a type of flash flood known as a glacial lake outburst flood (GLOF). Climate change is expected to result in an increase in the number and size of such lakes, and thus to an increase in the risk of such outbursts.

Before considering future approaches to disaster reduction and management, it is important to have a better understanding of the likely future situation. Two of the SGP studies looked at the potential impacts of climate change on water-related hazards.

Flash floods in the Poiqu/Bhotekoshi/Sunkoshi basin

Khanal et al. looked at flash floods in the Poiqu/Bhotekoshi/Sunkoshi watershed, with a focus on the assessment of historical flash floods and their impacts, and future simulation of flash floods under different climate change scenarios (as well as vulnerability and adaptation which are discussed here in a later section). The study followed from an earlier study in the basin which used dam break and hydrodynamic modelling to simulate the outburst of a GLOF and the propagation of the flood along the river valley downstream, and model the potential impacts of the GLOF on settlements, agricultural land, and infrastructure. (Khanal et al. 2013).

Future climate scenarios were developed for the period 2046–2065 using the ECHAM5 climate model and the A1B, B1, and A2 emission scenarios. The semi-distributed HBV-light model was used for runoff modelling. The watershed extends from the Tibetan plateau in China to the edge of the lowland plains in Nepal, and has an elevation range from about 650 to 8,000 masl. Thus it has high spatial and temporal variation in both precipitation and temperature, with average annual precipitation ranging from less than 600 to 3,600 mm, and average annual temperature from 3.9 to 21.2°C. Future climate scenarios were developed for two sub-watersheds. All three climate scenarios projected an increase in average monthly temperatures (of the order 1–4°C) with the greatest changes in February and the least in March and November. Total precipitation was projected to decrease from June to August under all three scenarios.

Seasonal climatic variation is a major cause of the frequent floods in the study area, and changes in climate might be expected to affect flooding rates. The modelling results suggested that future discharge would not change significantly under the different climatic scenarios, but that lower flow levels will be accompanied by an increase in annual maximum daily discharge levels, especially at recurrence intervals of 25 years or less, with a maximum for recurrences at 5 and 10 years. This suggests that the number of less severe floods will increase.

Khanal et al. identified four types of flash floods in the basin: glacial lake outburst floods (GLOFs); floods triggered by heavy precipitation; landslide dam outburst floods (LDOFs); and floods triggered by blocking from flooded tributaries. The study focused on the potential for GLOFs, as these lakes generally form long before the flood event, offering some possibility for both prediction and mitigation. A total of 74 glacial lakes of different sizes were identified in the watershed. Most had increased in area between 1991 and 2012 (even doubling in size) and ten were assessed as critical or very critical with a potential for GLOF occurrence. It is not possible to predict the precise impact of climate change on the development of glacial lakes, but the projected increases in temperature indicate that they will continue to increase in size and number, thus increasing the risk of outburst.

Riverine floods in the Ganges-Brahmaputra-Meghna basin

The study by Hassan et al. on climate change and water availability in the Ganges-Brahmaputra-Meghna (GBM) basin (discussed above), also considered the potential impact of the changed climate scenario on flooding in the basin. Monsoon flow was projected to increase in all three basins. More than 60% of the annual flow across the basin occurs during the monsoon, and this percentage is also projected to increase by the 2050s. The increase in flow could result in more frequent flood events of higher magnitude. A frequency analysis of flood events under the climate change scenarios showed that in the Ganges basin, a 50-year flood will become a 20-year flood by the 2050s under the A2 and B1 scenarios, and a

10-year event under the A1B scenario. A similar tendency was also projected in the Brahmaputra and Meghna basins, with 50-year event becoming a 35-year event in the Brahmaputra basin and a 20-year event in the Meghna basin.

Results on Adaptation and Building Resilience

Adaptation and building resilience through better water management

The studies of water availability in the HKH region indicate that the present situation of scarcity and water stress is likely to become more marked in the future. Although average annual precipitation may not change greatly, there is likely to be more variability in the water supply, with climate change likely to impact seasonal water supplies more than annual water supplies, and heavy rainfall events being interspersed with longer periods of drought. Among others, higher temperatures are likely to result in increased evapotranspiration, leading to both reduced water availability and an increased requirement for irrigation water; population growth is likely to lead to intensification of agriculture, which will also increase the need for irrigation; and increased high rainfall events are likely to lead to higher rates of runoff and reduced percolation, accompanied by an increased risk of floods and reduced recharge. Many of these challenges can be addressed in part by improved water management practices, such as improving water storage, improving the efficiency of water distribution and use, and reducing high water use activities. A number of the SGP studies addressed water management issues. Most were related to agricultural practices, which are discussed in the next section, but two studies also looked at more general practices and reported a number of water management practices either adopted by local farmers or suggested as adaptation measures to address problems of scarcity.

Water management in the Indrawati sub-basin and Hakra Branch Canal area

As well as assessing the impact of climate change on water availability (discussed in above), Sijapati et al. looked at farmers' perceptions of change and their adaptation strategies at the two project sites in the Indrawati basin in the mid hills of Nepal, and the Hakra Branch Canal area in a semi arid part of Pakistan.

The great majority of respondents in the Indrawati basin had experienced a decline in water availability over the preceding decade, even though the observed data did not identify any overall trend in annual precipitation or overall water availability. In the study site area around the Hakra Branch Canal, water scarcity is already a major problem. The CROPWAT model shows that the crop water requirement for the major crops is about 661 mm (wheat) and 711 mm (cotton), which means there is water deficit of 1,089 mm fulfilled by irrigation. The water supply from the canal is insufficient, and inequitable distribution of water compounds the issue of water shortage. At present, the deficit is met by groundwater, but climate change is likely to further aggravate the situation and increase the need for more efficient use of the resources.

Farmers at both sites had adopted a number of water management strategies. The most important focused on collection and storage of rainwater. These included in situ moisture conservation (either through conservation agriculture or construction of rainwater control and management structures) and storage of rainwater for supplementary irrigation (through construction of farm ponds, water pans, sand/sub-surface dams, earth dams, tanks, and others). In some areas farmers still used traditional water harvesting practices, but elsewhere farmers need support to (re)introduce such methods.

In the Indrawati basin, farmers practised a traditional method of constructing terraces that facilitates soil and water conservation. In some areas, however, sloping land was being cultivated without terraces, and in view of the increasing water scarcity, it is now important to raise awareness among farmers of the benefits of levelling land, and the way in which terracing helps to reduce erosion and store water in the fields.

In Pakistan, farmers in semi-arid areas often grow trees around farm plots to serve as a barrier to the wind, thus reducing erosion and helping to decrease evaporation. However, very few trees were seen in the Hakra Branch Canal command area and this might be a useful practice to introduce. Construction of dikes along field boundaries can also help to increase soil moisture content and prevent erosion of the valuable top soil layer. Other options that serve the same purpose include mulching, (i.e., covering the fields with plant residues to preserve soil moisture), and furrow irrigation (making small trenches within the field in order to increase water uptake)

High efficiency irrigation techniques like sprinkler and drip irrigation schemes also serve as an adaptation measure to climate variability and drought due to their inherent ability to save water, but high installation costs and lack of skilled labour hinder adoption. In Pakistan, the Punjab Government has recently initiated the Punjab Irrigated Agriculture Productivity Improvement Programme Project (PIPIPP) to address this problem through the installation of (subsidized) high-efficiency irrigation systems and improvement of community irrigation systems, among others. This project can help the farming community in the study area to become more efficient water managers.

Water management in the Koshi basin

Yang et al. studied people's perceptions of climate variability and change, and their coping and adaptation approaches, in the Koshi basin in Nepal. The study used primary information obtained through focus group discussions and key informant interviews in 17 districts in three ecological zones – mountains, hills, and Terai (lowlands). People in the region have been experiencing increasing temperatures and greater variability in precipitation, including delayed onset of the monsoon, and increasing scarcity of water.

Communities have adopted different measures to cope with water scarcity. They include planting trees to protect catchment areas, revitalizing traditional irrigation schemes, building canals (pynes) and constructing plastic-lined ponds for irrigation, and introducing sprinkler irrigation.

Adaptation and building resilience through better agricultural practices

Agriculture is one of the most sensitive sectors to climate change. Changes in temperature, precipitation, wind speed, and atmospheric CO_2 concentration can all have significant impacts on crop productivity, and indirect impacts will also be felt in terms of water availability, changing status of soil moisture, incidence of pests and disease, and changing frequency of events such as drought and flood. Thus, climate is the single most important factor likely to shape the future of food security. However, the potential impact of climate change on agriculture is crop and location specific, and a much more sophisticated understanding of these dynamics is needed in order to address likely changes in growing season climatic conditions. Adaptation strategies will be needed to adjust agricultural practices so that they can continue to be effective as conditions change.

Given the importance of agriculture for human survival, and the fact that farmers have always had to deal with climate variability, there is no shortage of response strategies to changes in climate, both suggested and in use. These include changes to crops (alternative crop rotation, genetic development of new crop varieties), increasing efficiency in agricultural water use, altering the timing or location of cropping activities (change in cropping calendar), changes in crop management (change in input use, alternative tillage systems, and proper irrigation and drainage), and changes in agricultural policy. Irrigation is one of the possible adaptation strategies to climate change and variability, as it can address uncertainty associated with the natural precipitation regime in places that rely on rain to irrigate crops. Irrigated agriculture may be faced with a double hit, however, since not only will agriculture require more moisture in a dryer climate, there will also be less water available. Increased temperature and decreased humidity elevates the soil moisture deficit and hence dramatically raises the irrigation water demand. Adaptation through improved water management was discussed in the preceding section. In addition, a number of the SGP studies addressed other adaptation approaches, often site specific, related directly to agricultural practices. These adaptation approaches are summarized in the following.

Adaptation practices in the Indrawati sub-basin and Hakra Branch Canal area

The study by Sijapati et al. in the Indrawati basin and Hakra Branch Canal area focused on adaptation practices that farmers had either already adopted, or that could be considered, to address the expected impacts of climate change.

In the Indrawati basin the climate projections did not reveal any clear patterns of change in water availability under future climate scenarios, however farmers had already changed some crops in response to various factors including lack of water for irrigation and unfavourable climatic conditions. At the same time, however, they were cultivating more rice, which has a high water requirement, in response to changing dietary patterns and access to markets, and were also introducing more financially lucrative crops. In the Hakra Branch Canal area, climate modelling showed that the water requirement for the major crops could be reduced by a two-week shift in sowing date, and that this might become more critical in the future.

A number of adaptation strategies were identified most of which were relevant to a greater or lesser extent in both areas. A number of farmers had adopted an organic farming approach using compost-based fertilizers and locally produced bio-pesticides. This resulted in a rapid improvement of soil fertility and moisture content in the fields as well as reduced input of chemical fertilizers, and is an easily introduced and promising adaptation approach. Adjusting crop timing (delaying or early sowing of crops) according to shifts in the rainfall pattern is a useful option which some farming communities had already started using to cope with variability in the monsoon. Use of drought resistant crop varieties is another possibility for addressing changes in water availability. Farmers in both research areas tended to use indigenous seeds set aside from previous crops, and reported that these indigenous varieties were more resistant to drought than hybrids. Selection of drought resistant varieties, and promotion of crops that require less water, is another useful adaptation approach. Cultivating more than one crop at a time (mixed cropping) is a further promising adaptation strategy for small-scale farmers to reduce the risk of complete crop failure. Several styles of crop mixing were found in both research areas. Although mixed fields are more labour-intensive, they are less prone to pest attacks, allow for a diversified diet, and spread the risk of having no yield at all from failure of one crop.

Farmers need to know in advance about the likely onset and end date of the monsoon in their area, as well as other major weather events, so that they can adjust the timing of practices like sowing, irrigation, and harvesting. In Pakistan and Nepal, the weather forecast is disseminated by the relevant government departments, and weather updates are also normally available on the Internet in English. However, the literacy rate in the research area is low and access to the Internet is also very low, which means that the information seldom reaches the farmers. A weather information system is needed designed to meet the needs of the farming community in remote rural areas.

Adaptation practices in the Ganges-Brahmaputra-Meghna River basin

The study by Hassan et al. on water availability in the Ganges-Brahmaputra-Meghna (GBM) basin, analysed crop yield in two representative districts, Nachole in Bangladesh and Rasuwa in Nepal, under different climate scenarios, and looked at adaptation options.

The impact of climate change on the yield of major crops by the 2050s was assessed using the Decision Support System for Agro-technology Transfer (DSSAT) tool with the projections for future seasonal water availability, temperature, and CO_2 concentration. The model was used to simulate crop yield during the base period (1981–2012) and under the three climate scenarios (A1B, A2, and B1). In all cases, temperature and precipitation had a negative impact on yield; CO_2 had a positive impact on rice yield as a result of carbon fertilization, and a smaller positive impact on maize. Overall, the yield of monsoon season rice (transplanted aman) in Nachole was projected to increase by up to 3%, whereas the yield of dry season rice (boro) in Nachole was projected to decrease by around 4% and of maize in Rasuwa by 2–6%. The results indicate that dry season rice cultivation may not be sustainable in Nachole as the water demand is higher than the expected recharge.

The study tested three adaptation options in the model simulations to reduce yield loss and crop water requirement in Nachole: shifting the transplantation date, sowing a short duration crop variety, and crop diversification. For monsoon rice, transplanting 10 days earlier than at present would be the most effective way to reduce the crop water requirement and yield loss in wet, average, and dry years under all the emission scenarios. The reduction in crop water requirement and yield loss can be maximized by using short duration (135 days) monsoon rice varieties. As also suggested in the study by Sijapati et al., continuous weather forecast information should be provided to farmers so that they can adjust the transplantation date to reduce risk and sustain yields with less water. Moreover, farmers should be given training to help them understand the linkages between the weather and agricultural practices, and the benefits of agro-meteorological forecasting.

Transplanting dry season rice 10 days earlier also helps to reduce the crop water requirement, as does introduction of short duration dry season rice varieties. However, the scenario for local water availability indicates that despite the slight increase in groundwater recharge in the 2050s, there will be an irrigation deficit for growing dry season rice. Thus, dry season rice cultivation should be replaced in phases by low water requiring cereal crops such as wheat and maize, oilseeds, pulses, and winter vegetables.

Adaptation practices in the Koshi River basin

The study by Yang et al. of people's perceptions of climate variability and change and their coping and adaptation approaches in the Koshi basin in Nepal, also described some perceptions and adaptation approaches related to agricultural practices.

People in the region have been experiencing increasing temperatures and greater variability in precipitation, with impacts including increasing scarcity of water and decline in yield of agricultural crops. Those interviewed reported that the growing period for agricultural crops had been reduced, mainly due to an increase in temperature. The times of sowing, planting, and harvesting of agricultural crops had undergone considerable change. The sowing and harvesting time for summer crops such as rice, maize, millet, and potato were generally later by up to one month, whereas the sowing and harvesting time for winter crops such as wheat and barley had been shifted forward by 15-30 days.

A wide range of adaptation strategies was reported, with variations depending on the elevation and local conditions. Approaches included shifting the agricultural calendar, changing to crops that can cope with water and temperature stress (e.g., millet replacing rice, mustard replacing wheat), introducing crops with a shorter growing period, introducing improved seeds that promise high yields even under dry conditions, growing crops at higher elevations, cultivating more than one crop per year, mixed cropping of beans with maize to protect the maize plants from strong winds, introducing new crops such as ginger and turmeric that fetch higher prices and can better withstand water and temperature stress, cultivating off-season vegetables, mulching to increase soil moisture, and using stalks of failed crops as fodder.

Adaptation and building resilience to water-related hazards

The approach to flood risk management in the HKH region has changed over time from a conventional structural approach towards an integrated approach that embraces watershed management, river training, and community participation (WMO and GWP 2004). However, there is still a considerable lack of the scientific data, information, and knowledge about occurrence, causes, and likely future development of both hazards and risks that is required for effective planning and building resilience. For example, the efficiency and effectiveness of a flood control programme may depend largely on how well the risk assessment is carried out and whether effective flood forecasting and early warning systems are put in place. Much work needs to be done in terms of developing methodologies for risk assessment, including hydrodynamic modelling and the use of GIS for representation of risks in maps. Disaster management plans based on information and communication technologies for early warning systems need to be developed, together with institutional mechanisms that empower local communities and provide access to and the ability to use relevant information. In short, there is a need to explicitly treat the role of information systems in the integrated approach to flood risk management. The value of local knowledge and information in flood risk management has also been highlighted in a number of studies (e.g., Dekens 2007a,b; Baumwoll 2008; Asian Development Bank 2013, p 70), and local knowledge should be considered together with scientific knowledge in flood forecasting and early warning. One of the SGP studies focused explicitly on adaptation strategies to reduce risk from flash floods.

Building resilience to flash floods in the Poiqu/Bhotekoshi/Sunkoshi basin

The study by Khanal et al. on flash floods in the Poiqu/Bhotekoshi/Sunkoshi watershed not only looked at future simulation of flash floods under different climate change scenarios, discussed in a previous section, but also at the historical impact of flash floods, the socioeconomic vulnerability of exposed communities, and adaptation strategies for flash flood risk reduction. As the study recognized, upstream flash floods caused by extremely heavy precipitation, glacial lake outbursts (GLOFs), or landslide dam outbursts (LDOFs) can pose a severe threat to downstream life and property. Both hazard occurrence and risk are expected to increase as a result of both climate change and population growth, which is leading to increased exposure of communities.

The study used field observation, key informant interviews, and focus group discussions, including a community-based flood hazard mapping exercise, to gather information about the impact of past flood events and present day vulnerability. Information was also collected on socioeconomic conditions, indigenous knowledge, and local practices. The data were used to assess overall livelihood vulnerability and the adaptive capacity of individual households.

The annual loss from flooding in the study area is very high compared to that from other hazards. Six of 17 settlements on the China side of the border are exposed to flash flood risk from upstream GLOFs. On the Nepal side, 30 settlements are at risk from flash floods, and 10% of households either live or own property in flood-prone areas. The value of flood risk on the Nepal side was estimated to be more than USD 224 million, much of it in infrastructure, including roads and hydropower plants. Overall livelihood vulnerability was relatively high in the poorly accessible northern areas of the Balephi and Bhotekoshi watersheds in Nepal. These more susceptible communities also had a lower adaptive capacity.

Local people were aware of the causes of the different types of flash floods and reported several indicators that they used to forecast such events. They had developed a number of strategies to reduce the risks of flash flooding including forestation of barren land with local tree species, sowing of grass, regulation of grazing activities, gully control and diversion of water, and construction of dykes and embankments, but these are not sufficient to prevent catastrophic events.

The study concluded that the risk from flash floods remains high, and risk reduction should be addressed through development of an active monitoring and early warning system. Recommended sites for monitoring were identified taking into account the location of settlements and major infrastructural facilities determined to be at risk. Bilateral cooperation with a focus on information sharing across the border will be especially important.

Supporting Mechanisms for Adaptation

Adaptation and building resilience through a holistic basin-level approach

Adaptation to climate change and building resilience lie at the heart of the current discourse on adaptation. The impacts of climate change will be felt in a variety of ways, directly through changes in temperature and precipitation, and indirectly through changes related to cloud cover, glacial cover, and permafrost, for example. The hydrological cycle plays a central role in mediating climate change impacts on ecosystems and the people who live within them, through changes in water availability as well as in extreme events like floods, droughts, and storms (Keskinen et al. 2010). But climate change is not taking place in isolation, and climate change adaptation is a dynamic, development-oriented process that should also consider the broader socio-political context (Keskinen et al. 2010). Climate impacts are mediated by the physical and socioeconomic context of the area in which they take place, and they are only one effect among many other drivers of change. At the same time, the hydrological system in a river basin is itself complex, affected by physiographic characteristics, climate, land use, and infrastructure. Thus it is important to focus on an area-based adaptation approach to complement the sector-based approaches that tend to dominate present thinking. This more holistic, basin-based, approach to adaptation matches the move towards integrated management of the water resources in a basin (GWP 2009). Climate change adaptation should broaden its view to consider the environmental and socioeconomic context at different spatial and temporal scales. One way of capturing the more holistic context of change is to ask farmers' and communities about their actual experience. Information from farmers can help to reduce the complexity of the system and can also provide useful information where climate data is scarce. At the same time, information about current adaptation and coping strategies helps to identify what is important to farmers in their specific context, to assess what works and what does not work, and to provide a basis for future learning. One of the SGP papers looked specifically at the question of peoples' perceptions and adaptation approaches.

Yang et al. studied people's perceptions of climate variability and change, and their efforts to cope with the impacts, in the Koshi basin in Nepal. The study was based on primary information obtained through focus group discussions and key informant interviews in three ecological zones – mountains, hills, and Terai (lowlands). People in the region have been experiencing increasing temperatures and greater variability in precipitation, with impacts in different sectors that affect their livelihood options including increasing scarcity of water, increasing risk of flash floods, decline in yield of agricultural crops, shifting of eco-zones to higher elevations, loss of biodiversity, and increasing incidence of disease.

Several interesting points emerge from the paper. First, there are some commonalities in people's perception regarding climate change. For example, local people in all three ecological belts considered that the number of hot days had increased during the last 30 years. Heat waves in the plains occurred earlier, and cold waves in the mountains and plains later, than previously. The intensity and frequency of snowfall, frost, hail, and dew were also considered to have decreased. These changes are more or less consistent with meteorological data patterns. However, the general perception that winter precipitation had decreased did not match the climate data, which showed a slight increase. In this case the perception probably reflects reduced availability, possibly as a result of increased demand. People had noticed a number of impacts such as dried up springs; increase in pests and disease; disappearance of bird species; changes in flowering time, and cultivation of fruit trees shifting to higher elevations.

Although the perceived changes were similar, the responses were somewhat different in the different agro-climatic locations and more context specific. Adaptation measures to cope with water scarcity included planting trees around springs, revitalizing rotational irrigation schemes, building canals (pynes) and plastic-lined ponds for irrigation, and introducing sprinkler irrigation. Agricultural measures included changing cropping patterns and the cropping calendar, using failed crops as fodder, introducing crops with a shorter growing period, scattering ash or cow urine and using fire to kill pests, introducing integrated pest management, and constructing storage rooms to reduce post-harvest losses. Conservation of forests and biodiversity had also been addressed through conservation of marginal land, planting of different species, and community management and conservation of forest.

Adaptation and building resilience through incentive-based mechanisms for ecosystem services

Well-functioning ecosystems provide many different kinds of services that contribute to wellbeing and economic prosperity, including reliable and clean flows of water, timber and other natural resources, productive soil, relatively predictable weather, and sites for recreation. Today, however, many ecosystems and the services they provide are under increasing pressure. The fact that these services are often not valued or considered in decision-making is a key factor affecting ecosystem loss and degradation. As day-to-day decisions often focus on immediate financial returns, many ecosystem structures and functions are being fundamentally undercut. Against this background, there has been a growing interest in mechanisms that can better recognize the value of ecosystem services in practice. Such incentive schemes are built upon two simple premises: that ecosystem services have quantitable economic value, and that this value can be used to entice investment in restoration and maintenance (Katoomba 2008, DEFRA 2011). Payments for ecosystem services (PES) constitutes one such innovative approach (Tacconi 2012). According to Van Noordwijk (2012), there are three conditions for a functioning PES system: commodification of a defined ecosystem service (e.g., water); compensation for opportunities foregone; and co-investment in environmental stewardship. PES provides some key opportunities to link those involved in 'supplying' ecosystem services more closely with those benefiting from the same ecosystem services, and in doing so, potentially provide cost-effective ways of developing new streams of financing. This requires considerable innovation as, for many ecosystem services, both 'suppliers' and 'beneficiaries' may not currently be aware of their roles (DEFRA 2011).

In the context of the HKH region, providing incentives for the maintenance of ecosystem services takes on an additional dimension. In many cases services are provided upstream in remote hill and mountain areas inhabited by poor, poorly informed, and often marginalized communities for the benefit of people living hundreds of kilometres downstream, often in a different country. This is especially true for water. The great rivers that have their origins in the mountains provide water for agricultural, domestic, and industrial use, and production of energy from hydropower. But they are also a source of devastating floods, and the massive loads of silt and stones that they transport downstream can fill reservoirs and irrigation facilities, overwhelm settlements, and devastate agricultural land. The quality and quantity of water transported downstream is strongly affected by upstream activities, including land use change, loss (or gain) of natural water storage potential, use of water for irrigation, and construction of dams and reservoirs. Mechanisms are needed to ensure that essential services are maintained upstream, including compensating upstream communities for the services that they maintain. One of the SGP projects looked at an important aspect of this problem: benefit-sharing in hydropower projects.

Benefit sharing in hydropower projects

Historically, the discussions on water storage projects have focused on their immediate social and environmental impacts, mainly land submergence and population resettlement. However, in the HKH region, measures to overcome longer-term environmental barriers to the development of water storage projects may be just as important. For example, sedimentation continues to be one of the greatest challenges facing existing water storage reservoirs, both large and small, and the problem is likely to increase with climate change. Sustainability is of importance to hydropower because project operation requires management of the catchment area to maintain hydrological quality and minimize erosion that may lead to siltation of the reservoir. These concerns have led to the creation of benefit-sharing mechanisms in which both upstream and downstream communities receive compensation from hydropower developers and operators. In particular, hydropower offers the opportunity for 'payment for ecosystem services' (PES) schemes under which communities or landowners in the catchments could receive payments in return for land management practices appropriate for long-term operation of the hydropower project. The study by Pant et al. examined two projects, one in Nepal (the Kulekhani hydropower project) and the other in the state of Sikkim in India (the Teesta V hydropower project) in order to assess how benefit sharing schemes have been applied in practice, and to develop recommendations for future schemes.

The study gathered data from both primary and secondary sources. Primary data was obtained from a field study involving household surveys, key informant interviews, and focus group discussions; and secondary data was obtained from government documents, study reports, and existing research studies.

The mechanism for transfer of funds to the community from the operator of the Kulekhani storage reservoir type hydropower plant was based on a government benefit-sharing scheme with 12% of the royalties generated transferred to the district in which the powerhouse is situated; 38% among all the districts in the region, and an additional 1% to the directly affected village development committee (VDC) areas for rural electrification. In the Teesta hydropower project, the power developer pays 12% of the benefits as royalties to the state government and 1% to the community in the form of free power earmarked for local area development. The community also receives 1% from the state government's royalties. The policy aims to provide a higher living standard to 'project-affected people' by making them long-term beneficiaries and stakeholders in the project, and the revenue is expected to provide resources to support activities for income generation and infrastructure development This is achieved in Teesta V through provision of basic amenities, work opportunities, and vocational training.

The research showed that in both areas the royalty payments were mainly treated as a fund for development needs and did not promote conservation of the watershed, nor properly compensate residents for negative impacts from the hydropower projects. In Kulekhani the preference was for road construction, which can result in environmental damage and increased siltation. There is no legally binding component in the royalty for performance-based environmental service payments, even though upstream residents are responsible for providing environmental services to the hydropower project through appropriate land management. In Teesta V, respondents considered that benefit-sharing was non-uniform and mainly in the form of infrastructure development (roads, electrification, and others), as well as direct compensation to affected households. There was no attempt to address issues created by the project, for example noise, pollution, and loss of natural resources, or to pay for maintenance of environmental services.

The study noted that hydropower royalties should be used to compensate activities that maintain the long-term sustainability of the watershed and the livelihoods of the population living in the vicinity of the hydropower projects. The ultimate rationale for benefit sharing should be based on an incentive mechanism for promoting better watershed management, with payments conditional on appropriate land use, which is monitored and verified. There is a need for uniform policy and legislation on benefit sharing encompassing compensation, rehabilitation, acquisition of property, and royalty sharing, with clarity on the purpose of royalty provision, and support in the form of a monitoring and verification protocol. Clear procedures need to be developed for royalty sharing to ensure that benefit allocation is equitable; while the roles and responsibilities of local communities, in particular provision of environmental services, need to be associated with the benefit they receive. Community participation is essential throughout the entire project development and implementation process.

Policy Implications and Recommendations

The findings of the SGP projects have some important implications for policy; the major points are summarized in the following.

Improved water management practices

- Options for increasing upstream water storage should be investigated: surface runoff during the wet season could be used to augment the lean season flow. In the Langtang and Kafni sub-basins, there may be a potential for harnessing and storing glacial and snow meltwater, and a similar potential may also exist at high altitudes in other catchments. Such approaches should be rigorously researched to identify options that are agreed upon by the co-riparian countries.
- Ensuring long-term water resource sustainability in rural microwatersheds in the Himalayas requires attention in terms of investments, management and governance. Further understanding from scientific investigations carried out on the hydrology and geohydrology of the mountain watersheds is required to inform such actions.

- In some parts of the Indrawati sub-basin, sloping land is being cultivated without terraces. In view of the increasing water scarcity, it is important to raise awareness among farmers here and elsewhere in the HKH of the benefits of levelling land, and the way in which terracing helps to reduce erosion and store water in the fields.
- In the Yellow River basin, the water stress situation will become more stressed under future climate scenarios, and the need to address water scarcity constraints by limiting new development of irrigation areas should be considered.
- The impacts of climate change on the hydrological regime will be different from east to west and upstream to downstream and will depend on the relative contributions of rainfall (monsoon and westerly), snowmelt, ice melt, and groundwater to the overall river flow. The impacts of climate change will also have seasonal differences. In general, studies suggest that the annual water availability will increase with more increase in the wet season but the possibility of some decreases in the dry season. The seasonal differences will pose some challenges to future water resources management. Strategies to address climate impacts should incorporate this diversity.
- Large changes in the seasonality of precipitation and water availability in the region are expected by the 2050s. Both the likely strengthening of the spatial and temporal dimensions of water availability, and the likely increase in water-related risk, point to the opportunities for water-based cooperative development and management of the large basins.

Improved agricultural practices

- Studies of water availability and climate change are severely limited by the lack of good hydrometeorological and agricultural data in the region. Mechanisms for collection and sharing of regional hydrometeorological and agricultural information need to be strengthened.
- Agricultural practices will need to adapt to the changing conditions in timing and amount of precipitation, and temperatures. In order to determine optimum planting, transplanting, and harvesting dates, farmers need both seasonal forecasts and up-to-date weather information. Governments should provide long-term forecasts and continuous hydrometeorological forecast information direct to farmers based on regional and local assessments.
- There are no single viable generic solutions for sustaining crop yield and ensuring food security in the GBM basin (and in other basins) under climate change. It will be necessary to adopt a context-specific mix of policy interventions and preferred routes for water resources development at multiple spatial scales including a number of the elements outlined in these sections.
- The future climate and water situation are likely to have disruptive effects on agricultural production; investment in agricultural research and extension should be increased to help farmers meet the challenges. Research is needed to identify new climate resilient short duration variety crops, to improve knowledge on likely impacts on specific crops at specific locations, and to identify water efficient approaches including timing of agricultural

activities. Improved agricultural extension is needed to help farmers' understand the need for rapid adaptation in terms of cropping practices, crop diversification, and irrigation, and to strengthen farmers knowledge networks to raise awareness.

Flood risk management

- Lead time is very important in flood warning so that loss of life and property can be avoided. In transboundary basins like the Poiqu/Bhotekoshi/Sunkoshi, mutual cooperation between the riparian countries is required to support timely sharing of information and manage flood risk. Active monitoring and early warning systems should be installed downstream of critical areas and glacial lakes that take into account the location of settlements and major infrastructural facilities that are at risk.
- Approaches to support resilience building at community level should be explored; these include measures to reduce exposure (e.g., zoning regulations), to reduce vulnerability (e.g., awareness building), and to enhance coping capacities (e.g., early warning systems). Knowledge institutions can help in identifying and evaluating the suitability of such measures for specific communities, and in developing institutional mechanisms for their implementation in those communities.

Holistic basin-level approach to climate-change adaptation

- Climate change risk management approaches and strategies and climate resilient planning tend to focus predominantly on sectoral approaches. This ignores the spatial variation in the types, magnitude, and intensity of climate change and its impacts in different eco-zones. Spatial variation should also be considered when formulating national policies and strategies for climate change risk management. This is along the lines of the integrated river basin management approach, which has been considered by the IPCC to be an adaptive measure for climate-change impacts.

Benefit sharing to support environmental management

- Royalties from hydropower projects are often seen as a fund for development, and may even be used for activities that are harmful for both the watershed and power production. Allocation of hydropower royalties should be based on the compensation of activities that maintain the long-term sustainability of the watershed and the livelihoods of the population living in the vicinity of the hydropower projects. The ultimate rationale for benefit sharing should be based on an incentive mechanism for promoting better watershed management such that payments are conditional to appropriate land use which is monitored and verified. Uniform policies and legislation on benefit sharing should be developed that have clarity on the purpose of royalty provision, and support provided in the form of a monitoring and verification protocol. Clear procedures need to be developed for royalty sharing to ensure that benefit allocation is equitable; while the roles and responsibilities of local communities, in particular the provision of ecosystem services, need to be associated with the benefit they receive.

The Way Forward

The Hindu Kush Himalayan countries have shown a quite impressive capacity for developing policies, plans, and strategies. National water resources strategies, akin to integrated water resources management at a national level, have been prepared in Bangladesh and Nepal, and action plans have been developed for implementation. India has also recently undertaken rigorous exercises in planning for water and hazards in preparation for its 12th periodic plan. However, implementation of these plans and policies has left much to be desired.

New knowledge on regional solutions to regional problems related to water and hazards – generated by knowledge institutions in the region itself may help. Capacity building of knowledge institutions to support scientific and policy-relevant research, and a regional network of those institutions to support collaborative research, may also help. Developing a participatory and cooperative process among knowledge institutions from different countries in the Hindu Kush Himalayan region working on common problems of regional concern may also help to promote regional water cooperation – which is so vital for solutions of water-related problems.

The Small Grants Programme has helped to add to the quantum of knowledge essential for managing water resources and water-related hazards in the region. It has shown how climate and hydrological models can be used to assess potential future climate-change impacts. It has demonstrated how modelling exercises can also be used to derive pointers for policy to support improvements in agricultural and water management practices and manage water-related hazards. And, it has demonstrated how socioeconomic studies based on field study data can be used to arrive at ways of improving supporting mechanisms for climate-change adaptation. However, these are only a small contribution to a much bigger task of water and development in the Hindu Kush Himalayan region. There are many other water-related challenges waiting to be addressed in the Hindu Kush Himalayas: challenges related to social and environmental aspects of water use for energy generation, to the proper use of surface and ground water for irrigation, to the impact of population growth and industrial activities on the health of river systems, and to the protection of aquifers that sustain mountain springs, among others.

Next, since there are wide differences in research capabilities within the knowledge institutions in the region, the value added through capacity building has been a focus of attention in the activities of the grantees in the first phase of the programme. Explicit capacity-building activities included exchange visits, workshops, and training programmes organized in China (Yunnan), India (Sikkim), Nepal, and Pakistan in the course of implementation of the SGP projects. For example, the training programme led by the China National Committee on Irrigation and Drainage organized at the Pakistan National University of Science and Technology under the SGP project helped build research capacity in stochastic hydrological analysis substantially in a structured manner. And the training Programme by CEGIS in Nepal on seasonal and medium-range weather forecasting, organized under the SGP project on climate change impacts on water and agriculture in Bangladesh and Nepal, helped broaden the awareness and knowledge of scientists on weather forecasting. Training programmes have also helped scientists from other countries not directly involved in an SGP project prepare for future research. For example, Afghan scientists from Kabul University participated in the training programme for the SGP project led by the faculty and researchers at Kathmandu University on the study of hydrological regimes in glacier-dependent river basins.

Finally, the Small Grants Program has successfully developed a mechanism through which knowledge institutions from two or more countries could collaborate on policy-relevant research across borders. Probably, the most valuable long-term impact of the programme will be the regional networks of knowledge institutions across borders that it has helped to develop for collaborative research. Such a network will have important implications for regional cooperation on water resources development and management in the region. We hope that these networks, and the capacity built during the execution of the programme, will help in finding regional solutions to regional problems in the Hindu Kush Himalayas as the collaboration moves from capacity development to joint problem solving.

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2

Research Papers

Estimation of Discharge from Glacierized River Basins: Case Studies from Langtang Valley, Nepal and Kafni River Basin, India

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Abstract

A projection was made of future discharge from two glacierized river basins – the Langtang River basin in Nepal and the Kafni River basin in India – using a positive degree day (PDD) model. Input data for the model were precipitation and temperature, which were validated with observed values and projected for 2010 to 2050. The PDD model was able to reproduce the hydrological processes fairly well with a coefficient of determination of 0.82 after calibration. The model outputs showed an increase in discharge from the Langtang River basin from 2010 to 2050, with pronounced interannual variability. Discharge was also projected to increase from the Kafni River basin, but only until 2040, after which the discharge gradually decreased. A sensitivity analysis performed for the Langtang River basin for the period 2040 to 2050 showed that the sensitivity of discharge to changes in temperature was higher than the sensitivity to changes in precipitation, and that the sensitivity to changes in snow/ice cover area was relatively low. Snow and ice contributed an average of 47% of total discharge in the Langtang River basin over the period 2010–2050, with a slightly decreasing proportion over time. The river discharge in the Kafni River basin was rainfall dominated (81%); the contribution of both rainfall and snow/ice melt to discharge was projected to increase under the future climate scenario. Overall, the PDD model performed well and was able to capture the glacio-hydrological dynamics of the glacierized river basins and should be considered as a promising tool for understanding the hydrology of such basins.

Introduction

The Himalayas play a crucial role in the surface and sub-surface hydrology of the South Asian region, and the significant snow and glacier storage contribute to the provision of essential freshwater for people living downstream. The snow and ice melt from glaciers make a significant contribution to basin discharge and contribute to the water availability of the entire Himalayan region. The recent warming and increase in precipitation variability are likely to affect the Himalayan glaciers and related hydrology significantly in most of the Himalayan river basins (Cruz et al. 2007; Immerzeel et al. 2009). Accurate projection of future discharge under the climate change perspective is essential to understand the likely changes in glacio-hydrology in the Himalayan catchments. It is important to assess the hydrological response to the changing climate using appropriate hydrological modelling in order to estimate the future water supply, which affects more than one-sixth of the global population in the downstream river basins who rely on water from glacier and snow melt in the dry season. Application of snow and ice melt hydrological modelling in the glacierized river basins of the Himalayas is relatively new and studies are limited. Several empirical relations such as ablation gradient and snow melt estimation (Racoviteanu et al. 2013), critical air temperature (Sharma et al. 2000), and degree day factor (Immerzeel et al. 2010) have been formulated to estimate the snow and ice melt contribution of the Himalayan glaciers. Kayastha et al. (2005) studied ice melt for different thicknesses of debris on the Khumbu Glacier using a positive degree-day (PDD) model. Similarly, Immerzeel et al. (2012) used the enhanced degree-day factor for debris-covered glaciers to reproduce the ice-melt processes. The PDD model is a simple but reasonable method for estimating melting in the Himalayas that requires minimal field data.

In the present study, a PDD model (Kayastha et al. 2005) was used to estimate snow and ice melt and its relative contribution to basin runoff based on mean monthly air temperature and precipitation. The PDD model described by Kayastha et al. (2005) was refined by adding infiltration, baseflow, and evaporation components. The main objective of the research was to simulate the monthly discharge under present and future climate scenarios from the glacierized Langtang and Kafni River basins using the revised PDD model.

Methods

Study area

The study was carried out in two glacierized river basins: the Langtang River basin in Rasuwa district, Nepal (Figure 5a) and the Kafni River basin in northwest India in Bageshwar, Uttarakhand (Figure 5b). The Langtang River basin has a total area of 353.6 km^2 of which 39% (137.5 km^2) is covered by glaciers (debris-covered and clean ice) and 61% (216.1 km^2) by rock and vegetation. The elevation ranges from 3,652 to 7,215 masl. The Kafni River basin has a total area of 28.6 km^2 of which 14% (4.14 km^2) is glacierized (debris-covered and clean ice), and 86% (24.45 km^2) is covered by rock and vegetation. The elevation ranges from 3,930 to 5,447 masl. The two river basins were selected because of their different precipitation characteristics. The major physical characteristics of the basins are presented in Table 8.

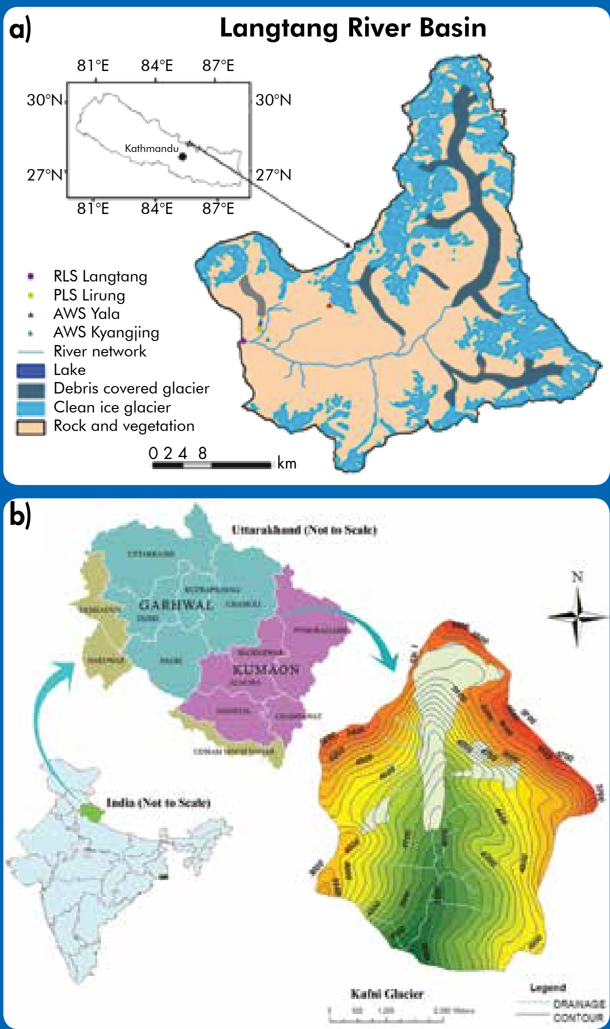
Model setup and data

A PDD model was used to estimate and project the discharge from the selected river basins. The model is based on the positive degree days calculated from monthly mean temperature

Table 8: **Main physical characteristics of the investigated basins**

	Langtang River basin	Kafni River basin
Location	Langtang Valley, Rasuwa, Nepal	Bageshwar, Uttarakhand, India
Elevation (masl)	3,652–7,215	3,930–5,447
Latitude	28°08′–28°23′	30°13′–30°16′
Longitude	85°35′–85°48′	80°2′–80°5′
Area (km^2)	353.59	28.59
Glacier proportion of area (%)	39	14
Mean annual precipitation (mm)	674 (1988–2007)	1,399 (1961–2002)
Mean annual temperature (°C)	3.2 (1988–2007)	3.7 (1961–2002)

Figure 5: **Location and maps of the Langtang River basin, Nepal (a) and Kafni River basin, India (b)**



(Braithwaite 1985). In this study, we simulated monthly discharge rather than daily discharge because monthly discharge simulated by a PDD model in previous studies of the Langtang River basin (Kayastha et al. 2005) showed similar results in monthly and daily simulation, and other studies on glacio-hydrological modelling in the Nepalese Himalayas also showed no significant difference between daily and monthly simulations (Nepal et al. 2013). The snow and ice ablation from glacial and rocky areas was calculated by multiplying the monthly PDDs with the PDD factor (DDF). The degree day factor for snow and ice was derived from the summer values obtained on Glacier AX010 in east Nepal and the Yala Glacier in the Langtang valley (Kayastha et al. 2003, 2000). The ice melt under debris was computed as explained by Kayastha et al. (2000). The method requires DDF for ice ablation and a relation between degree-day factor and debris properties, namely, the ratio of degree-day factor for a given debris thickness (kd) to the factor for ice ablation (kb), and the ratio of thermal resistance of debris (R) to thermal resistance for critical debris thickness (Rc) (Figure 6 in Kayastha et al. 2000). The relation between DDF and debris properties was obtained by field observation carried out on a debris-covered part of the Lirung Glacier for a short period in June 1995 (Rana et al. 1996). The calculated value of kd/kb of 0.54 was used for the Langtang River basin. Since the thickness of debris is thicker on the lower part of the glacier, different values of kd/kb were used for the lower and higher parts: namely 0.50 for elevation bands 4,100–4,300 masl, and 0.58 for the remaining bands, giving a mean of 0.54. This means that 8% more ice will melt under the thinner debris layer. The monthly ice melt under a debris layer was calculated using the following equation:

$$\text{Monthly ice melt} = PDD * k_d/k_b * DDF \qquad (1)$$

The total monthly discharge was estimated by adding the rainfall; snow and ice melt from glacier area; snow melt from rock and vegetation area; ice melt under debris; and baseflow and subtracting the potential evapotranspiration (PET) and infiltration. The parameters and factors used in the study are shown in Table 9. A baseflow of 1.94 $m^3 s^{-1}$ was estimated for the Langtang River by plotting a hydrograph from the observed monthly discharge data (1993–2006) which was derived by applying the Baseflow Separation Method II described in Subramanya (2010). A baseflow of 0.3 $m^3 s^{-1}$ was assumed for the Kafni River. According to the Blaney-Criddle formula (Subramanya 2010), the PET in a crop-growing season is given by

$$PET = 2.54\ K\ F$$

and

$$F = \Sigma\ P_h\ T_f / 100 \qquad (2)$$

where PET is in cm, K is an empirical coefficient depending on the type of crop, F is the sum of monthly consumptive use factors for the period, P_h is the monthly percentage of annual day-time hours and depends on the latitude, and T_f is the mean monthly temperature in °C. The value of K depends on the month and locality, a value of 0.8 for natural vegetation was used in the studied basins. The monthly sunshine hours at 30° latitude were used for both basins.

Table 9: **Parameters and factors used in the model**

Parameter	Description	Value
k_s	Degree day factor for snow ablation	4.0 – 10.0 mm d-1°C-1 (up to 5,000 m) 7.5 – 13.5 mm d-1°C-1 (above 5,000 m)
k_b	Degree day factor for ice ablation	5.0 – 11.0 mm d-1°C-1 (up to 5,000 m) 6.5 – 12.5 mm d-1°C-1 (above 5,000 m)
k_d/k_b	Ratio of degree day factor for debris covered ice to degree day factor for bare ice	0.5 – 0.58
Low PDD factor	Positive degree days correction factor	0.15 (Mar – Aug); 0.6 (Sept – Oct)
Infiltration	Infiltration from soil	3 mm/d (Sakai et al. 2004)
Base flow	Monthly mean base flow	1.94 m^3/s (Langtang River basin) 0.3 m^3/s (Kafni River basin)

Table 10: **The RCM data used for the Langtang and Kafni river basins**

Basin	RCM	Horizontal resolution (km)	Scenario	Analyzed period	Institution	Parameters used
Langtang River basin, Nepal	Weather Research and Forecasting (WRF)	12	RCP4.5	1996–2050	Bjerknes Center for Climate Research (BCCR)	Temperature and precipitation
Kafni River basin, India	Providing Regional Climates for Impacts Studies (PRECIS)	50	A1B	1961–2050	Indian Institute of Tropical Meteorology (IITM)	Temperature and precipitation

Observed climatic data (precipitation and temperature) for the Langtang basin (Kyangjing station) for 1988 to 2007 were acquired from the Department of Hydrology and Meteorology (DHM), Nepal. Observed climatic data (precipitation and temperature) were obtained from the Indian Meteorological Department (http://www.imdaws.com) for the Bageshwar station from 1961 to 2002 and extrapolated to the Kafni River basin. A temperature lapse rate of 6°C km^{-1} was used for temperature extrapolation; precipitation was increased by a factor of +20%. Regional climate model (RCM) data were used for the future climate projection. Different RCMs were used for the two basins: the Weather Research and Forecasting (WRF) model for Langtang and the Providing Regional Climates for Impact Studies (PRECIS) model for Kafni, based upon the availability of data (Table 10).

RCM data analysis

The RCM output was corrected for bias. Temperature bias correction was performed using the equation given by Cheng and Steenburgh (2007) for the Langtang River basin (equation 3) and the equation given by Terink et al. (2010) for the Kafni River basin (equation 4). Precipitation bias correction for both river basins was performed using the equation given by Nazrul (2009) (equation 5).

$$T^* = (T_{mod} - T_{mod}) * (SD\ (T_{obs})\ /\ SD\ (T_{mod})) + T_{obs} \quad (3)$$

$$T^* = T_{obs} + SD\ (T_{obs})/SD\ (T_{mod})\ (T_{mod} - T_{obs}) + (T_{obs} - T_{mod}) \quad (4)$$

$$P^* = \alpha\ Pmod + \beta \quad (5)$$

Where T* and P* are bias corrected temperature and precipitation; T_{obs} and T_{mod} are the observed and model monthly temperature; the over bar represents mean values; SD is the standard deviation; and α is the slope and β the intercept of the regression line obtained from a scatter plot of precipitation from model estimation and observation for the considered period.

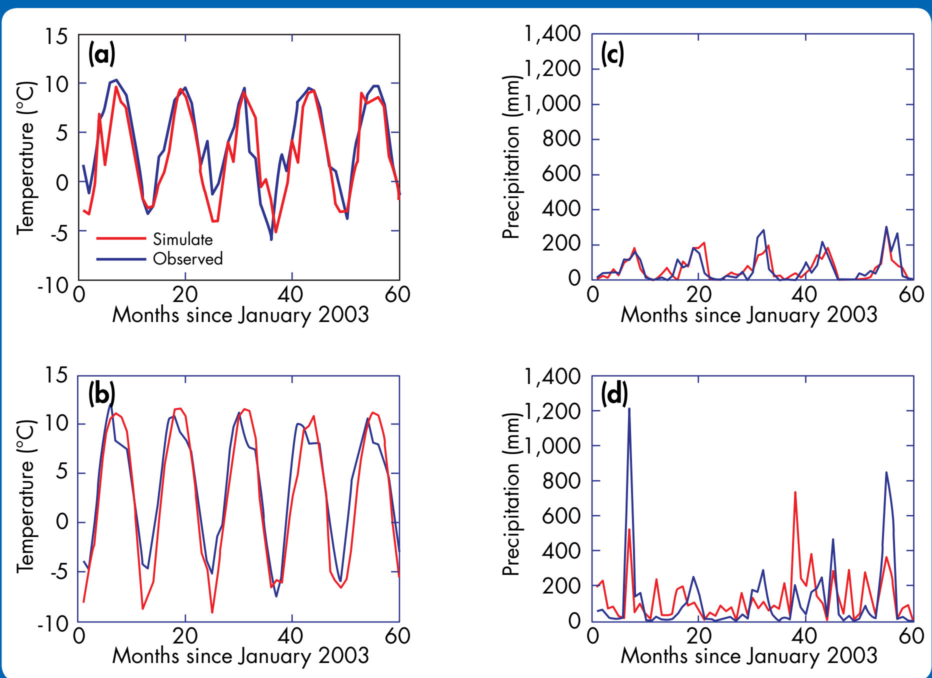
The bias corrected model data were compared with the observed data. The results are shown in Figure 6.

Results and Discussion

General climatic conditions and future climate projection

The observed temperature and precipitation data from 1988 to 2007 for Kyangjing station in the Langtang Valley showed a positive trend with pronounced inter-annual variability. The observed annual temperature data for the Kafni River basin from 1961 to 2002 also showed a positive trend (0.012°C $year^{-1}$), but precipitation showed a decreasing trend (-8.25 mm $year^{-1}$). The projected annual temperature and precipitation from 2010 to 2050 in the wet and dry

Figure 6: **Observed and simulated monthly temperature (left panel) and precipitation (right panel) in Langtang River basin (a, b) and Kafni River basin (c, d)**



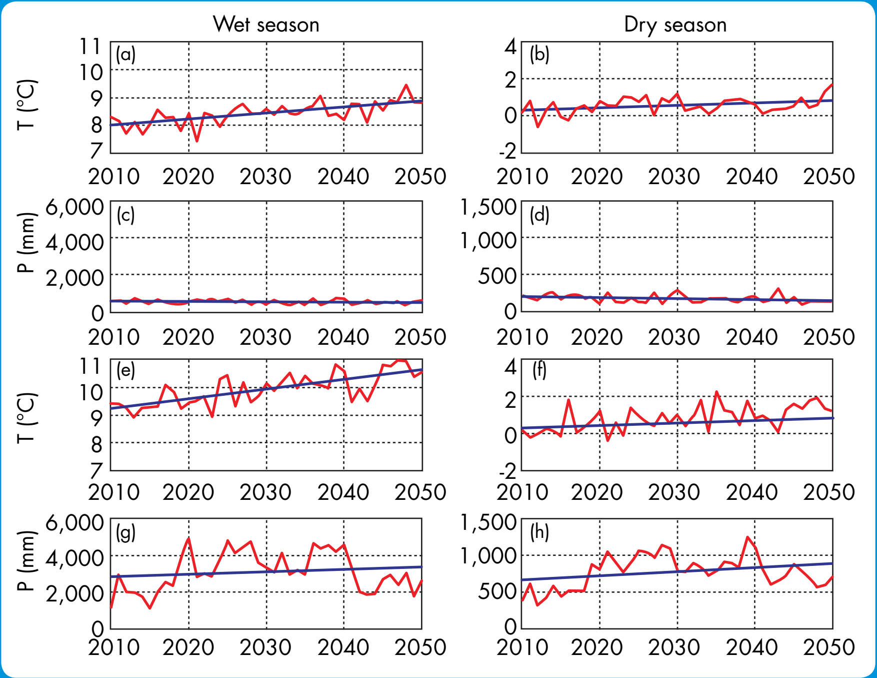
seasons in the Langtang and Kafni River basins is shown in Figure 7. In Langtang, the projected temperature shows an increasing trend of 0.015°C year^{-1} and the projected precipitation a slight negative trend of -1.903 mm year^{-1}, with the same trend in both the wet (June–September) and dry (October–May) seasons. In the Kafni basin, the projected trends were positive for both temperature (0.033°C year^{-1}) and precipitation (18.50 mm year^{-1}) and in both wet and dry seasons (Figure 7c-d).

The Mann-Kendall test was used to test the significance of the precipitation and temperature trends. Neither trend was statistically significant at a 95% confidence level.

Model validation and calibration

Model validation and calibration were performed for the Langtang River basin only, due to the unavailability of observed discharge data for the Kafni River basin; temperature and precipitation data for 2001 and 2005 were not used due to inconsistency in data and data quality. The mean monthly model outputs during the calibration (1995–2003) and validation (2004 and 2006) periods in the Langtang River basin are shown in Figure 8. For the model calibration, positive degree days and positive degree day factors were tuned for the best results. During the calibration period, the monthly observed and simulated low flow for January to March were fairly comparable, the late pre-monsoon and early monsoon from May to June

Figure 7: **Annual projected temperature and precipitation from 2010 to 2050 in the Langtang River basin (a–d) and the Kafni River basin (e–h) for wet season (left panel) and dry season (right panel)**



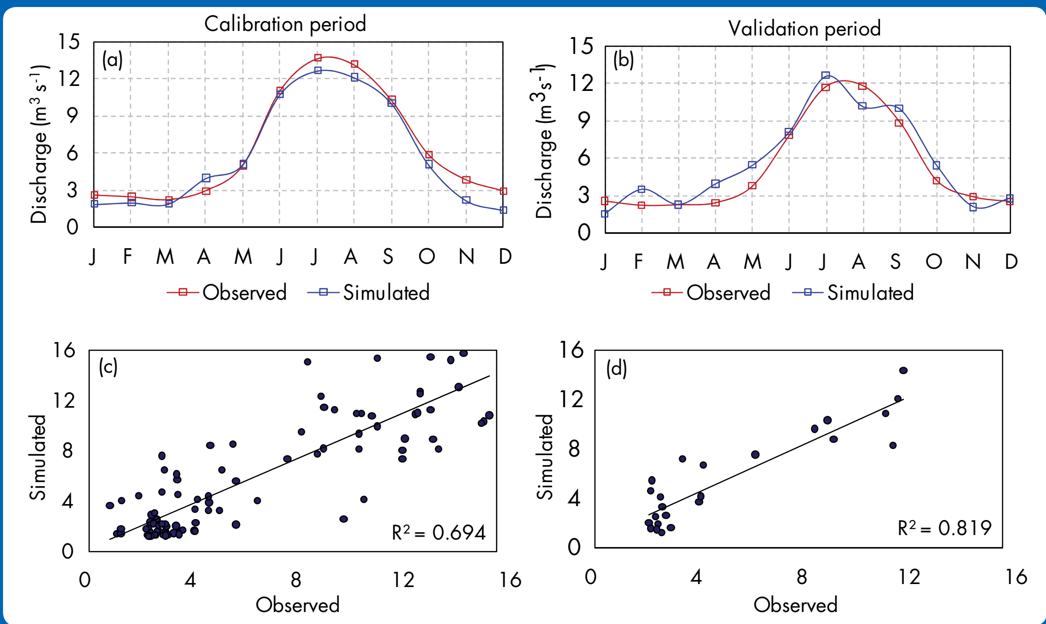
was captured well by the model, but there was some under prediction from July to December (monsoon and post-monsoon). During the validation period, low flow was overestimated by the model, early monsoon (June–July) was reproduced well, although with a slight overestimation in July, the monsoonal peak in August was underestimated, and late monsoon/post-monsoon in September and October were again slightly overestimated. The monthly scatter plots of observed versus simulated discharge for the calibration (Figure 8c) and validation (Figure 8d) periods show a better coefficient of determination (R^2) during the validation than the calibration periods, indicating that the model performed well after calibration.

Discharge projection

The projected annual discharge from the Langtang River basin showed a positive trend of 0.003 m^3s^{-1} $year^{-1}$ over the period 2010 to 2050. In order to investigate the seasonal discharge, the monthly discharge was divided into wet (June–September) and dry (October–May) seasons. The results show an increasing trend in the wet season (0.024 m^3s^{-1} $year^{-1}$); and slightly decreasing trend in the dry season (-0.005 m^3s^{-1} $year^{-1}$) (Figure 9). The negative trend in the dry season may be the result of decreasing precipitation in this season (-1.02 mm $year^{-1}$) (Figure 7d).

The projected annual discharge from the Kafni River basin also showed an overall positive trend (0.012 m^3 $s^{-1}year^{-1}$) consistent with the increasing precipitation, but with a marked

Figure 8: **Comparison of observed (red) and simulated (blue) mean monthly discharge in the Langtang River basin in the calibration (1995–2003) and validation (2004–2006) periods (top panel). Scatter plots for monthly observed and simulated data from 1995–2003 for the calibration and validation periods (bottom panel)**



decrease after 2040, which may be due to decreasing precipitation in the same period. The river discharge showed a similar rate of increase in both wet and dry seasons (wet season 0.028 m^3s^{-1} $year^{-1}$, dry season 0.003 m^3s^{-1} $year^{-1}$), consistent with the change in precipitation (Figure 7h).

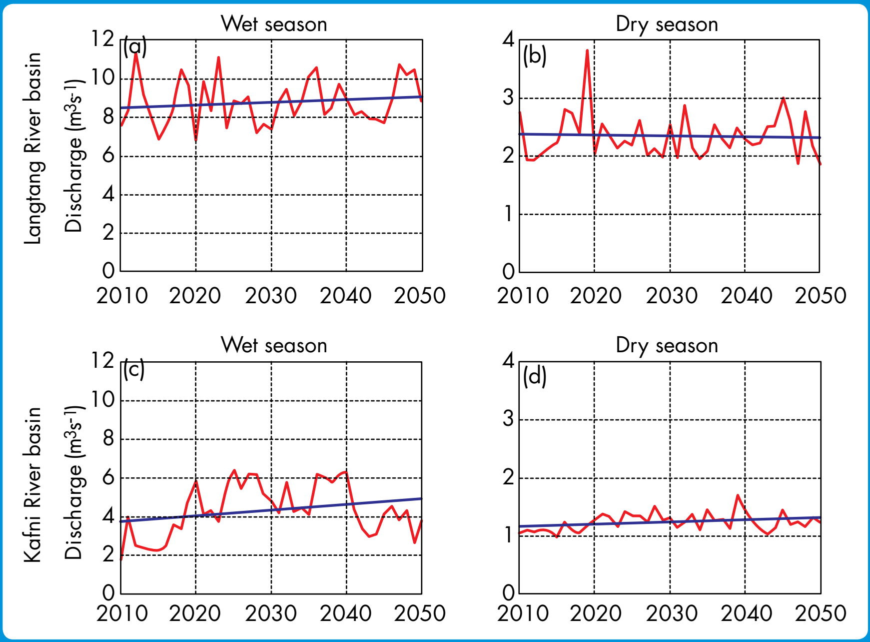
Sensitivity analysis

Sensitivity analysis was performed for temperature, precipitation, and snow cover in the Langtang River basin from 2040 to 2050 using different approaches. (Sensitivity analysis was not done for the Kafni River basin.) The results are summarized in Table 11 and shown in Figure 10. There were some noticeable changes with respect to the default control run. In particular, the change in discharge with change in temperature was higher than that

Table 11: **Change in discharge for different sensitivity experiments**

Parameter	Experiment	Change in discharge (%)
Temperature	-1°C	-5.68
	+1°C	+11.35
	-2°C	-15.08
	+2°C	+26.72
Precipitation	+10%	+0.36
	-10%	-3.19
	+20%	+9.39
	-20%	-7.11
Snow/ice cover	-30%	-0.70
	-50%	-2.09

Figure 9: **Seasonal future discharge projection for the Langtang River basin (a, b) from 2010–2050, and the Kafni River basin (c, d) from 2010–2050, in the wet season (left panel) and dry season (right panel)**

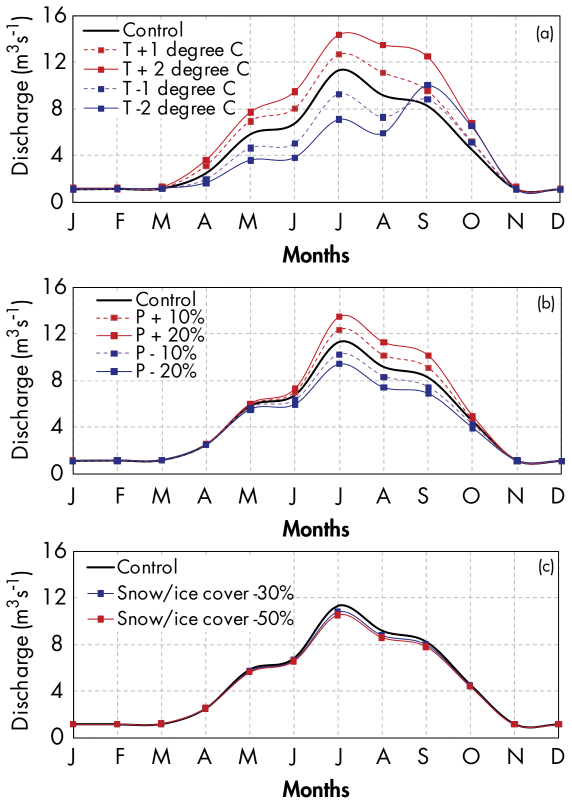


with precipitation, and the change with change in ice/snow cover area was small in comparison.

The discharge responded to all four simulations with change of temperature (±1°C and ±2°C) but with higher magnitudes of change for increase in temperature than for the same decrease in temperature (increase by 11.4% and 26.7% for an increase in temperature of 1°C and 2°C; decrease by 5.7% and 15.1% for a decrease in temperature of 1°C and 2°C) (Figure 10a). The peak hydrograph shifted by two months (July to September) with a -2°C change in temperature, and simulations with both -1°C and -2°C showed two rising limbs.

The discharge also responded to all four simulations with a change in precipitation (±10% and ±20%) but mainly confined to the monsoon season (June–September) and with a slightly higher sensitivity to an increase than to a decrease in precipitation (+9.4% discharge for +20% precipitation, -7.1% discharge for -20% precipitation) (Figure 10b).

Figure 10: Results of sensitivity analysis for change in (a) temperature, (b) precipitation, and (c) snow/ice cover area in Langtang River basin



The discharge was less sensitive to change in glacier snow/ice cover (Figure 10c). A decrease (of -30 and -50%) in snow/ice cover area change resulted in a small decrease in discharge (-0.6 and -2.9% respectively), but this was not significant compared to the changes induced by change in temperature or precipitation. The low sensitivity of the model to snow/ice cover change may be due to the relatively small areal coverage of glacier snow and ice compared to the total basin area.

Snow/ice contribution

The relative contribution of snow/ice and rainfall/baseflow to total discharge was analysed in the model output values. The model simulation for the present day climate (1995–2003) in the Langtang River basin showed 49% of the total river discharge as contributed by snow/ice melt. Similarly, snow/ice melt contributed 47% of the projected annual discharge for 2010–2050 (Figure 11a). The contribution of snow/ice melt to total discharge was higher in the pre-monsoon to monsoon season and significantly lower during the post-monsoon and winter seasons; it was about 12% in the winter season (October–February), 38% in the pre-monsoon season (March–May), and 57% in the monsoon season (June–September). In contrast, rain/baseflow dominated the projected river discharge in the Kafni River basin throughout the year, with an overall average of 81%; only 20% of discharge was contributed by snow/ice during the monsoon season (June–September) and 31% during the pre-monsoon season (Figure 11b).

Figure 12 shows the projected average annual contribution of snow/ice melt and rainfall/baseflow to total discharge in the period 2010 to 2050 in (a) the Langtang River basin and (b) the Kafni River basin. In the Langtang basin, the annual contribution of snow/ice melt to total discharge showed a small negative trend (-0.005 m^3s^{-1} $year^{-1}$), whereas rainfall/baseflow contribution showed a small positive trend (0.009 m^3s^{-1} $year^{-1}$). The relative amounts contributed remained similar, but with a slightly higher contribution by rain/baseflow over time. This is

Figure 11: **Projected relative mean monthly contribution of snow/ice and rainfall/baseflow to total discharge for the period 2010–2050 in (a) the Langtang River basin, and (b) the Kafni River basin**

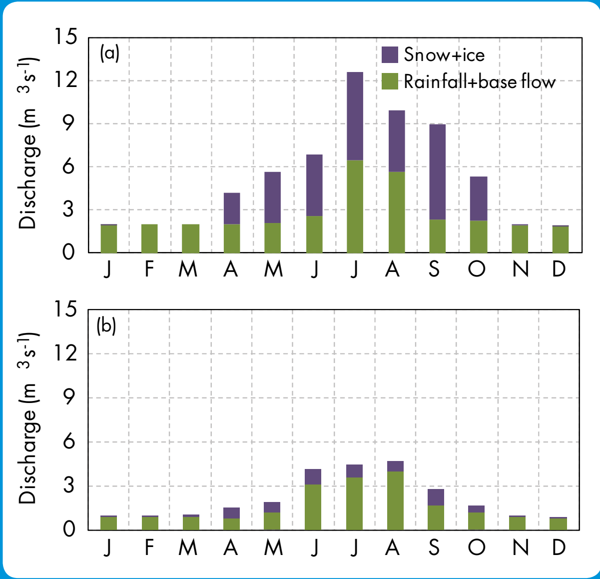
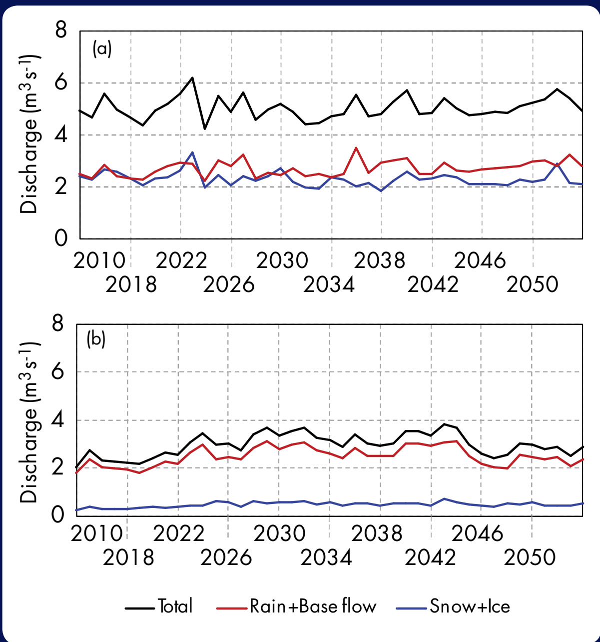


Figure 12: **Projected annual contribution of snow/ice melt and rainfall/baseflow to total discharge during the period 2010–2050 in (a) the Langtang River basin and (b) the Kafni River basin**



because more precipitation falls as rain than snow under the future climate scenario. A study conducted by Immerzeel et al. (2012) for the period 2000 to 2100 in the Langtang River basin came to similar conclusions, with increasing runoff due to rainfall after 2050.

In contrast, in the Kafni River basin both snow/ice and rain/baseflow showed an increasing contribution to total discharge, with rain/baseflow significantly higher than snow/ice melt (Figure 12b). The higher contribution of rain to the discharge is mainly attributed to the future increase in rainfall. The relatively small glacier area (7.6%) also explains the smaller contribution of snow/ice melt. The sharp decline in discharge after 2040 is largly due to the decrease in precipitation (Figure 7g-h).

Conclusion

The PDD model used to estimate the discharge in two glacierized river basins was able to represent the hydrological characteristics and river discharge of the Langtang River basin and could then be used to estimate discharge in the Kafni River basin in India. Under the future climate scenario, the temperature is expected to increase in both the wet and dry seasons in the Langtang and Kafni River basins. However, precipitation is expected to decrease in the Langtang River basin and increase in the Kafni River basin, in both wet and dry seasons. The projected discharge from 2010 to 2050 showed an overall positive trend in both river basins, although it decreased after 2040 in the Kafni basin. The contribution of snow/ice melt to the discharge from the Langtang River basin was nearly equal to the contribution of rainfall/ baseflow. In the Kafni River basin, rainfall/baseflow contributed a much greater proportion of discharge than did snow/ice melt. The PDD model should be considered as a promising tool for understanding the hydrology of glacierized river basins. The results of this research can provide important information to support planning for future water availability in the Himalayan region. Similar research should be carried out in other river basins to investigate the potential impact of future climate change on the Himalayan catchments.

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Vulnerability Assessment of Flash Floods in the Poiqu/Bhotekoshi/ Sunkoshi Watershed

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Abstract

China and Nepal share many transboundary rivers that originate in the Himalayan mountain region. Most of these rivers are subject to flash floods that may be further exacerbated by ongoing climate change. This study focused on the Poiqu/Bhotekoshi/Sunkoshi River, which originates in Tibet Autonomous Region (TAR) in China and flows through Nepal. It was designed with the following objectives: 1) assessment of historical flash floods and their impacts; 2) simulation of flash floods under different climate change scenarios; 3) determination of socioeconomic vulnerability; and 4) recommendation of adaptation strategies for flash flood risk reduction. Four types of flash floods that resulted in loss of life and property were reported from the study area: glacial lake outburst floods (GLOFs); floods triggered by heavy precipitation; landslide dam outburst floods (LDOFs); and floods triggered by blocking from flooded tributaries. The modelling results indicated that future average annual discharge would not change significantly under the different climatic scenarios, but that the annual maximum daily discharges would increase at lower recurrence intervals (5 and 10 years), in other words the number of less extreme floods is likely to increase. The overall livelihood vulnerability is relatively high in the poorly accessible northern areas of the Balephi and Bhotekoshi watersheds in Nepal. The local people have some knowledge and a limited capacity to manage the challenges, but their ability to reduce risk and manage catastrophic events is far from adequate. A number of measures are suggested that should be implemented through bilateral cooperation.

Introduction

Flash floods occur frequently in the Himalayas, often causing loss of life and property. These hazards and associated risks are likely to increase as global warming continues, especially as the Himalayan region appears to be experiencing more rapid warming than the global average (Shrestha et al. 1999; Shrestha et al. 2000; Ding et al. 2006; Yang et al. 2006; Baidya et al. 2008; UNEP 2009; Gosain et al. 2010; Kaltenborn et al. 2010; Nie et al. 2010; Tan et al. 2010; Zhang et al. 2012). Upstream flash floods caused by extremely heavy precipitation or by glacial lake outbursts (GLOFs) pose severe threats to downstream life and property. Flood risk management in transboundary watersheds is especially complicated and requires vigorous cooperation among the riparian countries in understanding flood risk and its management, and opportunities and constraints.

China and Nepal share many transboundary rivers, all of which originate in the Himalayan mountain region. Most of these transboundary rivers are subject to flash floods that may be further exacerbated by ongoing climate change. It follows that efforts are urgently needed to reduce the risk of disasters by adaptation planning with proper assessment of vulnerability to flash floods.

The Poiqu/Bhotekoshi/Sunkoshi watershed was selected for this study. This transboundary river originates in the Tibet Autonomous Region (TAR) in China and flows through the high mountains before emerging in Nepal as the Koshi River. The upstream section transects Chinese territory, and there are more than a hundred glaciers and glacial lakes within the watershed (Wu et al. 2005; Bajracharya et al. 2008; Chen et al. 2005, 2007). According to reliable local records, during the last century several glacial lakes in this upstream section have burst (GLOFs) and caused great loss of life and property downstream (Xu 1987; Xu et al. 1989; Chen et al. 2005, 2007; Khanal et al. 2013). The observed recent retreat of the glaciers and increased snow-ice melt, augmented by global warming, has increased the size and water level of some of the existing glacial lakes, and even caused the formation of new ones (Chen et al. 2005, 2007). This indicates a future potential for higher risk from GLOFs.

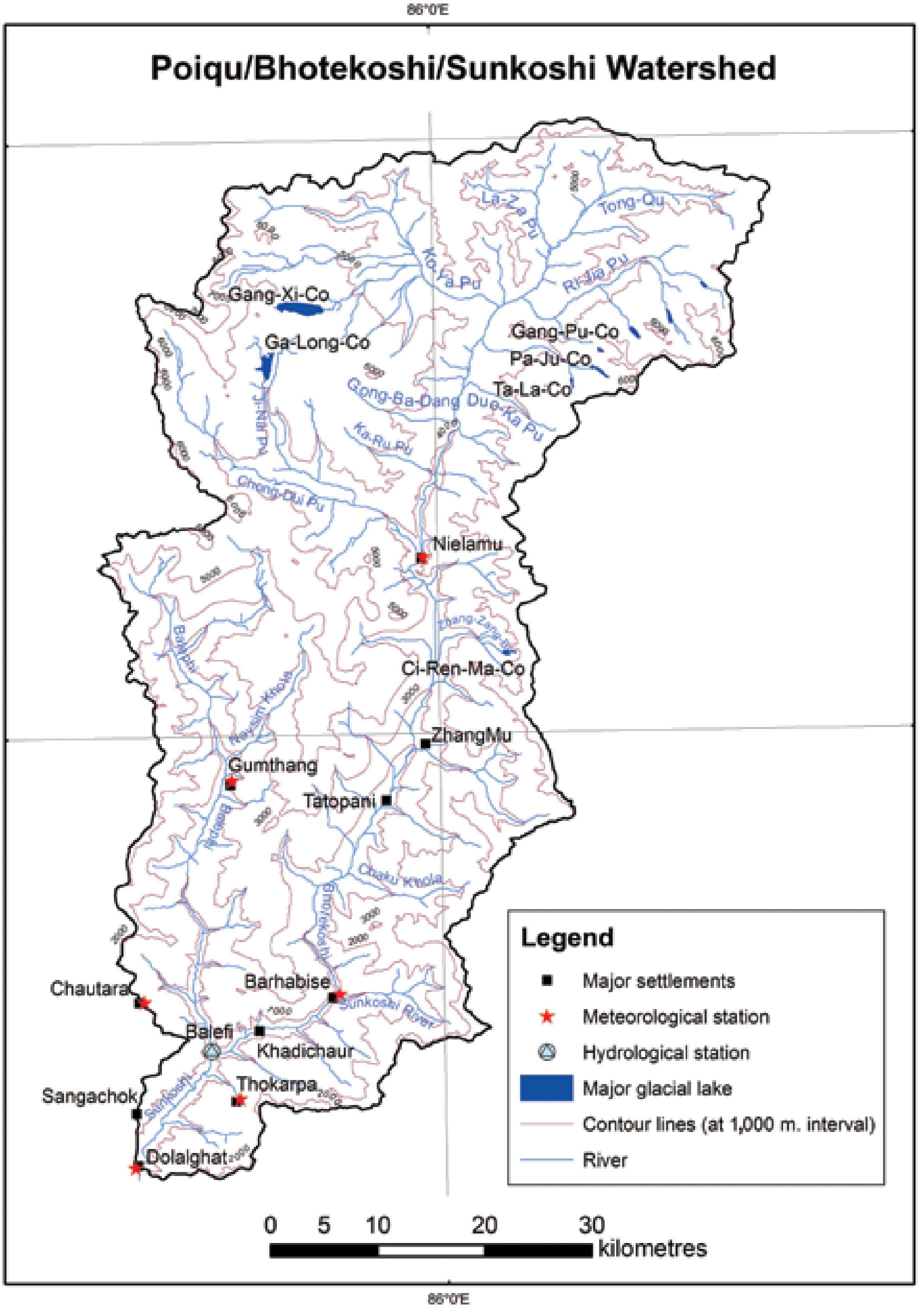
The gradual strengthening of the socioeconomic links between China and Nepal, and the rapid development of the regional socioeconomy of the Poiqu-Bhotekoshi watershed, is resulting in a progressive increase in the prospect for losses from mountain flash floods. However, there is a serious lack in understanding of the threats that this poses and of the vulnerability of people in the watershed. This lack of understanding is a major obstacle to the development of effective flash flood risk management. Therefore, this study was designed with the following objectives: 1) assessment of historical flash floods and their impacts; 2) simulation of flash floods under different climate change scenarios; 3) determination of socioeconomic vulnerability; and 4) recommendation of adaptation strategies for flash flood risk reduction.

Methods

Study area

The study area comprised the Poique/Bhotekoshi/Sunkoshi watershed upstream from Dolalghat, the confluence of the Sunkoshi and Indrawati rivers (Figure 13). The total watershed area is about 3,400 km^2, with an elevation range from about 650 to more than 8,000 masl. The upper part of the watershed is characterized by steep rocky outcrops and bare ground. Cultivated land is confined to the lower part of the watershed. Approximately

Figure 13: **Study area**



13% of the total area is permanent ice and snow, 40% is bare land, 24% is forest, 14% is farmland, and 9% is shrub. The river in the study area has a total length of 146 km, of which 78 km lies in China and 68 km in Nepal. The Friendship Bridge marks the border crossing point. The mainstream is called the Poiqu in the Chinese section and becomes the Bhotekoshi in Nepal, changing its name to Sunkoshi after joining the smaller river at Barhabise. The river has many tributaries including the Balephi, Sunkoshi Nadi, Chong-Dui Pu, Ko-Ya Pu, Ru-Jia Pu, Ta-Ji-Lin Pu, and Zhang-Zang-Bo.

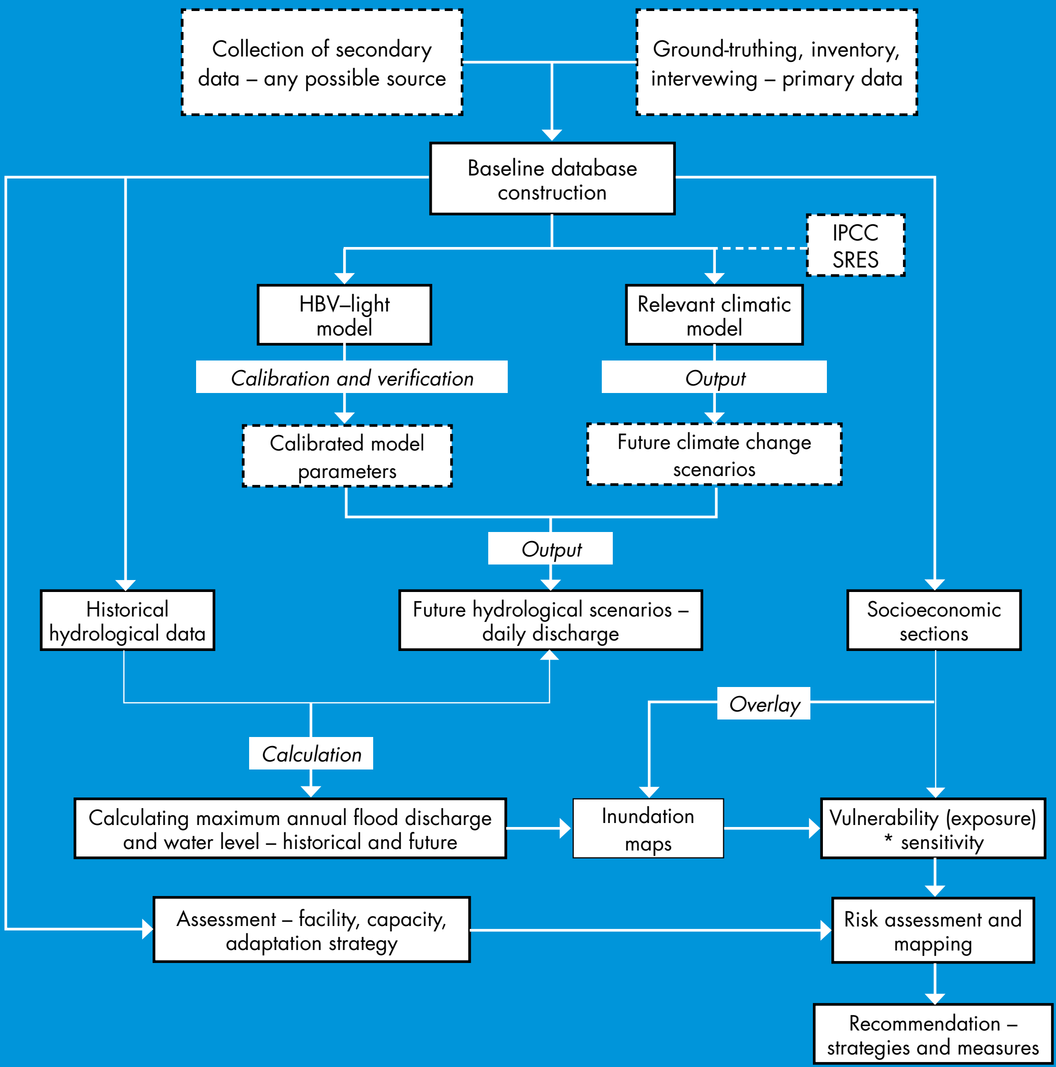
There are 17 villages within the three townships of Chongdui, Ya Lai, and Zhang Mu (Khasa) in the upstream Nyalum county, China, and 50 village development committee (VDC) areas downstream from the Friendship Bridge in Nepal. The watershed has a total population of about 203,000, of whom close to 5,500 (about 2.7%) live in China. Agriculture, including animal husbandry, is the major source of rural family income on both sides of the border. The China-Nepal highway running through the watershed, which continues from the border to Kathmandu and beyond, is the only international highway directly linking TAR, China with Nepal. It is the most important bilateral channel for political communication, and economic and cultural exchange. Trade and business are becoming increasingly important sources of income on both sides of the border. According to the Tatopani Customs Office records, the value of Nepalese imports from China increased from NPR 4,827 million in 2006/07 to NPR 13,289 million in 2011/12. In 2011/12, the volume of exports through this customs point exceeded NPR 408 million.

Other economic activities in the watershed include the generation of revenue from tourism and supply of hydroelectricity. The number of tourists visiting the area increased from 69,000 in 2009 to 97,000 in 2011. The Bhotekoshi/Sunkoshi River has become famous for rafting and bungy jumping, and annually some 14,000 international and domestic tourists visit the area for these activities on the Nepal side of the border. There are nine hydroelectric power plants with a capacity of 53.76 MW located along the Nepalese section and one hydropower plant on the Chinese side. A further six hydroelectric power plants, with a combined capacity of 106.84 MW, are under construction and applications from interested parties have been submitted to develop another 669.46 MW, also on the Nepalese side.

Methodological Framework

Figure 14 shows the methodology adopted in this study. Both primary and secondary data were collected. Different tools, such as focus group discussions and key informant interviews, were used to collect socioeconomic data, and field observations were carried out to assess the risk of glacial lake outbursts. In addition, meteorological and hydrological modelling, vulnerability and sensitivity evaluation, and risk assessment and mapping, were undertaken. Based on the findings, potential adaptation strategies and measures have been recommended.

Figure 14: **Methodological framework**



Climate Modelling

After reviewing the meteorological data collected from relevant stations located within the watershed and nearby, daily precipitation from six stations (Nyalum, Barhabise, Gumthang, Dhap, Nawalpur, and Chutara) and daily temperature from three stations (Nyalum, Jiri, and Panchkhal) were used for modelling. Four climate models (ECHAM5, GFDL, CSIRO, and HADGEM1) were selected to output and then bi-linearly interpolate daily precipitation and temperature from the selected stations for the baseline period (1981–2000). Correlation coefficients were calculated between the interpolated and observed daily precipitation and temperature data at corresponding stations. The results showed that the ECHAM5 model was more effective than the other three models.

Daily precipitation and temperature were simulated for relevant stations within the baseline period 1981–2000 using ECHAM5 and bi-linear interpolation. Daily precipitation and temperature for the same stations were then projected for the period 2046–2065, under the SRES B1, A1B and A2 models by coupling the ECHAM5 modelling with the delta ratio method (Shrestha et al. 2011; Zhao and Xu 2007) to give future climate scenarios.

Hydrometeorological Modelling

Jalbire and Barhabise are the only two hydrological stations located on the main Bhotekoshi river and its Balephi tributary. Considering the limited availability of data and the remote and high elevation characteristics of the watershed, the semi-distributed HBV-light model was selected for runoff modelling. The HBV model reproduces discharge reasonably well and handles the glacial component adequately under present climate conditions. It performs satisfactorily at the daily timescale, and it produces better results in runoff modelling than the model driven by data from the meteorological stations (Seibert 2005; Seibert and Vis 2012). This was also tested and recommended for the entire Hindu Kush-Karakorum-Himalayan region (Akhtar et al. 2008, 2009; Pellicciotti et al. 2012). A detailed description of the HBV-light model and its uses can be found in Seibert (2005) and Seibert and Vis (2012). The model requires daily precipitation and temperature data from within, or in the vicinity of, the catchment. Other necessary data include daily discharge from gauge stations, and observed or estimated mean annual evaporation. A digital elevation model is required for determination of basin boundary, area, area-elevation distribution curve, river network, and slope. Information on land use and land cover, including snow cover, was generated using Landsat images.

In the application of the HBV-light model, the watershed was divided into two hydro-meteorological modelling units (Jalbire and Barhabise) based on the river network and the two stations. The Thiessen polygon interpolation method was used to derive the daily average precipitation for the Jalbire and Barhabise sub-watersheds. Area-weighted average precipitation was calculated as the weighted mean of precipitation at the different stations (Nyalum, Gumthang, Barhabise, Dhap, Nawalpur, Chautara). Because precipitation varies significantly with elevation, the sub-watershed was divided artificially into several elevation zones. For each zone, precipitation was adjusted assuming a standard increase with elevation above sea level (usually 10–20% per 100 m). Temperature data were needed in catchments with snow; these were calculated as the weighted means of values from stations in and close to the catchment. When different elevation zones were used, temperature was adjusted by -0.6°C per 100 m.

The HBV-light model requires two periods of data, one for calibration and one for validation. The calibration period should include a variety of hydrological events. Normally five to ten years of data are sufficient for calibration of the model and validation of its performance; each should be derived from independent periods (Seibert 2005). Discharge data from 1964 to 2008 were collected from Jalbire in the Balephi unit, and Barhabise in the Bhotekoshi unit. Annual maximum and minimum daily discharge data from 1970 onward were used because they provided a long unbroken period. For Barhabise, there were no observed daily discharge data from 1 January 1999 to 15 July 2004. The missing data were fitted through a linear equation of daily discharge (natural logarithm) at Jalbire and Barhabise. Cross-section data for the Jalbire and Barhabise stations were also used.

An automatic genetic algorithm package (GAP) optimization was applied and then manually calibrated to refine the parameters by trial-and-error. In addition to visual comparison of the simulated time series with the observed ones, several objective criteria were used to assess the best parameter set: Nash-Sutcliffe efficiency, logarithmic model efficiency (emphasizing the weighting of low discharges), coefficient of determination, volume error, and peak efficiency. Validation was undertaken with the calibrated parameter sets.

Digitized elevation data were acquired from topographic maps (1:50,000 scale in China and smaller scale in Nepal) and from the ASTER Global Digital Elevation Model (GDEM). The contour interval of the topographic maps (1:50,000 in China in 1979 and in Nepal in 1996) is generally 10 m, and 20 m in the mountain region, but horizontal resolution is coarse. Spatial resolution, horizontal accuracy, and vertical accuracy of ASTER GDEM are approximately 30, 20, and 30 m, respectively.

After examining the quality of the hydrological data at the two stations, the daily discharge calibration period was set at 1988–1997 and the validation period at 1999–2008 for Jalbire, and the calibration period at 1971–1980 and the validation period at 1988–1998 for Barhabise. The calibration and validation efficiencies were 0.838 and 0.802, respectively, for Jalbire, and 0.884 and 0.494, respectively, for Barhabise. The validation efficiency at Barhabise was low compared to Jalbire. This low value is associated with extreme discharge events recorded in 1988 (1,370 cm) and 1991 (1,200 cm). Results obtained using the HBV-light model in other areas also show that peak values are generally underestimated, whereas discharge during low flow periods is satisfactorily simulated (Akhtar et al. 2009).

Groundtruthing and Social Interviews

An inventory of glacial lakes was prepared based on interpretation of Landsat TM (1991/11/30 and 2002/10/11) and Landsat ETM+ (2012/10/22). An attempt was also made to assess the level of risk of the 74 glacial lakes identified in the watershed during the desk study. This provided the basis for field investigations carried out in September and October 2012. Detailed studies of ten glacial lakes in the study area were completed during this period.

Methods for generating information on the impact of past flood events and vulnerability included field observation; key informant interviews (KII); and focus group discussions (FGDs). Field observation and key informant interviews were used in the headwater area (in China) and FGDs in Nepal. A community-based flood hazard mapping exercise was also carried out during the FGDs. The participants were asked to delineate three hazard zones on the map

– high, medium, and low – at a scale of 1:25,000 in the lower area in Nepal and 1:50,000 in the upper area in Nepal, and asked for information about the elements exposed in each hazard zone as perceived by the community. Information was also collected on socioeconomic conditions, previous hazard events, indigenous knowledge, and local practices. Three types of information collection tools were used: a checklist for past hazard assessment; a questionnaire to provide a socioeconomic profile, including indigenous knowledge; and a checklist to record elements exposed in the different hazard zones. Sixty-three focus group discussions were organized between Friendship Bridge in the north and Dolalghat in the south.

Livelihood vulnerability determination (Hahn et al. 2009) was adopted using relevant indicators: the proportion of the economically active population, literacy rate, proportion of households with income from non-agricultural sectors, and proportion of households with annual income exceeding NPR 80,000. These data were used as indicators of the adaptive capacity of the individual family units. Similarly, the proportion of households with food sufficiency from their own production for less than six months, average travel time to health services and road head, proportion of households without telephone, and without TV, were used as indicators of degree of sensitivity. Loss of life and magnitude of property loss from previous disaster events – land, crops, houses, and sheds – located in hazard prone areas, were taken as indicators of exposure. The value of each parameter and component was normalized to a scale of 0 to 1 and a vulnerability index value was calculated for all 63 communities on the Nepalese side of the border.

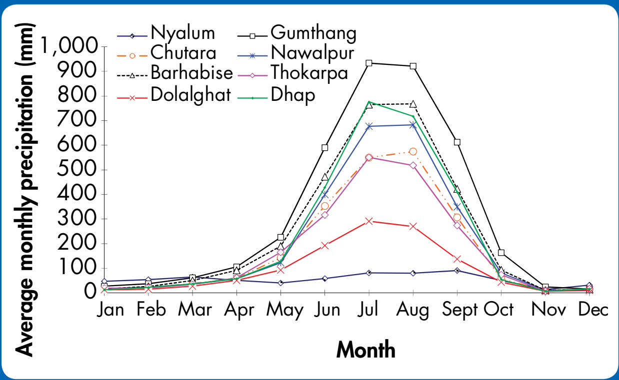
Results and Discussion

Climate

There is high spatial and temporal variation in precipitation in the watershed. Average annual precipitation varies from less than 600 mm in the northern part (Nyalum), to 1500 to 3600 mm in the Nepalese part. About 77–88% of total annual precipitation on the southern slopes of the Himalayas occurs during the summer monsoon season (June–September), but only 47% at Nyalum (Figure 15). The rainy season also begins earlier in Nyalum than in the Nepalese sector.

The average monthly temperature (AMT) at individual stations is shown in Figure 16. All temperatures follow the universal monthly pattern for the northern hemisphere, but

Figure 15: **Average monthly precipitation at individual stations**



with significant spatial variation in the values. The average annual temperature at Panchkhal and Dhulikhel was 21.2°C and 17.0°C, respectively, while at Nyalum, it was only 3.9°C.

The average annual precipitation and average annual temperature at the stations shown in Figures 16 and 17 indicate that the southern part of the catchment has a sub-tropical Indian monsoon climate (warm and humid); the central mountain region, a sub-tropical alpine climate (cold and moist to dry); and the northernmost section, an alpine and plateau climate (cold and extremely dry). This significant seasonal climatic variation is a major cause of the frequent floods in the watershed.

Climate and Hydrological Changes

Figures 17 and 18 show the projected future average monthly temperature and precipitation at Jalbire and Barhabise. All three SRES models (A1B, B1, and A2) show an increase in average monthly temperatures, with A1B projecting the highest temperatures. The projected increases in November and March are less than those for other months, whereas the projected increase in winter (December to February) is higher than in the other seasons. There is no clear pattern in the projected change in precipitation. SRES B1 predicts a sharp decrease in average monthly precipitation in June and September. All three models (and especially A2 and B1) predict lower total precipitation from June to August, in other words future summer monsoon precipitation is predicted to be lower than at present.

Figure 16: **Average monthly temperature (AMT) at individual stations**

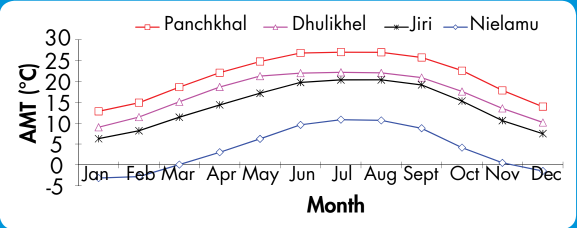


Figure 17: **Change in average monthly temperature and precipitation (area-weighted) compared to baseline in the Balephi sub-watershed**

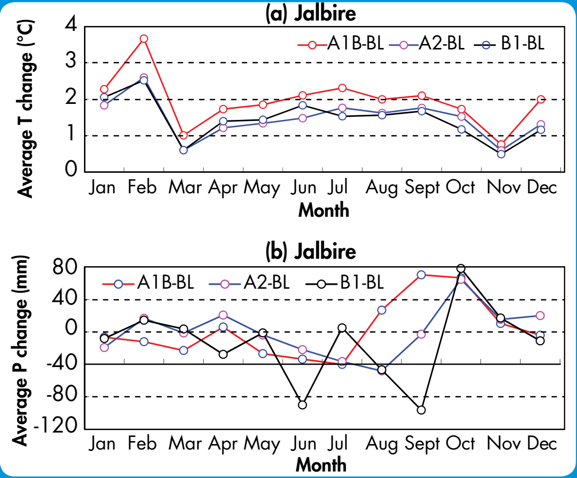


Figure 18: **Change in average monthly temperature and precipitation (area-weighted) compared to baseline in the Bhotekoshi sub-watershed**

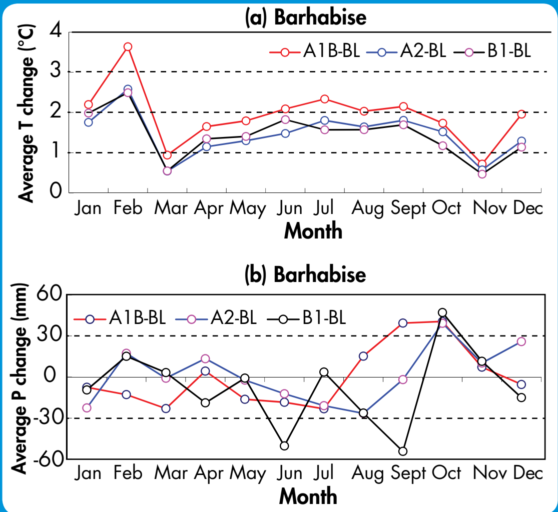
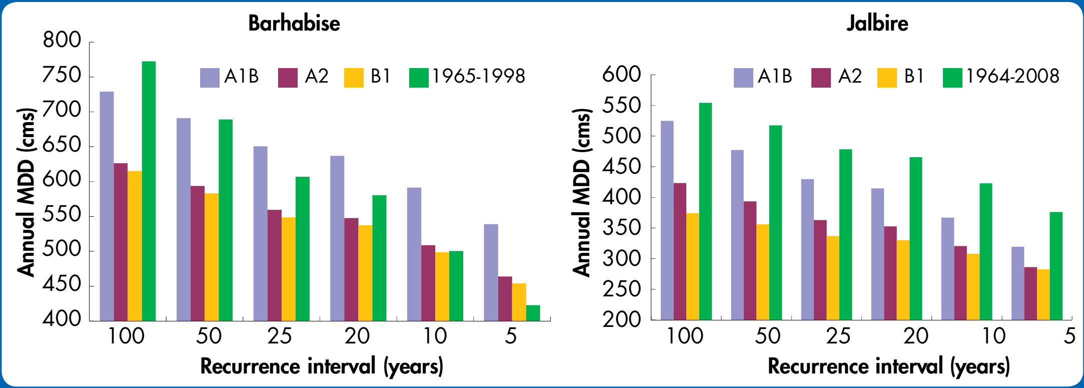


Figure 19: **Maximum daily discharge (MDD) at recurrence intervals of 5, 10, 20, 50, and 100 years in the historic and future (2047–2065) periods at Jalbire in Balephi and Barhabise in Bhotekoshi calculated using SRES A1B, B1 and A2**



Daily discharge under different climate change scenarios was projected using the HBV-light model with the area-weighted average daily projected precipitation and temperature for the hydrological stations at Jalbire and Barhabise. Figure 19 shows the Pearson-III distribution frequencies of annual maximum daily discharges at recurrence intervals of 5, 10, 20, 25, 50, and 100 years at Jalbire and Barhabise within the historic period 1965–2008, and within the projected period 2047–2065, under the SRES A1B, B1, and A2 scenarios. Daily discharge was higher under the A1B than the B1 or A2 scenarios. It was lower than in the historic period under all three scenarios at Jalbire; whereas at Barhabise it was predicted to increase for recurrence intervals of 25 years or less, with a maximum for recurrence intervals of 5 and 10 years, indicating that the number of less extreme floods is likely to increase.

Table 12 shows the recorded maximum water level in metres and the calculated and predicted water levels for different recurrence intervals based on the historical data and climate change projections. The predicted level of water at both stations is lower under the climate change scenarios than for the historical and observed data except for the recurrence interval of five years using the A1B scenario at Barhabise.

Potential Glacial Lake Outburst Floods (GLOFs)

Glacial lake outburst is an important cause of flash flooding in the study area. Seventy-four glacial lakes of various sizes were identified (Figure 20). Most increased in area between 1991 and 2012 (even doubling in size); six were classified as stable, seven as critical, and three as very critical (Table 13).

Table 12: **Water levels at the two hydrological stations under different climate change scenarios and flood recurrence intervals (in metres)**

Recurrence interval (years)	Jalbire				Barhabise			
	Historical period	Climate change scenario			Historical period	Climate change scenario		
		A1B	A2	B1		A1B	A2	B1
1000	10.59	8.00	7.28	6.80	10.98	5.99	5.62	5.58
200	9.66	7.53	6.94	6.60	9.44	5.75	5.40	5.36
100	9.21	7.31	6.78	6.49	8.69	5.64	5.29	5.25
50	8.72	7.07	6.61	6.38	7.89	5.51	5.17	5.13
25	8.19	6.82	6.42	6.26	7.03	5.38	5.04	5.00
20	8.01	6.73	6.36	6.22	6.74	5.33	5.00	4.96
10	7.42	6.45	6.15	6.07	5.80	5.16	4.85	4.80
5	6.77	6.15	5.91	5.89	4.86	4.96	4.66	4.62
Maximum recorded height of water	8.88				7.37			

Table 13: **Number of glacial lakes with different levels of risk for a GLOF**

Risk of GLOF event	Number	Name of lake
Stable (less chance of potential GLOF)	6	Gong-Co; Ta-Ro-Co; Yinra Co
Critical (moderate chance of potential GLOF)	5	Ga-Long-Co; Gangxi Co; Pa-Ju-Co; Cha-Wu-Qu-Deng; Ta-La-Co
Very critical (high chance of potential GLOF)	2	You-Mo-Jian-Co; Qie-Ze-La-Co
Critical with past event of GLOF	2	Ci-Ren-Ma-Co; Jiang-Gu-Co
Very critical with past event of GLOF	1	Jia-Long-Co
Not studied in detail	58	
Total	74	

Source: Interpretation of Landsat images and field investigation

Flash Floods and their Impact

Flash floods occur frequently in the study area and have caused significant loss of life and property. Four different types have been reported from the Nepal side: GLOFs; floods triggered by heavy precipitation; landslide dam outburst floods (LDOFs); and floods triggered by blocking of tributaries. Four GLOF events have been reported: Jian-Gu-Co in 1935, Ci-Ren-Ma-Co in 1964 and 1981, and Jia-Long-Co in 2002. The GLOF of 1981 was the most destructive in terms of value of property lost. Of the nine major floods reported by local people in Nepal between 1948 and 2012, one was a GLOF, two were LDOFs, and five were triggered by high intensity precipitation (Table 14). Although losses from individual flash floods due to high precipitation tend to be comparatively modest, this type of flood is more frequent than the others so that cumulative loss is more marked. Nearly 23% of total property loss resulted from floods triggered by heavy precipitation, 47% from GLOFs, and 30% from

Figure 20: **Areal growth of glacial lakes in the Bhotekoshi watershed (only larger lake locations shown)**

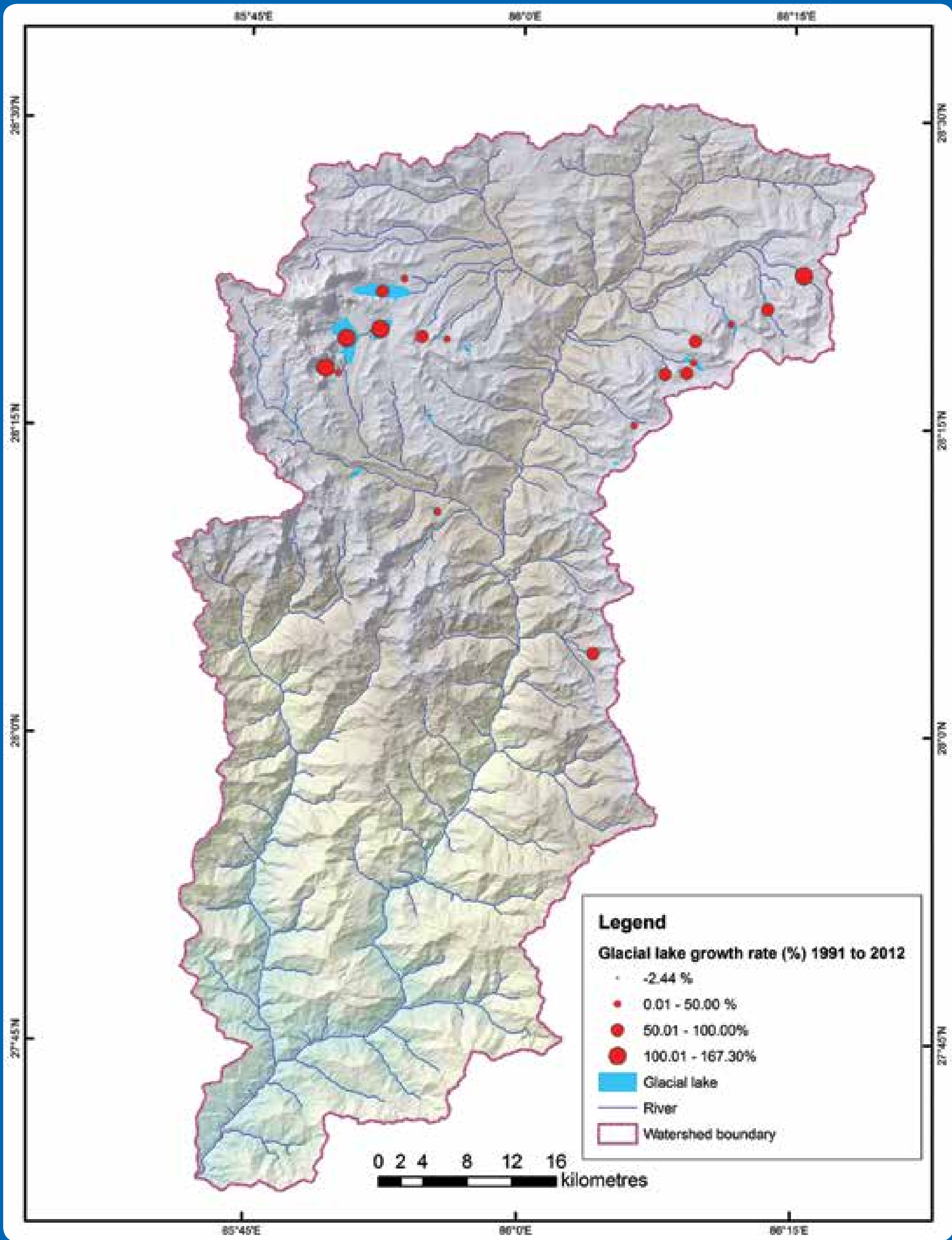


Table 14: Occurrence of different types of devastating flash floods in the watershed

Year	Loss of Life and Property						Remarks
	Lives	Animals	Houses	Crops (tonnes)	Land (ha)	Value ('000 USD)	
1948	5	0	3	2.8	1.8	0.1	Blocking by tributaries of Balephi
1981	5	23	91	68.2	39.9	1115	Outburst of Ci-Ren-Ma-Co
1982	97	70	18	52.5	24.1	57	Landslide dam outburst flood in Balephi
1987	98	309	229	49.1	33.5	262	High intensity precipitation in Sunkoshi
1992	0	0	0	4.8	2.9	90	High intensity precipitation in Khandichaur
1996	54	100	22	1.2	0.7	663	Landslide dam outburst flood in Larcha
2001	0	13	5	4.7	3.4	67	High intensity precipitation in Gumthan
2008	0	0	1	6.2	4.4	75	High intensity precipitation in Balephi
2011	1	0	0	2.4	1.2	40	High intensity precipitation in Chaku

Source: Field survey 2012

Figure 21: **Loss of life from floods (1944–2012)**

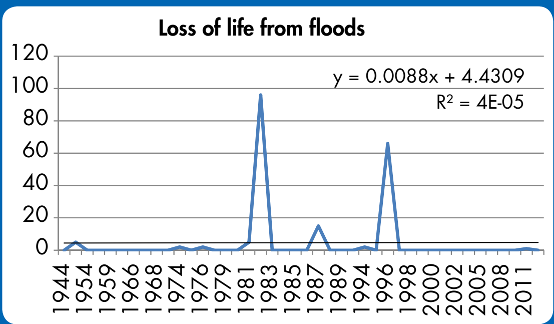
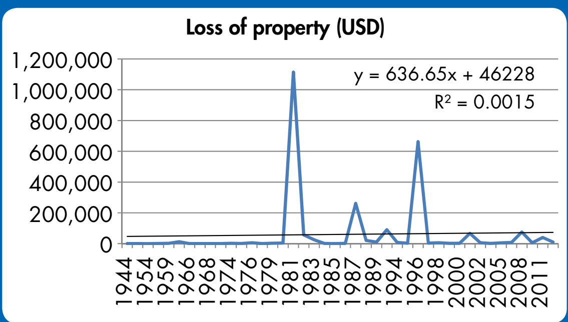


Figure 22: **Loss of property from floods (1944–2012)**



LDOFs. The loss of life from LDOFs was extremely high compared to other types of flood, as was the loss of life from one of the high intensity precipitation events.

The annual loss from flooding is very high compared to other hazards such as landslides, debris flows, earthquakes, drought, fire, hailstorms, windstorms, and lightning strikes. Annual loss of property reported by local people was about USD 32,000 on the Nepal side alone. Loss of life and property between 1944 and 2012 as reported by the local people during group discussions is illustrated in Figures 21 and 22. Losses were significantly higher in certain years, with no noticeable trend.

Flood Risk and Vulnerability

Upstream of the Friendship Bridge in China, six of the 17 settlements, with a total population of 1,854, are exposed to flash flood risk from upstream glacial lake outburst floods, as are 21 bridges and one hydropower plant. In Nepal, 30 settlements, with a total population of 20,900 in about 3,600 households are at risk of being impacted directly by flash floods as a result of residing or owning property within flood hazard prone areas. This comprises about 10% of all households in the area.

Local people prepared flash flood hazard maps during the focus group discussions based on their past experience (see Figure 23 for an example).

Table 15 summarizes the types and amount of property exposed to flash floods in the Nepal sector of the study area. It includes close to 457 ha of cultivated land, 1,352 tonnes of agricultural crops, and 312 tonnes of vegetables (cash crops), as well as a large amount of infrastructure such as private houses, commercial and industrial units, public buildings, roads, transmission lines, irrigation canals, drinking water projects, hydropower plants, bridges, and water mills. The estimated value is close to USD 163 million. In addition, annual revenue generated from international trade (about USD 45 million) and revenue from sale of hydroelectricity (USD 17 million) are likely to be affected if the flow of people and goods are interrupted due to damage to roads, bridges, hydroelectricity projects, and transmission lines during flood events. The total estimated value of flood risk in the watershed downstream from the Friendship Bridge exceeds USD 224 million.

Figure 24 shows the exposure, sensitivity, adaptive capacity, and livelihood vulnerability of the communities in the Nepal part of the study area. Communities located in the Bhotekoshi, Balephi, and Sunkoshi sub-watersheds are exposed to a relatively high flood risk. Those in the

Table 15: **Elements exposed to flash floods in the Nepal sector of the study area**

Elements exposed	Hazard zones			Total
	High	Medium	Low	
Cultivated land (ha)	116	138	204	457
Agricultural crops (tonnes)	368	399	585	1,352
Vegetables and fruit (tonnes)	88	100	124.5	312
House and sheds (no.)	116	95	136	347
Public buildings (no.)	67	48	31	146
Roads (km)	27	21	22	70
Trails (km)	9	18	28	55
Irrigation canals (km)	4	6	7	18
Transmission lines (km)	20	26	32	77
Bridges (no.)	42	11	26	79
Drinking water schemes (no.)	11	5	4	20
Hydropower plants (no.)	7	4	1	12
Water mills (no.)	43	15	19	77
Commercial and industrial units (no.)	330	376	191	897

Source: Field survey 2012

Figure 23: **Example of a community-based flash flood hazard map**

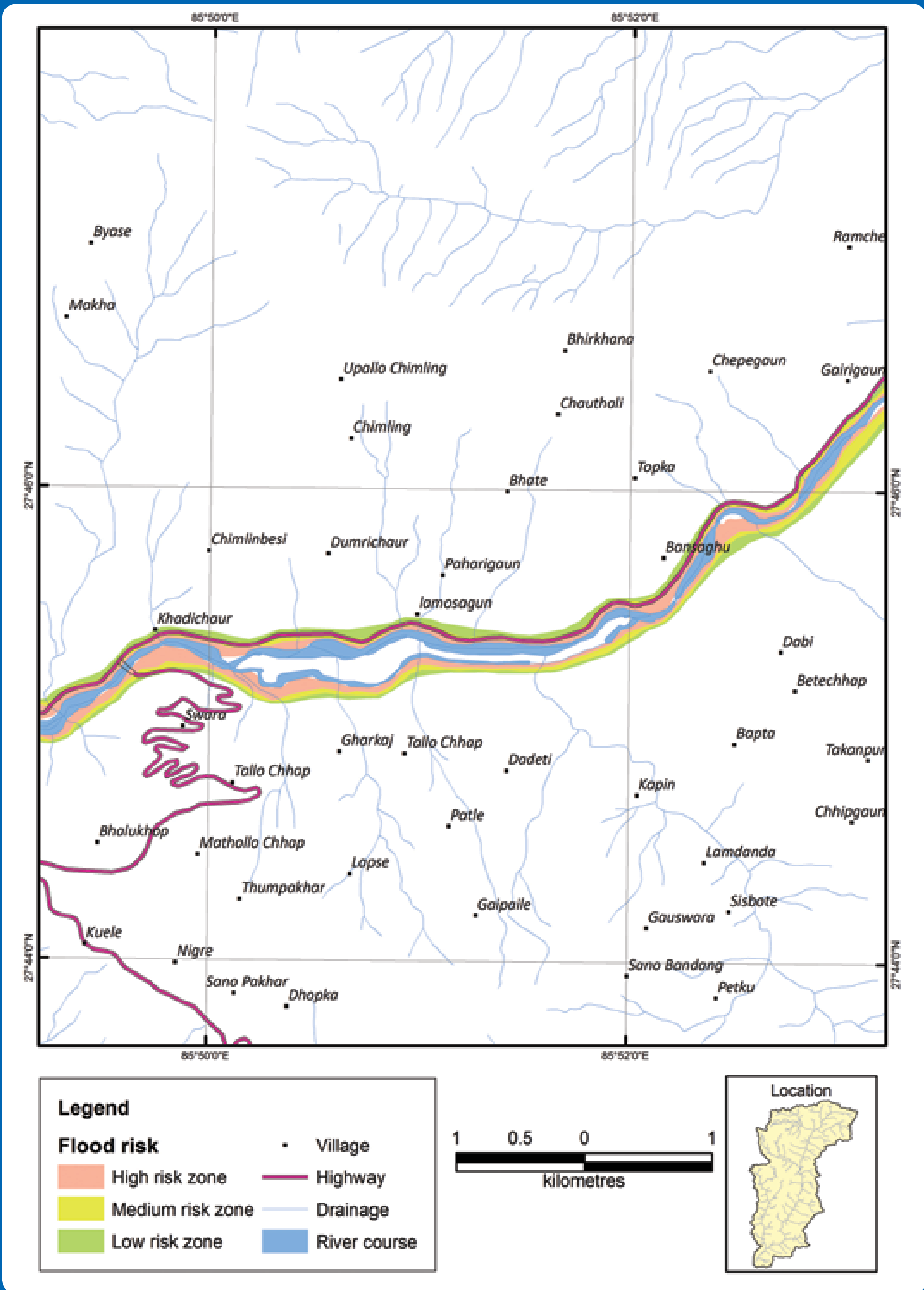
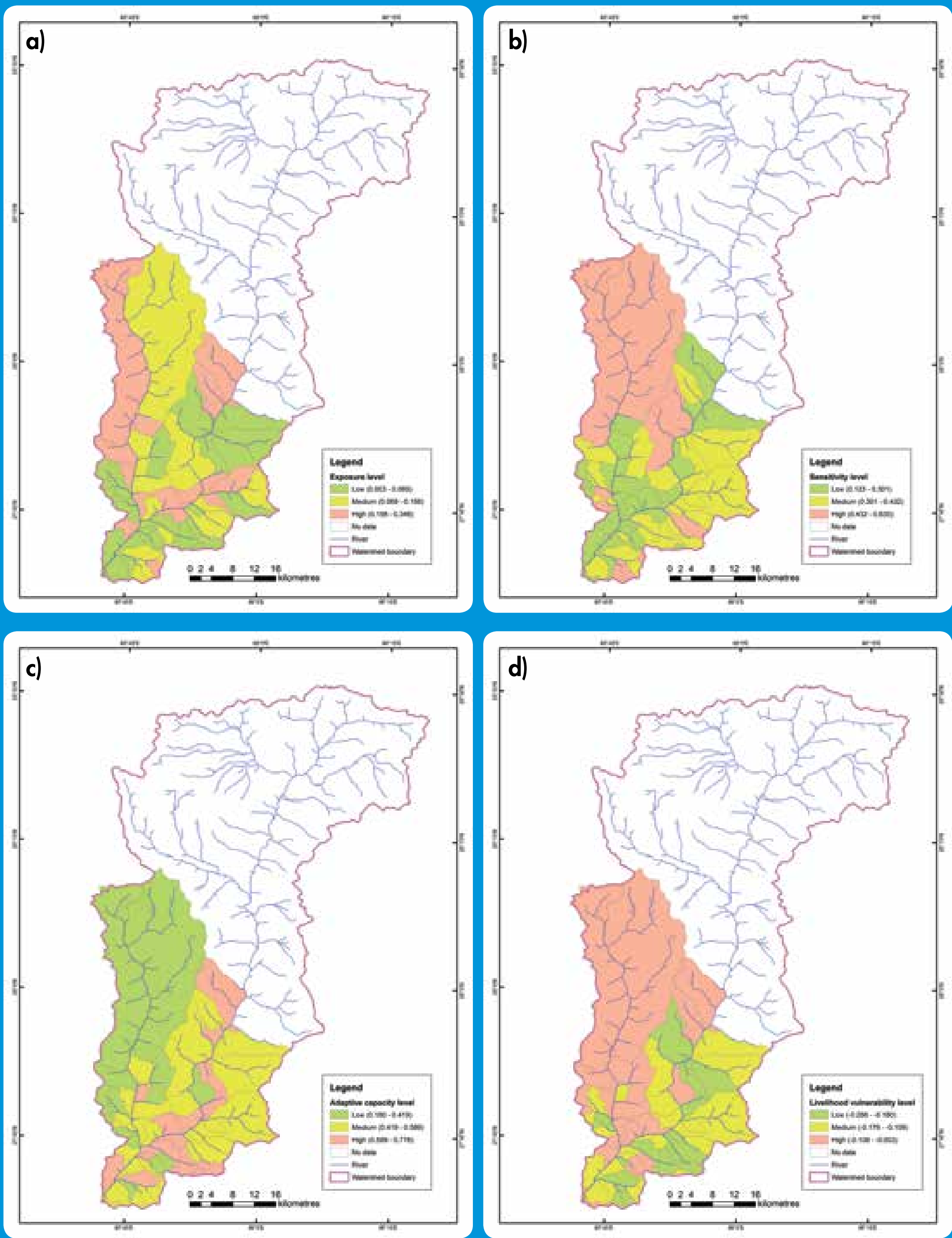


Figure 24: **Values for (a) exposure, (b) sensitivity, (c) adaptive capacity, and (d) livelihood vulnerability of the communities in the Nepal part of the study area**



northernmost part, in the Balephi sub-watershed, are relatively more sensitive to flood risk since they live in remote areas with limited access to service infrastructure such as health care, communications, and markets and are subject to severe food shortages. These more susceptible communities also have a lower adaptive capacity in terms of levels of literacy and diversification of household income. Although the adaptive capacity of communities located in accessible valleys is relatively higher, their degree of exposure to flash flooding is very high and the existing adaptive capacity is not adequate to cope. The overall livelihood vulnerability is relatively high in the poorly accessible northern parts of the Balephi and Bhotekoshi watersheds. Preparedness planning and its adoption are necessary in all the communities located within the watershed in order to reduce the prevailing risk.

Local people are aware of the causes of the different types of flash floods as they have experienced such events in the past. They also reported that severe floods have become more frequent following an increase in erratic heavy precipitation events in recent years. Based on past experience, they reported several proxy indicators for forecasting flash floods: 1) black clouds across the sky; 2) prolonged rainfall in the watershed area; 3) high intensity rainfall; 4) a sunny day following prolonged rainfall; 5) downward movement of snakes; 6) movement of crabs onto land from the river; 7) regular crying of crows and thirsty birds (kakakul); and 8) active landslides on hillsides upstream. Strategies adopted by the local people to reduce the risks of flash flooding include forestation of barren land with local tree species, sowing of grass, regulation of grazing activities, gully control and diversion of water, and construction of dykes and embankments.

National Policies and Strategies

National policies in both China and Nepal have given priority to flood risk management. The National Adaptation Strategies for Climate Change and National Disaster Reduction Plan (2006–2010) in China listed flood risk prevention as a priority. China is the only country in the Hindu Kush Himalayan region that deals with flash floods separately from other floods and disasters (Shrestha and Bajracharya, 2013). Existing policies in China ensure consideration of flash flood hazards during construction planning, and there is a mechanism for allocation of funds for their prevention. This provision includes both short-term and long-term management plans. The short-term plans focus on non-structural measures such as monitoring, telecommunication, forecasting, and warning and combines them with structural measures in specific regions. Long-term plans involve comprehensive flash flood hazard prevention and a reduction system that combines non-structural and structural measures for all flash flood prone areas.

Although there is no separate policy for dealing with flash floods in Nepal, some national policies include strategies and programmes to reduce the risk, including the Sustainable Agenda for Nepal, 2003; the Water Resource Strategy, 2002; the National Water Plan, 2005; the Disaster Reduction Strategy, 2009; the National Adaptation Programme of Action to Climate Change, 2010; and the Climate Change Policy, 2011. Monitoring of glacial lakes, implementation of structural measures, establishment of early warning systems, forecasting and preparedness in downstream communities, and support for vulnerable communities, are some of the recommended programme activities contained in the National Adaptation Programme of Action and Climate Change Policy of Nepal.

Both China and Nepal hope to strengthen cooperation and to formulate a general mechanism for information exchange. This has been listed by both countries in their international cooperation strategies and embraces plans to adapt future climate and disaster reduction (e.g. Nepal National Water Plan, 2005; China Disaster Reduction Actions, 2009).

The recently drafted National Water Resources Policy of the Government of Nepal emphasises the establishment of a Transnational Water Resource Unit. The objective is to prepare strategies for joint implementation of development projects based on mutual benefits by fostering joint understanding with the neighbouring countries. This includes the development of understanding and an atmosphere of cooperation at bilateral, multilateral, regional, and international levels.

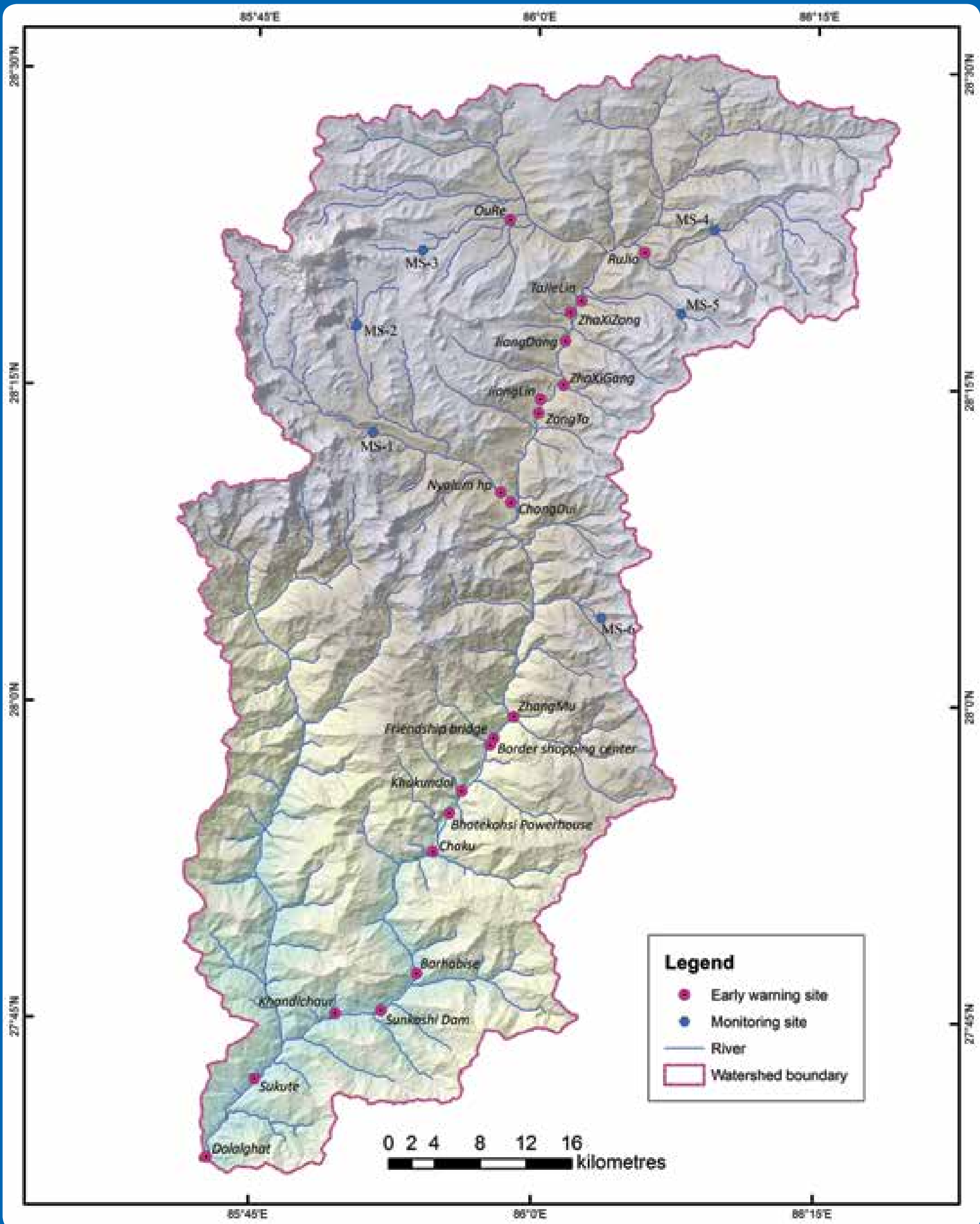
Several joint efforts have been executed in the past to assess and manage the risks attributed to GLOFs. A Sino-Nepalese investigation of glacial lake outburst floods in the Poiqu/Bhotekoshi/Sunkoshi watershed was carried out in 1987 by scientists from China, Nepal, and Canada by conducting the first expedition to the region's glaciers and glacial lakes. However, the project was not continued. Both countries have realized the need for mutual cooperation in managing flood risk along transboundary rivers, such as the Poiqu/Bhotekoshi/Sunkoshi. However, such cooperation has not yet materialized. Nepal has established an early flood warning system for the Poiqu/Bhotekoshi river downstream from the Friendship Bridge (international boundary), but because of the very short lead time, the advantages of this early warning system have not yet been fully demonstrated. Mutual cooperation between the two countries is essential.

Conclusions and Recommendations

Future climate projections suggest that average monthly temperatures will increase, especially under the A1B scenario. No clear change in precipitation is indicated, but summer monsoon season rainfall is expected to be lower than at present. Hydro-meteorological modelling suggests that future discharge in the watershed will not change significantly, but lower flow levels will be accompanied by an increase in annual maximum daily discharge levels. This suggests that the number of less severe floods will increase.

A total of 74 glacial lakes of different size were identified in the watershed. Most of them increased in area between 1991 and 2012. Of the 16 that were studied in detail, seven were classed as critical with a moderate chance of outburst, and three as very critical with a high likelihood of producing a GLOF. In view of these results, there is an urgent need to develop an active monitoring and early warning system. Following the field survey, sites recommended for monitoring were identified (Figure 25). These recommendations took into account the location of settlements and major infrastructural facilities that were determined to be at risk. Bilateral cooperation is necessary for sharing GLOF-related information at different levels of government in the two countries. This is especially important when it is considered that some of the potential GLOFs would occur high in the watershed (on Chinese territory) but extend into Nepalese territory downstream with the possibility of causing severe damage and loss of life.

Figure 25: **Recommended monitoring and early warning sites in the Bhotekoshi watershed**



Annual loss from floods within the watershed is very high compared to other hazards. Flash floods from GLOFs, triggered by heavy precipitation, from LDOFs, and triggered by tributaries blocking main streams have all caused loss of life and property in the past. Five GLOF events that have caused extensive damage have been reported since the 1930s. Loss of life from LDOFs is extremely high compared to that from other types of flash flood, although occasionally loss of life from floods triggered by heavy precipitation can also be high.

The combination of flash flood potential and rapid socioeconomic development means that losses are projected to increase. The local people have some knowledge and a limited capacity to manage these challenges, but their ability to reduce risk and manage catastrophic events is far from adequate.

The results of the risk and vulnerability analysis lead to a recommendation that flood risk management strategies should be designed to limit the exposure of life, property, and infrastructure development in areas prone to flood hazard. Similarly, means should be put in place to improve the livelihood and service facilities in the communities that are relatively more susceptible to flood damage. Limitations in time and resources meant that the study was not sufficiently comprehensive to be able to ensure the fuller understanding needed to support capacity building for risk management of flash floods in the watershed under investigation. More efforts are needed, and emphasis should be placed on assessing the magnitude of potential glacial lake outbursts and their downstream impact. It is vital to develop high resolution topographic information and carry out capacity building among the local communities. Climate and hydrological models suitable for such mountain watersheds need to be further refined.

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The Impacts of Climate Change on Water Stress Situations in the Yellow River Basin, China*

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Abstract

This study used a back-propagation (BP) neural network to conduct statistical downscaling based on data (two factors, precipitation and temperature) downscaled by the National Climate Centre of China from more than 20 general circulation models (GCMs), and input these downscaled data into a basin-wide holistic integrated water assessment (BHIWA) model to analyse the irrigation water demand and water stress situations in both water quantity and water quality in the Yellow River basin, China. The results for the changes in climate in scenarios A1B, A2, and B1 showed that the irrigation water demand will increase and the water situations will get more stressed in 2030 and 2050, although there is still some increase in precipitation in most of the sub-basins in these scenarios. Meanwhile, with the same variation range of precipitation and the reference evapotranspiration (ET_o), ET_o will have a bigger impact on irrigation water demand and water stress situations than precipitation; this implies that ET_o is a more dominant factor influencing water demand and water stress situations than other meteorological parameters such as precipitation. In addition to this, groundwater quality is more vulnerable to climate change than surface water quality and better water management will result in a decrease in irrigation water demand.

Introduction

Designated as 'the cradle of Chinese Civilization', the Yellow River basin has played a key role not only in the country's economic development but also in the historic and cultural identity of the Chinese people (Giordano et al. 2004). The water-related problems, especially the water shortage, in the Yellow River basin are a source of overwhelming concern in academic circles and among the public (Liu et al. 2004). Generally, the water resources in the Yellow River

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basin are decreasing (Zhang et al. 2009) and water stress represents the most pressing issue in basin water management (Li 2002; Liu et al. 2003). As such, addressing the problem of water scarcity is the number one priority in Yellow River basin management (Huang et al. 1995).

Moreover, the streamflow in the Yellow River basin will possibly continue to decline due to climate change, which may further increase the vulnerability of water supply for poor people in the basin (Liu 1997; Xu et al. 2008). Studies from Yang et al. (2004) and Cong et al. (2009) indicated that apart from the rapid increase in artificial water consumption, the drier climate that has existed since the 1990s is the main cause of the aggravation of the drying up downstream of the Yellow River during the same period. Gou et al. (2007) also stated that annual streamflow of the Yellow River has decreased in recent years (1980 to 2000) because of climate change and human activity. In addition, the trend of natural runoff is roughly consistent with precipitation change trend, overall in a declining trend, reduction of runoff is greater than precipitation (Yellow River Conservancy Commission (YRCC) 2008). With the application of a general circulation model (GCM) and a hydrological model, Liu (1997) predicted that the water deficit in the Yellow River basin will reach 1.9–12.1 billion cubic metres as a result of climate change. Studies from Xia et al. (2005) and Ye (2006) show that climate factors will have a significant impact on the course of hydrology; an increase in precipitation by 10% will exert greater impact on runoff than a decrease by 10%. Hao et al. (2006) predicted that in the coming 100 years, the temperature in the source region of the Yellow River will continue to increase, and evaporation will significantly increase even with some increase in precipitation. Overall, the future climate change will cause a reduction in the volume of water resources to a certain extent.

This study was designed to help in analysing the impact of climate change on future water stress situations and irrigation water demand. Climate change adaptation and mitigation strategies and policies, integrated with the development policies, including economic, social, and other environmental dimensions, are helpful for the sustainable development of the Yellow River basin. Accordingly, agricultural water savings will help enhance the potential for adaptation to climate change in order to achieve the ultimate goal towards optimal water productivity – or output of 'crop per drop'. So the primary objectives of this study are: (a) to estimate the future water situations under different scenarios of climate change; and (b) to determine some optimal water management options to mitigate the impact of climate change on future water stress situations.

Methods

Study area

The Yellow River is the second longest river in China and the sixth longest in the world. The Yellow River gets its name from the colour of the heavy sediment concentration that it transports while flowing through an extensive loess plateau covering 640,000 km^2. It is estimated to have carried an average 1.6 billion tons of sediment each year in recent decades

Table 16: River-reach parameters of the Yellow River

Reach	Drain area (km²)	River length (km)	Elevation drop (m)	Channel slope (1/1,000)	No. of tributaries
Upper	428,000	3,470	3,500	10	43
Middle	344,000	1,200	890	7	30
Lower	23,000	790	90	1	3
Basin total	795,000	5,460	4,480	8	76

Source: YRCC 2002

(Giordano et al. 2004). The river drains a basin of 795,000 km², with an east-west extent of 1,900 km and a north-south extent of 1,100 km. The river is commonly divided into eight sub-basins for analysis. Table 16 shows the characteristic parameters of the three river reaches.

The Yellow River basin is located in the mid-north of China and is classified as a monsoon climate. The region is humid in the southeast, semi-arid in the middle, and arid in the northwest. The average temperature is -4.0 to 9.3°C in the upper reach, 9.4 to 14.6°C in the middle reach, 14.2°C in the lower reach, and 4 to 14°C over the entire basin. The average rainfall during 1956–2000 was 372 mm in the upper reach, 523 mm in the middle reach, 671 mm in the lower reach, and 454 mm over the entire basin. The irrigated area is less than half of the rainfed area. The annual irrigation from existing major, medium, and minor surface water projects was in the order of 5.04 million ha in 2000. Wheat, maize, cotton, and oil crops are the dominant crops.

While the Yellow River basin has played and continues to play a critical role in China's social and economic development, it, in fact, has relatively limited water resources (Wang et al. 2001; Giordano et al. 2004). Water use in the Yellow River basin is currently considered to come from two sources, ground and surface, and serve three sectors: agriculture, industry, and domestic. Data on use by source and sector for recent years is shown in Table 17. As seen in the table, the average annual withdrawal from the Yellow River basin has been

Table 17: Yellow River basin water withdrawal, 1998-2000 (BCM).

Year	By source			By sector				
	Surface water	Groundwater	Total	Agriculture	Industry	Urban	Rural	Total
1998	37	12.7	49.7	40.5	6.1	1.6	1.5	49.7
1999	38.4	13.3	51.7	42.6	5.7	1.8	1.5	51.7
2000	34.6	13.5	48.1	38.1	6.3	2.1	1.6	48.1
Average	36.7	13.2	49.8	40.4	6	1.8	1.5	49.8
Share	74%	26%	100%	81%	12%	4%	3%	100%

Note: Groundwater withdrawal includes 2.7 BCM pumping in regions lower than Huayuankou.
Source: 1998, 1999, and 2000 YRCC water bulletins.

approximately 50 billion m^3 (BCM), of which approximately 74% was from surface water and 26% was from groundwater. Agriculture is by far the largest user of water, accounting for 80% of the total withdrawal, with industrial, urban, and rural domestic sectors sharing the remaining 20%.

Water scarcity, overuse of resources, and environmental degradation are now rising to the top of the water management agenda in the Yellow River basin. As shown from data during 1956 to 2006, the decrease of outflow to the sea in the basin is much more prominent than the decrease in precipitation. So apart from the rapid increase of irrigation water consumption, climate change, particularly the increase of temperature and decrease of precipitation, could be the dominant drivers for the decrease of runoff in this river basin.

Models Methodology

In this paper, a basin-wide holistic integrated water assessment (BHIWA) model (Mu et al. 2008) developed by the International Commission on Irrigation and Drainage (ICID) was first used to assess future water needs under different scenarios of development and management, and then to analyse the impact of different policy options on the volume of water availability and water stress situation at the basin level (Yellow River basin), after calibration with simulated and observed current data. This will eventually be used to optimize water allocations among agricultural, industrial, domestic, and environmental sectors within a basin context. The BHIWA model uses an environmental and water cycle simulation approach. The BHIWA model is a semi-lumped model with a Microsoft Excel interface. It is able to account for the whole land phase of the hydrological cycle, including the consideration of hydrological changes due to changes in land use and agricultural use. The model is capable of depicting surface and groundwater balances separately and allowing interaction between them, as well as defining the impacts of storage and depletion through withdrawals. Four water situation indicators were propounded in the model to depict the level of water use (withdrawals) and potential risks (due to return flows) to water quality:

- Indicator 1: Total surface water withdrawal/Total surface water inputs
- Indicator 2: Total returns to surface water/Total surface water inputs
- Indicator 3: Total groundwater withdrawals/Total groundwater inputs
- Indicator 4: Total returns to groundwater/Total groundwater inputs

Then a back-propagation (BP) neural network was used to conduct statistical downscaling on the data (two factors only, precipitation and temperature) downscaled by the National Climate Centre of China from over 20 GCMs. Scenarios for climate change were developed based on the downscaled results and were then applied to the BHIWA model to analyse the impacts of various climate change scenarios on future irrigation water demand and water stress situations in the Yellow River basin.

The original BHIWA model developed by the International Commission on Irrigation and Drainage (ICID) was only suitable for application in small basins. To extend its application into a large river basin, the authors updated it for this paper. The updates to the model include extending the maximum number of sub-basins from the previous five to eight, and changing some input data from constants for the whole basin to variables at the sub-basin level. For example, the model constants, like the proportion of excess rainfall after meeting potential evapotranspiration (PET) requirements and soil moisture capacity, which contributes towards surface runoff (quick runoff)/ground water storage, the exponential index linking soil moisture availability to the actual evapotranspiration (AET)/PET ratio, and the recession coefficient for groundwater reservoir have been changed into variables for the sub-basins. All temporal data which changes with time but does not change with sub-basins in the original ICID BHIWA model, like soil moisture capacity, return flow and irrigation system efficiencies, K factors (crop coefficient), agricultural factors, irrigation factors, and paddy factors, have been changed by the authors to vary with sub-basins as well. This is helpful in assessing future water demand and exploring relevant water development and management policies in larger river basins.

However, the BHIWA is not a distributed hydrologic model and cannot deal with each land use geographically distributed throughout the basin (Khan et al. 2005). All such parcels need to be conceptually lumped into a single land use unit. The BHIWA model also does not depict the spatial variations in rainfall, potential evapotranspiration, intensities of cropping, or irrigation, or slow horizontal groundwater movement from one area to another.

Results and Discussion

Observed climate change in the Yellow River basin

In the past 50 years, the air temperature has shown a significant increasing trend in the Yellow River basin (Jia et al. 2007), which is consistent with global warming. The temperature has increased by 0.5–3°C in most parts of the basin, and the mean temperature has increased by 1.5°C. While the mean annual precipitation fluctuations show a decreasing trend in the basin in general over the past 50 years, as shown by Figure 26. The average precipitation during 1956–1960 was 463 millimetres, while the average precipitation during 2001–2006 was 444 millimetres, a difference of 19 millimetres, or 4.1%. Qiu et al. (2003) found that though the average annual temperature in the Yellow River basin increased during 1960–2000, the pan evaporation decreased significantly. The pan evaporation in the 1970s was equivalent to that in the 1960s, and the pan evaporation in the 1990s was equivalent to that in the 1980s, but the pan evaporation during the 1970s–1980s decreased by 136 mm, or 7.5% than that during the 1960s–1970s. Meanwhile, the pan evaporation increased

Figure 26: **Mean annual precipitation in the Yellow River basin 1956-2006**

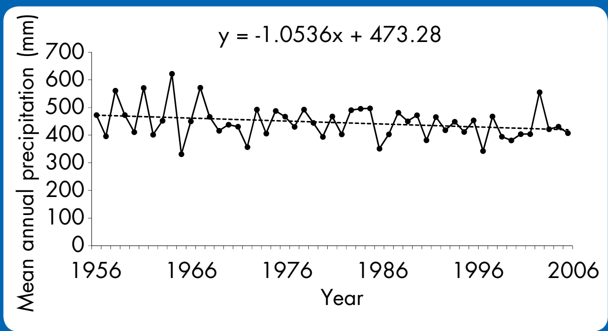


Table 18: **Statistics of pan evaporation in the Yellow River basin in different decades (mm)**

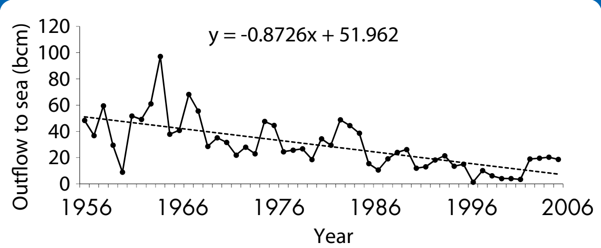
Decades	Climatic zone					Season			
	Whole basin	Arid zone	Semi-arid zone	Semi-humid zone	Humid zone	Spring	Summer	Autumn	Winter
1960-69	1810	2260	2000	1660	1280	600	740	330	160
1970-79	1800	2230	1990	1660	1350	600	710	330	160
1980-89	1660	2140	1870	1500	1210	550	640	310	150
1990-99	1690	2120	1860	1560	1220	530	650	330	160

a little in the 1990s than that in the 1980s. Moreover, they added that the decrease of pan evaporation mainly occurred in summer and spring, while there was little change in autumn and winter, as shown in Table 18. Cong et al. (2006) observed that pan evaporation, precipitation, and runoff in the Yellow River basin had all decreased in the past 50 years. Studies from Liu (2004) revealed that though pan evaporation trends were downward, the actual evaporation increased significantly (Liu, 2004). The decline in pan evaporation mainly results from the drop in global radiation, while the increase of actual land surface evaporation is caused by the increasing irrigation water consumption. The decrease of outflow to the sea in the Yellow River basin from 1956–2006 is much more prominent than the decrease of precipitation (Figure 27). Therefore apart from the rapid increase of irrigation water consumption, climate change, particularly the increase of temperature and decrease of precipitation, could be the drivers for the decrease of runoff in this river basin. This has already been verified by one study carried out in China (Jia et al. 2008). The decrease in runoff will result in degradation of the environment, posing more challenges to the sustainable development of water resources in this river basin.

Statistical downscaling of GCMs

The simulated effects for future climate changes are different from various GCMs; it has been shown by some scientists that the effects from the average of many models are better than those from a single model. Therefore, after interpolating and downscaling the simulated results from over 20 GCMs with different resolutions from the fourth report of the Intergovernmental Panel on Climate Change (IPCC), the National

Figure 27: **Outflow to sea 1956-2006**



Climate Centre of China integrated these into one resolution, and validated its simulated effects in East Asia. Integrating the multi-models with the reliability ensemble averaging (REA) method, the National Climate Centre of China came up with a set monthly average data (two factors, precipitation and temperature) between 1901 and 2100 for use by scientists conducting research on climate change impacts (17 models averaged for A1B and A2, and 16 for A2) (averaging) (Xu et al. 2009; Giorgi et al. 2002 and 2003). The resolution for these climate change projection products is 1°×1°.

However, since the grid size of the generated GCM outputs are relatively large, downscaling of the output data should be conducted when using the simulated results from GCMs. There are two downscaling methods: statistical and dynamic. This research used the simpler statistical downscaling approach, which included three statistical methods: transfer function, circulation based differentiation, and using weather producer. The commonly used method in transfer function is multiple linear regressions, such as stepwise regression, integrated principal component analysis (PCA) and multiple linear regression, integrated PCA and stepwise regression, etc. In addition to this, it also includes some nonlinear methods, such as neural network. This research used a BP neural network to conduct statistical downscaling By first, building the relations between the observed precipitation in 1956–2000 and the predicted precipitation from GCMs in 2001–2049 with the BP neural network, then predicting the precipitation in 2001–2049 based on the predicted precipitation from GCMs in 2001–2049 and the built BP neural network model. The temperature in the study area in 2001–2049 can also be predicted with the same method. The average values generated from GCMs from Sub-basin 1 to Sub-basin 8 were used for statistical downscaling.

The annual precipitation in the eight sub-basins with A1B, A2, and B1 three different emission scenarios are shown in Figures 28, 29, and 30. Table 19 shows the variation range of the predicted precipitation and temperature in the coming 20 (2010–2030) and 40 years (2010–2050) compared to the historical annual averages (1956–2000).

As shown from Table 19, the precipitation and temperature in the coming 40 years will vary differently in each sub-basin under different emission scenarios. The precipitation in Sub-basin 3, Sub-basin 6 and Sub-basin 7 during 2010–2030 and 2030–2050 increases by over 5% under the A1B scenario, but decreases in sub-basin 3 and sub-basin 5 by around 10% in 2030–2050 under the A2 scenario, and by 5% and 12% respectively in sub-basin 6 and sub-basin 8 in 2030–2050 under scenario B2. Meanwhile, in most sub-basins, the temperature will increase under various scenarios. In particular in Sub-basin 4 and Sub-basin 8, the temperature under the A2 and B1 scenarios will increase by over 20% during both 2010–2030 and 2030–2050. But it is projected that the temperature in Sub-basin 1 during 2010–2030 will drop by around 10% under the A1B scenario, and by over 30% under both A2 and B1 scenarios during 2010–2030.

Table 19: **Predicted precipitation and temperatures under different emission scenarios for each sub-basin between 2010–2030 and 2030–2050**

Sub-basin	Emission Scenario	1956–2000		2010–2030		2030–2050	
		Precipitation	Temp	Precipit	Temp	Precipit	Temp
SB-1	A1B	486	-2.2	485	-2.0	531	-2.9
	A2	486	-2.2	493	-1.6	477	-1.1
	B1	486	-2.2	486	-1.5	515	-2.5
SB-2	A1B	479	1.1	477	1.9	570	2.3
	A2	479	1.1	480	1.9	515	2.3
	B1	479	1.1	483	1.2	529	1.9
SB-3	A1B	262	7.1	278	6.6	280	6.5
	A2	262	7.1	258	7.2	240	5.9
	B1	262	7.1	268	5.8	269	5.8
SB-4	A1B	434	8.5	434	7.8	435	7.6
	A2	434	8.5	423	10.3	426	10.3
	B1	434	8.5	444	10.3	447	10.3
SB-5	A1B	540	9.8	532	11.2	544	11.2
	A2	540	9.8	521	9.0	498	8.9
	B1	540	9.8	548	11.3	549	11.3
SB-6	A1B	658	12.7	709	11.8	705	11.7
	A2	658	12.7	644	13.6	670	13.6
	B1	658	12.7	595	12.7	627	12.7
SB-7	A1B	648	12.3	785	13.3	736	13.4
	A2	648	12.3	662	11.8	674	11.8
	B1	648	12.3	646	11.8	685	11.8
SB-8	A1B	272	7.6	281	6.5	268	6.5
	A2	272	7.6	298	9.4	310	9.5
	B1	272	7.6	255	9.5	239	9.5

Scenarios development for climate change

General circulation models (GCM) are powerful tools accounting for the complex set of processes which will produce future climate change (Karl et al. 2003). However, GCM projections are currently subject to significant uncertainties in the modelling process (Mearns et al. 2001; Allen et al. 2002; Forest et al. 2002), so that climate projections are not easy to incorporate into hydrological impact studies (Allen et al. 2002). Therefore there is a wide range in results for the projection of both precipitation and temperature (the major factor driving evapotranspiration) changes. In addition to this, there are also significant differences in the projections from different scenarios in the same GCMs. In particular, what makes it difficult to gauge the reliability of results for precipitation changes is that some models predict increase under climate change while others predict decrease. So the present research developed scenarios not only based on the outputs directly generated from GCMs, but also referring to studies made by other scientists, giving some increasing or decreasing

Figure 28: **Sub-basin-wise predicted precipitation from model A1B**

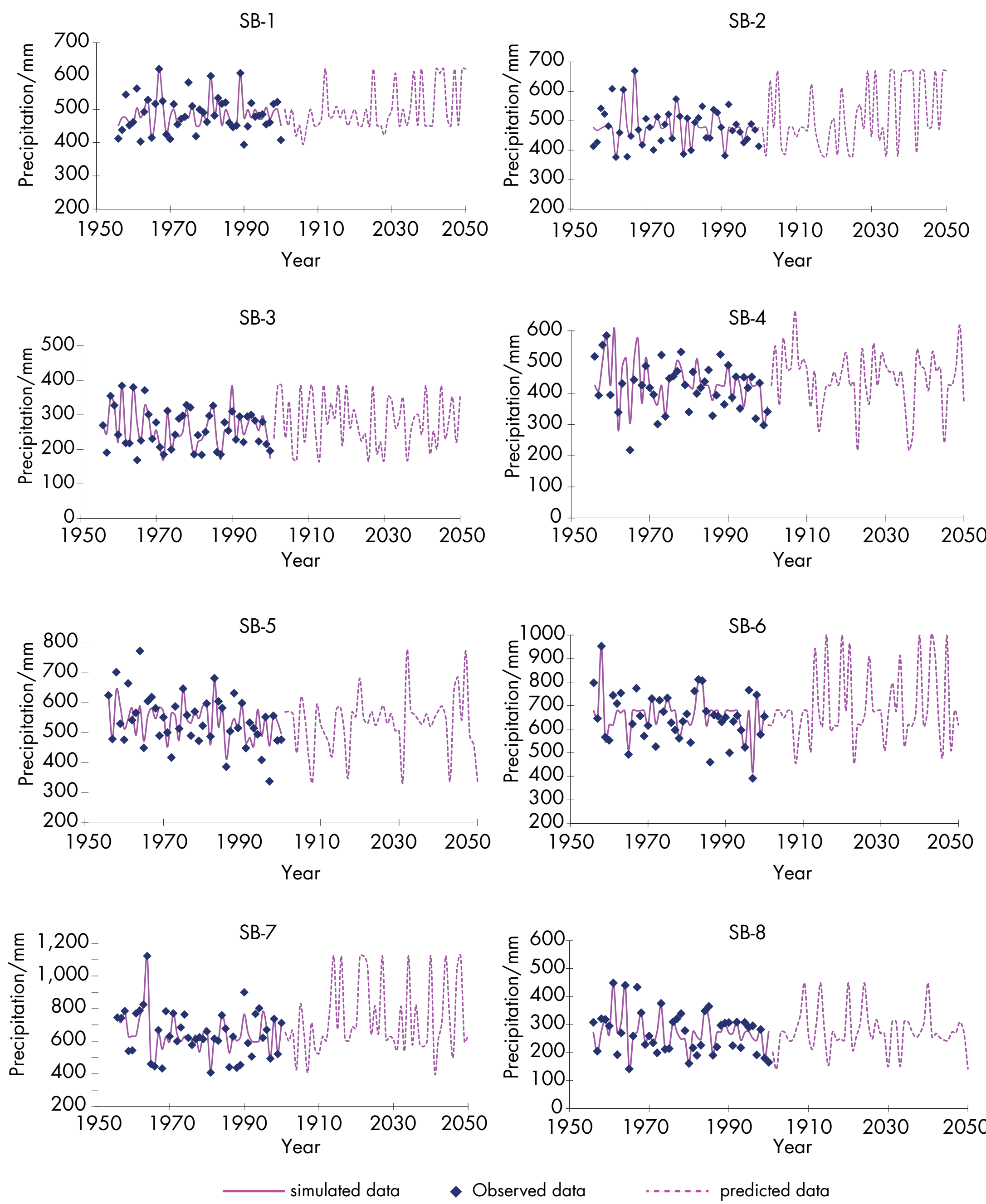


Figure 29: **Sub-basin-wise predicted precipitation from model A2**

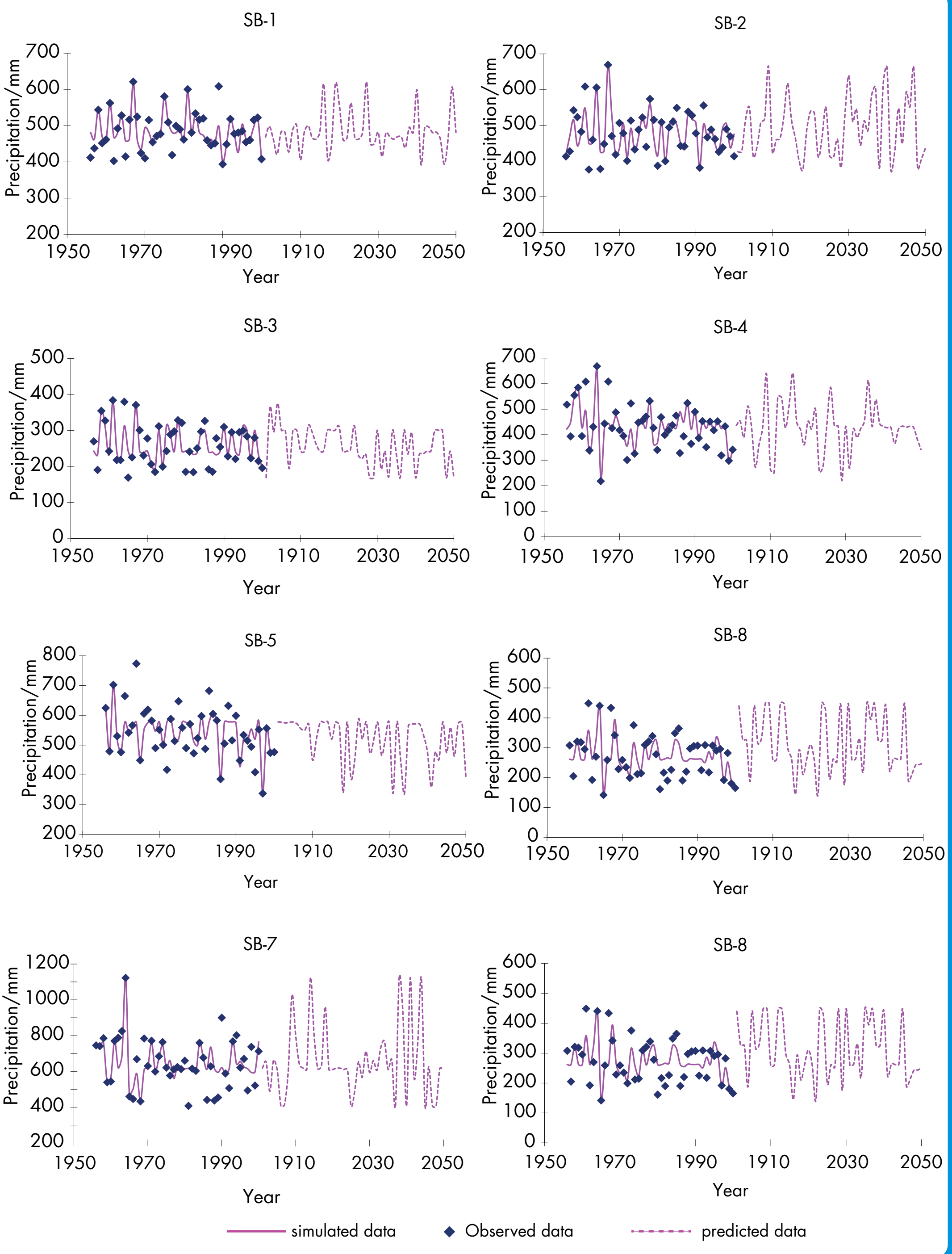
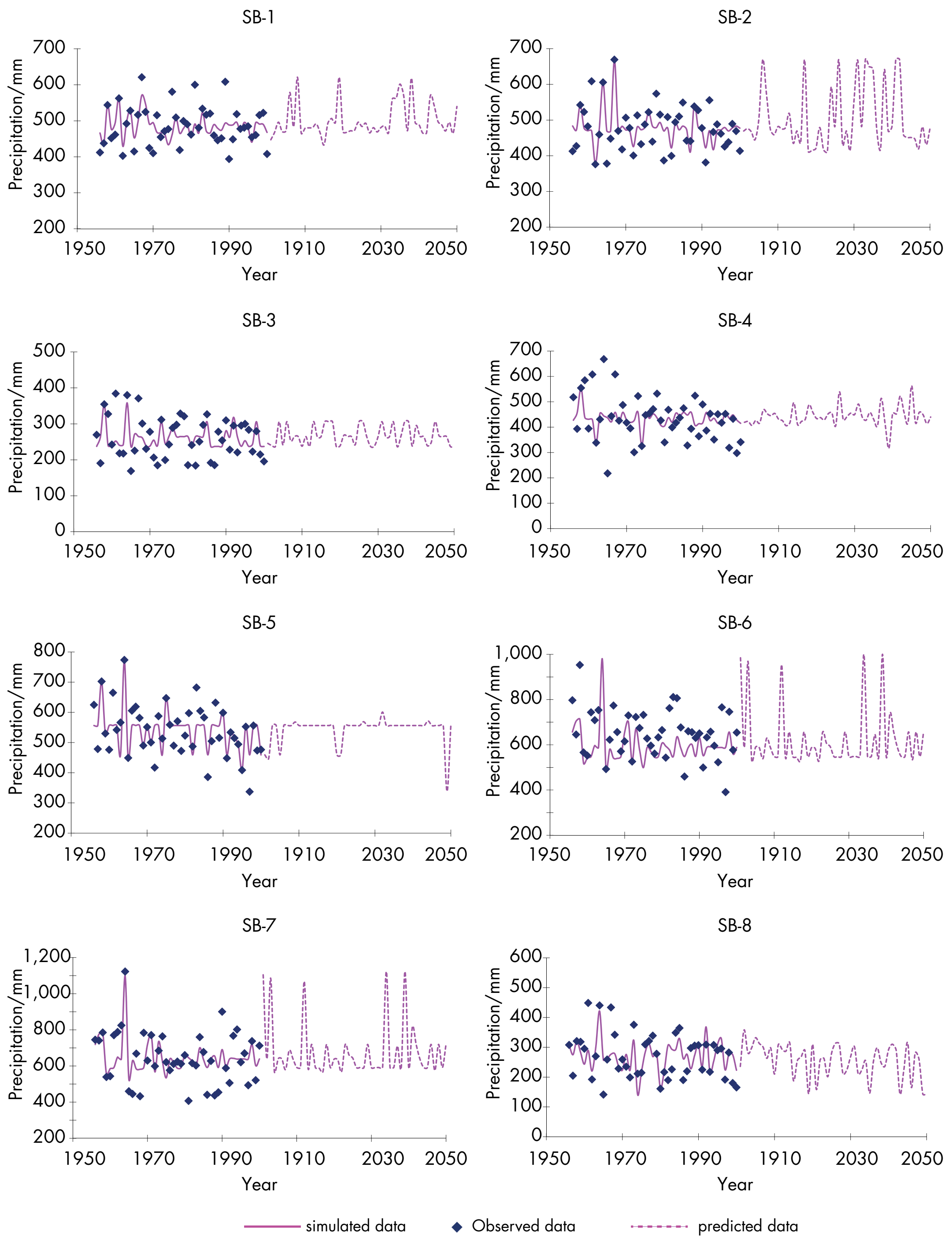


Figure 30: **Sub-basin-wise predicted precipitation from model B1**



percentages for precipitation and ET_o in the BHIWA model, two major meteorological factors that drive irrigation water demand. ET_o is reference evapotranspiration, which can be calculated using the Penman-Monteith method (Allen et al. 1998) (eq. 1). It can be seen from this equation that air temperature (T) is a major driver for the calculation of ET_o. However, this research did not consider the calculation of ET_o by developing scenarios for air temperature, due to the lack of other meteorological data, such as radiation, wind speed, and so on, in the Yellow River basin.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where

ET_o	reference evapotranspiration [mm day^{-1}]
R_n	net radiation at the crop surface [MJ m^{-2} day^{-1}]
G	soil heat flux density [MJ m^{-2} day^{-1}]
T	mean daily air temperature at 2 m height [°C]
u_2	wind speed at 2 m height [m s^{-1}]
e_s	saturation vapour pressure [kPa]
e_a	actual vapour pressure [kPa]
e_s-e_a	saturation vapour pressure deficit [kPa]
Δ	slope vapour pressure curve [kPa °C^{-1}]
γ	psychrometric constant [kPa °C^{-1}]

With the rationale mentioned above and the projections generated from GCM models, six scenarios were developed in 2030 and 2050, on the basis of the mean annual values in the Yellow River basin. The scenarios for future climate change in terms of precipitation and ET_o are summarized in Table 20, neglecting the impact of the other meteorological factors. Out of these, only the scenarios of S-A2 for both precipitation and ET_o, of S-A1B for precipitation, of S-B1 for precipitation, and of S-B2 for ET_o were directly generated from GCM model; the others were developed by giving some increasing or decreasing percentage to give a rough understanding of how much climate change will impact the future water stress situation in the Yellow River basin. Scenario 4 (S-4) is the worst scenario with precipitation decreasing by 5% and 10% in 2030 and 2050, respectively, while ET_o increased by 10% and 15% in years 2030 and 2050, respectively, in all the sub-basins; the precipitation will increase by 5% and 10% in 2030 and 2050, respectively; while ET_o will decrease by 10% and 15%, respectively, in 2030 and 2050 in Scenario 5; and in Scenario 6 (S-6) both precipitation and ET_o will decrease, by 5% in 2030 and by 10% in 2050, respectively, in all the sub-basins.

Moreover, scenarios with long-term average annual values of rainfall (1956–2000) and ET_o (1980–2000) were used as the benchmark for scenario development with climate change. Under the benchmark scenario, only future water and agricultural development were considered. There are a total of four scenarios in each of 2030 and 2050 under the

Table 20: **Scenarios for climate change in the Yellow River basin in 2030 and 2050**

Sub-basin	Emission scenario	1956–2000		2010–2030		2030–2050	
		Precip	ET_o	Precip	ET_o	Precip	ET_o
SB-1	S-A1B	486	830	485 (0%)	910 (+10%)	530 (+9%)	960 (+15%)
	S-A2			493 (+1%)	880 (+6%)	477 (-2%)	950 (+14%)
	S-B1			486 (0%)	910 (+10%)	515 (+6%)	950 (+14%)
	S-4			462 (-5%)	910 (+10%)	437 (-10%)	960 (+15%)
	S-5			510 (5%)	750 (-10%)	535 (10%)	710 (-15%)
	S-6			462 (-5%)	790 (-5%)	437 (-10%)	750 (-10%)
SB-2	A1B	479	830	477 (0%)	910 (+10%)	570 (+19%)	960 (+15%)
	A2			480 (0%)	860 (+4%)	515 (+7%)	920 (+11%)
	B1			483 (+1%)	910 (+10%)	529 (+10%)	910 (+10%)
	S-4			455 (-5%)	910 (+10%)	431 (-10%)	950 (+15%)
	S-5			503 (5%)	750 (-10%)	527 (10%)	710 (-15%)
	S-6			455 (-5%)	790 (-5%)	431 (-10%)	750 (-10%)
SB-3	A1B	262	1210	278 (+6%)	1330 (+10%)	280 (+7%)	1390 (+15%)
	A2			258 (-1%)	1280 (+6%)	240 (-8%)	1370 (+13%)
	B1			268 (+2%)	1360 (+12%)	269 (+3%)	1370 (+13%)
	S-4			249 (-5%)	1330 (+10%)	236 (-10%)	1390 (+15%)
	S-5			275 (5%)	1090 (-10%)	288 (10%)	1030 (-15%)
	S-6			249 (-5%)	1150 (-5%)	236 (-10%)	1090 (-10%)
SB-4	A1B	434	1290	434 (0%)	1420 (+10%)	435 (0%)	1480 (+15%)
	A2			423 (-2%)	1340 (+4%)	426 (-2%)	1420 (+10%)
	B			444 (+2%)	1420 (+10%)	447 +3%)	1430 (+11%)
	S-4			412 (-5%)	1420 (+10%)	391 (-10%)	1480 (+15%)
	S-5			456 (5%)	1160 (-10%)	477 (10%)	1100 (-15%)
	S-6			412 (-5%)	1230 (-5%)	391 (-10%)	1160 (-10%)
SB-5	A1B	540	910	532 (-1%)	1000 (+10%)	544 (+1%)	1050 (+15%)
	A2			521 (-4%)	960 (+5%)	498 (-8%)	1010 (+15%)
	B1			548 (+1%)	1010 (+11%)	549 (+2%)	1020 (+15%)
	S-4			513 (-5%)	1000 (+10%)	486 (-10%)	1050 (+15%)
	S-5			567 (5%)	820 (-10%)	594 (10%)	770 (-15%)
	S-6			513 (-5%)	870 (-5%)	486 (-10%)	820 (-10%)
SB-6	A1B	658	950	709 (+8%)	1050 (+10%)	705 (+7%)	1090 (+15%)
	A2			644 (-2%)	1000 (+5%)	670 (+2%)	1060 (+11%)
	B1			595 (-10%)	1050 (+11%)	627 (-5%)	1060 (+12%)
	S-4			625 (-5%)	1040 (+10%)	592 (-10%)	1090 (+15%)
	S-5			691 (5%)	850 (-10%)	724 (10%)	810 (-15%)
	S-6			625 (-5%)	900 (-5%)	592 (-10%)	850 (-10%)

Sub-basin	Emission scenario	1956–2000		2010–2030		2030–2050	
		Precip	ET_o	Precip	ET_o	Precip	ET_o
SB-7	A1B	648	940	785 (+21%)	1030 (+10%)	736 (+14%)	1080 (+15%)
	A2			662 (+2%)	1040 (+11%)	674 (+4%)	1160 (+23%)
	B1			646 (0%)	1170 (+24%)	685 (+6%)	1180 (+25%)
	S-4			616 (-5%)	1030 (+10%)	583 (-10%)	1080 (+15%)
	S-5			680 (5%)	850 (-10%)	713 (10%)	800 (-15%)
	S-6			616 (-5%)	890 (-5%)	583 (-10%)	850 (-10%)
SB-8	A1B	272	1560	281 (+3%)	1720 (+10%)	268 (-1%)	1790 (+15%)
	A2			298 (+10%)	1790 (+11%)	310 (+14%)	1950 (+25%)
	B1			255 (-6%)	2030 (+30%)	238 (-12%)	2030 (+30%)
	S-4			258 (-5%)	1720 (+10%)	245 (-10%)	1790 (+15%)
	S-5			286 (5%)	1400 (-10%)	299 (10%)	1330 (-15%)
	S-6			258 (-5%)	1480 (-5%)	245 (-10%)	1400 (-10%)

Note: – the numbers in the brackets show the increase or decrease percentage and zero means no change

benchmark scenario without considering climate change, i.e., F-I 2030 to F-IV 2030 and F-I 2050 to F-IV 2050. The scenarios studied included emerging possibilities, developmental plans, and the adoption of improved water and soil management practices. In particular, the west route of the South-to-North Water Transfer Project which diverts water from the Yangtze River to the Yellow River was considered in future scenarios. However, neither a major shift from water intensive crops nor changes in livelihood patterns and food imports (virtual water trading) from other basins were considered. There are plans and possibilities for increasing storage, extending or rehabilitating some existing irrigation districts, and constructing some new irrigation schemes in some sub-basins. Considering these factors, various scenarios studied under the benchmark were formulated. They are shown in Table 21.

Results from climate change impacts

The six scenarios in Table 20 and the benchmark scenario were applied to the BHIWA model to analyse the impact of climate change on future water demand and water stress situations in the Yellow River basin. The simulated results for irrigation water demand and water situation indicators under different climate change scenarios in 2030 and 2050 are summarized in Tables 22 and 23.

In Scenario A1B with unchanged or increase in both precipitation and ET_o in most of the sub-basins in 2030 and 2050, except in SB-5 and SB-8 with a small decrease in precipitation in 2030 and 2050, respectively, the total irrigation water demand from both surface water and groundwater increased due to the increase of evapotranspiration, by 14–15% in future scenarios for 2030 and by 22% in future scenarios for 2050. The water stress situations will get worse in the future, particularly for surface water quantity, and groundwater quantity and quality. For example, Indicator 1 (withdrawals/ total input to surface water) increased from 0.44 to 0.48 in Future-I (B as U) 2030, and from 0.40 to 0.43 in Future-I (B as U) in 2050;

Table 21: Brief description of future water and agricultural development scenarios

Scenarios		Key attributes	Brief description
2030	Future-I (B as U)	Business as usual with South-to-North Water Transfer project	Irrigation expansion with a proportionate increase in surface irrigation due to more water storage, diversion and lifting schemes as well as the South-to-North Water Transfer project, the coverage rate of forest increases by 6% based on current development speed, and a slight improvement in water management (system efficiencies)
	Future-II	With more irrigation expansion and shift in cropping pattern	The coverage rate of forest maintains the same level as that in 2000, shift in cropping pattern, and better water management
	Future-III	With more industrialization and better water management	Agricultural development similar to F-2 2030, greater development of industries in the basin requiring 50% more withdrawal for industrial water use, and better water management
	Future-IV	With adjustment of groundwater use and more water for environment	Increase in groundwater irrigation in the upper reaches of the Yellow River basin, reduction in groundwater irrigation in the middle and lower reaches due to overexploitation, better water management, and more allocation of water for the environment.
2050	Future-I (B as U)	Business as usual with South-to-North Water Transfer project	Irrigation expansion with a proportionate increase in surface irrigation due to more water storage, diversion, and lifting schemes as well as the South-to-North Water Transfer project, the coverage rate of forest increases by 10% based on current development speed, and a slight improvement in water management
	Future-II	With more irrigation expansion and shift in cropping pattern	The coverage rate of forest maintains the same level as that in 2000, shift in cropping pattern, and better water management
	Future-III	With more industrialization and better water management	Agricultural development similar to F-II 2050, greater development of industries in the basin requiring 50% more withdrawal for industrial water use, and better water management
	Future-IV	With adjustment of groundwater use and more water for environment	Increase in groundwater irrigation in the upper reaches of the Yellow River basin, reduction in groundwater irrigation in the middle and lower reaches due to overexploitation, better water management, and more allocation of water for the environment

Indicator 3 (withdrawals/ total input to groundwater) increased from 0.35 to 0.38 in Future-I (B as U) in 2030, and from 0.37 to 0.41 in Future-I (B as U) in 2050; Indicator 4 (returns/ total input to groundwater) increased from 0.19 to 0.22 in Future-I (B as U) in 2030, and from 0.14 to 0.17 in Future-I (B as U) in 2050; while Indicator 2 (returns/total input to surface water) remained nearly unchanged in all future scenarios, which means that the variation of evapotranspiration has little impact on surface water quality. In general, the variation of evapotranspiration has a major impact on future water demand and water stress situations. A slight increase in ET_o will result in a big increase in irrigation water demand, and higher stressed water situations in terms of both quantity and quality.

All of the changes in both precipitation and ET_o in the future for Scenario A2 were generated from GCM models. It can be seen from Table 22 that the total irrigation water demand also increased in 2030 and 2050, but the irrigation water demand increased less in 2030 and more in 2050 compared to Scenario A1B. The changes in water situation indicators in this scenario are quite similar to Scenario A1B except for a slightly greater increase in Indicator 3 in 2050.

Table 22: **Irrigation water demand under different climate change scenarios in 2030 and 2050 (106 m^3)**

Scenarios	2030				2050			
	F-I	F-II	F-III	F-IV	F-I	F-II	F-III	F-IV
Bench mark	31100	28900	28900	25900	28800	26800	26800	23700
S-A1B	35600	33100	33100	29600	35000	32600	32600	28800
	(14%)	(15%)	(15%)	(14%)	(22%)	(22%)	(22%)	(22%)
S-A2	34800	32300	32300	29000	36300	33800	33800	29900
	(12%)	(12%)	(12%)	(12%)	(26%)	(26%)	(26%)	(26%)
S-B1	38300	35600	35600	31700	35300	32800	32800	29100
	(23%)	(23%)	(23%)	(22%)	(23%)	(22%)	(22%)	(23%)
S-4	37400	34600	34600	30900	38400	35800	35800	31600
	(20%)	(20%)	(20%)	(19%)	(33%)	(34%)	(34%)	(33%)
S-5	25800	24300	24300	21700	20700	19200	19200	17000
	(-17%)	(-16%)	(-16%)	(-16%)	(-28%)	(-28%)	(-28%)	(-28%)
S-6	25800	24300	24300	21700	20700	19200	19200	17000
	(-17%)	(-16%)	(-16%)	(-16%)	(-28%)	(-28%)	(-28%)	(-28%)

The total irrigation water demand increased by 22%–23% in Scenario B1 for 2030 and 2050; there is little change in irrigation water demand in the future under this scenario, but the irrigation water demand will increase more than in Scenarios A1B and Scenario A2. Meanwhile, the surface water quantity, and the groundwater quantity and quality, will get worse in the future, but there is little change in the water situation in surface water quality. This means that the increase in both precipitation and ET_o could offset their impact on surface water quality.

In Scenario 4 with precipitation decreased by 5% and 10% while ET_o increased by 10% and 15% respectively in 2030 and 2050, the irrigation water demand increased significantly, by 19–20% in 2030 and by 33–34% in 2050, which means that there will be more water deficit in the future, in particular in 2050. The surface water and groundwater will get into the most stressed situations in both quantity and quality in this scenario as well, with Indicator 1 increased from 0.44 to 0.49 in Future-I (B as U) in 2030, and from 0.40 to 0.47 in Future-I (B as U) in 2050; Indicator 3 increased from 0.35 to 0.41 in Future-I (B as U) in 2030 and from 0.37 to 0.46 in Future-I (B as U) in 2050; Indicator 2 remained relatively unchanged, but Indicator 4 increased markedly, from 0.19 to 0.24 in Future-I (B as U) in 2030, and from 0.14 to 0.20 in Future-I (B as U) in 2050. This means that climate change will have a greater adverse impact on groundwater quality than on surface water quality. In other words, groundwater quality is more vulnerable to climate change than surface water quality.

Table 23: Water situation indicators under different climate scenarios in 2030 and 2050

Scenarios	Indicators	2030				2050			
		F-I	F-II	F-III	F-IV	F-I	F-II	F-III	F-IV
Benchmark	Indicator 1	0.44	0.46	0.44	0.39	0.40	0.38	0.41	0.36
	Indicator 2	0.14	0.13	0.16	0.13	0.15	0.14	0.18	0.14
	Indicator 3	0.35	0.33	0.38	0.37	0.37	0.38	0.42	0.40
	Indicator 4	0.19	0.16	0.16	0.16	0.14	0.12	0.12	0.12
S-A1B	Indicator 1	0.48	0.50	0.48	0.43	0.44	0.43	0.45	0.40
	Indicator 2	0.14	0.13	0.17	0.14	0.15	0.14	0.18	0.15
	Indicator 3	0.38	0.36	0.42	0.40	0.41	0.41	0.46	0.44
	Indicator 4	0.22	0.18	0.19	0.19	0.17	0.14	0.14	0.14
S-A2	Indicator 1	0.47	0.49	0.47	0.42	0.45	0.44	0.47	0.41
	Indicator 2	0.14	0.13	0.16	0.13	0.15	0.14	0.18	0.15
	Indicator 3	0.38	0.35	0.41	0.40	0.43	0.44	0.48	0.47
	Indicator 4	0.22	0.18	0.18	0.18	0.18	0.16	0.15	0.15
S-B1	Indicator 1	0.49	0.51	0.49	0.44	0.44	0.43	0.45	0.40
	Indicator 2	0.14	0.13	0.16	0.13	0.15	0.14	0.18	0.14
	Indicator 3	0.40	0.37	0.43	0.42	0.41	0.42	0.46	0.44
	Indicator 4	0.24	0.20	0.20	0.20	0.17	0.15	0.14	0.14
S-4	Indicator 1	0.49	0.51	0.49	0.44	0.47	0.45	0.48	0.42
	Indicator 2	0.14	0.13	0.17	0.14	0.15	0.14	0.18	0.15
	Indicator 3	0.41	0.38	0.44	0.43	0.46	0.47	0.51	0.50
	Indicator 4	0.24	0.20	0.20	0.20	0.20	0.17	0.16	0.16
S-5	Indicator 1	0.36	0.39	0.37	0.31	0.28	0.27	0.31	0.25
	Indicator 2	0.12	0.12	0.15	0.11	0.12	0.12	0.16	0.12
	Indicator 3	0.29	0.27	0.32	0.30	0.27	0.27	0.32	0.28
	Indicator 4	0.15	0.12	0.12	0.12	0.09	0.08	0.08	0.07
S-6	Indicator 1	0.37	0.40	0.39	0.33	0.38	0.37	0.40	0.34
	Indicator 2	0.13	0.13	0.16	0.12	0.15	0.14	0.19	0.15
	Indicator 3	0.30	0.28	0.34	0.32	0.37	0.38	0.43	0.40
	Indicator 4	0.15	0.12	0.13	0.13	0.13	0.12	0.11	0.11

Scenario 5 is the most favourable scenario with precipitation increased by 5% and 10% while ET_o decreased by 10% and 15% in 2030 and 2050, respectively. The irrigation water demand decreased markedly, by 11–12% in 2030 and by 22% in 2050, far more than the variation of precipitation and ET_o. This also indicated from that a relatively smaller change in climate will result in a bigger change in irrigation water demand and water stress situations. Certainly the water stress situations in future scenarios also improved, with Indicator 1 decreasing from 0.44 to 0.37 in Future-I (B as U) in 2030 and from 0.40 to 0.29 in Future-I (B as U) in 2050 respectively.

In Scenario 6 with precipitation decreased by 5% and 10% and ET_o decreased by 5% and 10% in 2030 and 2050, respectively, the total irrigation water demand will increase by 16–17% in 2030 and by 28% in 2050; the stress situation for both surface water and groundwater quantity and quality will be eased in this scenario due to the decrease in ET_o; this implies that ET_o is a more dominant factor in water demand and water stress situations than other meteorological parameters such as precipitation.

Conclusions

Climate change affects freshwater quantity and quality with respect to both mean states and variability (e.g., water availability as well as floods and droughts). Water use is impacted by climate change, and also by changes in population, lifestyle, economy, and technology; and in particular by food demand, which drives irrigated agriculture, globally the largest water-use sector (Kundzewicz et al. 2007). This paper has analysed the impact of climate change on future water demand and water stress situations in the Yellow River basin, while keeping the impacts from other driving factors, like population and lifestyle as benchmarking scenarios. As indicated from the simulated results, climate change will have a huge impact on future water demand and supply situations. A decrease in ET_o or increase in precipitation will reduce the irrigation water demand and ease the water stress situations. Conversely, an increase in ET_o or decrease in precipitation will increase the irrigation water demand, and aggravate water stress situations.

In the Yellow River basin, a small change in climate will result in a big change in irrigation water demand, or water surplus/deficit conditions. The results for the changes in climate in scenarios A1B, A2, and B1 were all generated from a GCM model, and the simulated results indicate that the irrigation water demand will increase and the water situations will become more stressed in 2030 and 2050, although there is still some increase in precipitation in most of the sub-basins under these scenarios. Meanwhile, with the same variation range of precipitation and ET_o, ET_o will have a bigger impact on irrigation water demand and water stress situations than precipitation, as indicated by Scenario 6. This implies that ET_o is a more dominant factor influencing water demand and water stress situations than other meteorological parameters such as precipitation. In addition to this, groundwater quality is more vulnerable to climate change than surface water quality.

The results from this study can help the reader understand what impacts the likely changes in climate will have on future irrigation water demand and water stress situations in the Yellow River basin. Since the water stress situations in the Yellow River basin will become more stressed in the future due to climate change, there is a need to respond to the water scarcity constraints by limiting new development of irrigation areas. The BHIWA model presented in this paper has a potential for wider application for water resources planning in other basins around the world. There is also scope to add appropriate module(s) to evaluate the socioeconomic impacts of various future scenarios (Mu et al. 2008). There is also a need to add flexibility in considering greater spatio-temporal variability using a dynamic systems approach such as the VENSIM model. Furthermore, there will be more uncertainties in future water use, in particular with the impacts from climate change, so there is a need to perform stochastic analysis to manage risk in terms of their probability distributions and likelihoods of occurrence, in order to provide policy makers with more confident information for making optimal policy interventions for integrated and sustainable water resources management in the Yellow River basin.

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Climate Change and Water Availability in the Ganges-Brahmaputra-Meghna Basin: Impact on Local Crop Production and Policy Directives

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Abstract

Climate change is a growing food security concern for countries in the Ganges-Brahmaputra-Meghna (GBM) basin; it is expected to have a direct impact on crop yield as a result of changes in temperature, precipitation, and carbon dioxide (CO_2) concentration. Research is needed to identify the scale and distribution of the potential impacts and possible adaptation strategies to support policy development. This paper presents the results of a hydrological simulation of the components of water balance in the GBM basin in the 2050s under different climate scenarios. The impact on the yield of major crops in two representative districts in Bangladesh and Nepal was assessed using the Decision Support System for Agro-technology Transfer (DSSAT) tool with projections for future seasonal water availability, temperature, and CO_2 concentration. The results indicate that the predominance of the monsoon season in water availability will increase by the 2050s, that there will be more frequent flood events of higher magnitude, and that groundwater recharge will increase. The change in surface water availability will be more pronounced during the pre-monsoon season in Nachole, Bangladesh and during the dry season in Rasuwa, Nepal. In Nachole, yield of monsoon season rice is projected to increase and of dry season rice to decrease; maize yield in Rasuwa, Nepal is projected to decrease. Three adaptation options were tested for reducing yield loss and addressing water stress issues. The results are discussed with a view to suggesting agricultural adaptation options and supporting formulation of water resources policy.

Introduction

Climate change is a growing food security concern for countries in the Ganges-Brahmaputra-Meghna (GBM) basin due to the high rate of population growth and dependence on rainfed and surface and groundwater irrigated agriculture. Today, 60% of the cropped area is rainfed, and the rural economy hinges critically on the success of the summer monsoon. Changes in temperature, precipitation, and carbon dioxide (CO_2) concentration are expected to directly impact crop yield (Karim et al. 1998; Ahmad et al. 2000). Moreover, indirect impacts will also be felt in terms of water availability, changing status of soil moisture, incidence of pests and disease, and changing frequency of events such as drought and flood. Research is needed to assess the scale and distribution of the potential impacts and identify possible adaptation strategies as a basis for developing appropriate policies.

During the past decades, several research studies have been undertaken to identify climate- and water-related threats to agriculture in the GBM basin. Aerts et al. (2000) used the grid-based lumped hydrological water balance model STREAM (Deursen and Kwadijk 1994) to simulate the spatial distribution of water availability in the GBM region and found that the contribution of snowmelt to annual river discharge was 2.3% in the Ganges and 2.6% in the Brahmaputra. Farquharson et al. (2007) and IWFM and CEGIS (2008) used the gridded hydrological model GWAVA (Meigh et al. 1999) to simulate overland flow and accumulation under climate change scenarios; the spatial pattern of water stress did not appear to change, indicating that the current water demand is already stressful in many parts of the basin. The river discharge in the Ganges showed an increase of 6–25% by the 2050s for different climate models, while that in the Brahmaputra did not follow any specific trend.

HDR (2006) notes that most of the people living in the basin will be affected by water stress and scarcity by the 2050s. In 2010, the World Bank (Yu et al. 2010) projected a generally increasing trend in flow in the basin by the 2050s during the monsoon months (May–September) using the MIKE BASIN modelling tool. The average flow increment in August–September was about 12, 10, and 7% in the Ganges, Brahmaputra, and Meghna rivers respectively.

The impact of climate change on water availability and crop yield has been assessed by various studies. Timsina and Humphreys (2006a,b), Karim et al. (1994) and Hussain (2006) used biophysical crop models (e.g., DSSAT) to simulate the impact of climate change on plant growth. However, these models used available climate data only and did not assess the impacts of surface and ground water availability. Recently, Yu et al. (2010) and Ruane et al. (2013) assessed climate change impacts on crop yield incorporating both climate and water resources parameters. The results show that by the 2050s, yield of the major monsoon season crop (aus and aman rice) would not be impacted by climate change, while yield of the major winter crop (e.g., boro rice) might be reduced by about 5%.

Contemporary literature pertaining to the impacts of changes in climate, water availability, and crop yield overwhelmingly points to detrimental consequences for food security in the GBM basin. This basin scale view, however, fails to take into account farmers' adaptation strategies, which are deeply influenced by the local climate and water availability situation as well as economic, cultural, political, historical, and institutional factors at multiple scales.

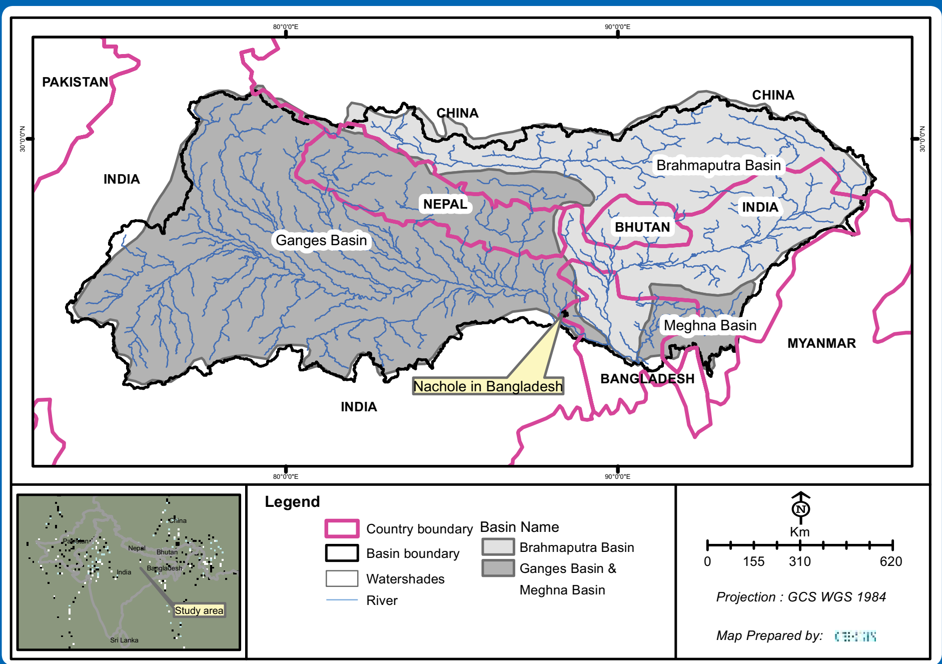
This paper presents the results of a hydrological simulation of climate change impacts on the components of water balance in the GBM basin, and uses this information to analyse the projected local seasonal surface and ground water availability in two districts, one in Bangladesh and one in Nepal. The yield of major crops under the changed climate and water situation is estimated, and a set of agricultural adaptation options for local farmers proposed. These outcomes should help in the identification of economically viable and locally acceptable adaptation options to ensure future food security.

Methods

Study area

The Ganges-Brahmaputra-Meghna (GBM) basin is composed of three sub-basins: the Ganges (China, Nepal, India, and Bangladesh), the Brahmaputra (China, Bhutan, India and Bangladesh), and the Meghna (India and Bangladesh) (Figure 31). The basin has a total area of more than 1.7 million km^2, distributed between India (64%), China (18%), Nepal (9%), Bangladesh (7%), and Bhutan (3%). Nepal is located entirely in the Ganges basin and Bhutan is located entirely in the Brahmaputra basin. The basin is home to 630 million people, the great majority of whom are poor. The population density is very high with 195,432, and 1,013 inhabitants/km^2 in the Nepal, India, and Bangladesh sections, respectively.

Figure 31: **GBM basins and case study districts (Nachole in Bangladesh and Rasuwa in Nepal)**



The basin is unique in terms of its diversity of climate. It is characterized by low precipitation to the northwest and high precipitation in the areas along the coast. The Meghna basin has the highest average annual precipitation of the three GBM basins; the highest average annual precipitation locally – greater than 5,000 mm/yr – is found in northeast Bangladesh. The average annual precipitation in the Ganges basin ranges from 500 mm to 3,000 mm, both extremes in the area within Nepal. The average annual precipitation in the Brahmaputra basin ranges from less than 500 mm in the section within China to 4,500 mm in India near the border with Bangladesh.

The case study district of Nachole is situated in the drought prone northwestern part of Bangladesh, while Rasuwa lies in north-central Nepal (Figure 31).

Agriculture – largely dependent on precipitation and surface water availability – is the primary income generating activity in both districts. The average annual precipitation during the base period (1981–2012) was 1,413 mm for Nachole and 2,808 mm for Rasuwa. Available annual surface water – based on simulated surface runoff of the area – was 525 mm for Nachole and 646 mm for Rasuwa, and groundwater recharge was 217 mm and 1,040 mm respectively. Rasuwa is considered highly vulnerable according to the vulnerability district mapping of Nepal (NAPA 2010) due to ecological and landslide-related threats.

Methods and data sets

The methods used in the study comprised a) collection of climate change scenario data based on biophysical and agricultural data and regional climate model(s); b) assessment of water balance at different temporal and spatial scales using a physically-based semi-distributed hydrological model (SWAT) (Arnold et al. 1998, Arnold et al. 2009a, 2009b); c) assessment of the impact of water resources availability on crop yields using the Decision Support System for Agro-technology Transfer (DSSAT) (Jones et al. 2003, Hoogenboom et al. 2010); and d) developing suitable adaptation options to address the water stress situation.

Climate change scenario data for the 2050s – ensemble average (50%) from 16 general circulation models (GCMs) – were obtained from the Climate Wizard tool (Girvetz et al. 2009) for the high (A2), medium (A1B) and low (B1) emission scenarios of the IPCC SRES scenario family (Nakicenovic et al. 2000). The datasets are 0.50 x 0.50 degree grids.

The SWAT model was calibrated and validated on a monthly scale using available observed discharge data from Nepal and Bangladesh. Before calibration, sensitivity analysis was performed using the Latin hypercube one-factor-at-a-time (LH-OAT) method (Van Griensven et al. 2002, 2005) to rank the simulation parameters of the model for each sub basin. The calibration and validation results were then evaluated against four performance measures – Nash-Sutcliffe efficiency (NSE), mean relative bias (PBIAS), ratio of the root-mean-square error to the standard deviation of measured data (RSR), and coefficient of determination (R2) (ASCE 1993; Moriasi et al. 2007). The calibrated and validated SWAT model was run for the baseline condition to simulate the temporal and spatial distribution of water in the case study districts. The model was then set up for the different climate change scenarios to simulate the climate change impact on water availability.

Basic meteorological, topographic, land use, and soil data were obtained from local and global sources. Topographic data were obtained from the Shuttle Radar Topography Mission (SRTM), USA (resolution 90 m, available from http://srtm.csi.cgiar.org); land use data for the GBM basin (spatial resolution 1 km) were obtained from the USGS database (United States Geological Survey – Global Land Cover 2000); and soil type data with soil properties for two depth layers (0–30 cm and 30–100 cm; spatial resolution 10 km) were obtained from the Food and Agriculture Organization database (FAO 1995). Weather data were obtained from NASA POWER (http://power.larc.nasa.gov). Daily weather data for 1981–2012 (precipitation and minimum and maximum temperature) were downloaded for the GBM basin (spatial resolution 0.5 degree grids). Monthly stream flow data for calibration and validation were obtained from the National Water Resources Database (NWRD) of Bangladesh and the Department of Hydrology and Meteorology (DHM) of Nepal.

DSSAT was used to simulate crop growth, development, and yield as a function of soil-plant-atmosphere dynamics. The data and information required for crop modelling and development and validation of adaptation options at the local level were obtained from agricultural organizations in Bangladesh and Nepal and global data sources.

Results and Discussion

Climate change and water balance

The Ganges-Brahmaputra-Meghna (GBM) basin covers an area of 1.7 million km^2 and is home to 630 million people. Changes in the climate and water availability will influence agricultural production and food security, ecology, biodiversity, river flows, floods, and droughts, water security, and human and animal health.

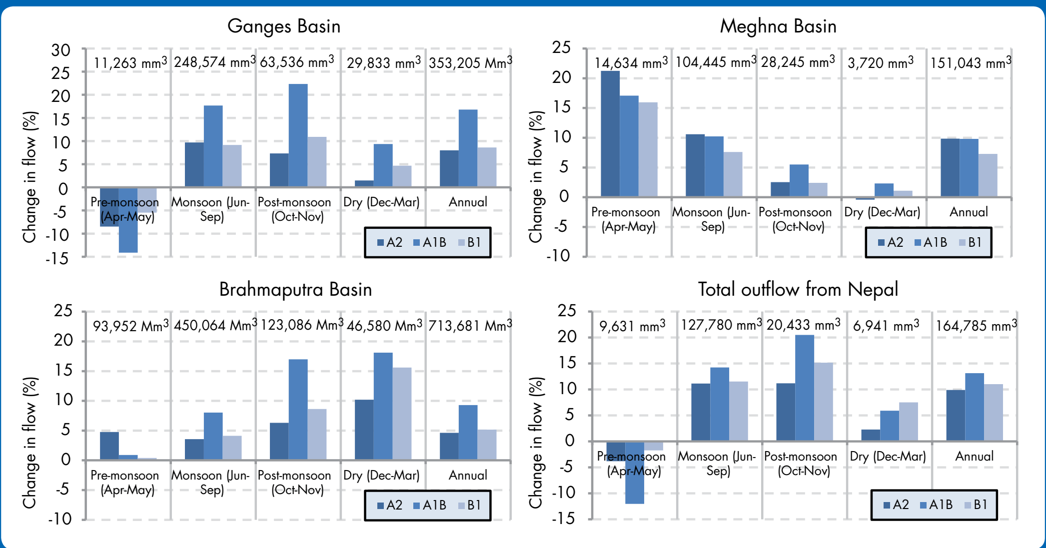
The annual water balance results indicated that the three GBM basins received 981 mm, 1,981 mm, and 3,816 mm average annual precipitation during the base period 1981–2012. The model results indicated that in the Ganges basin, 59% of the precipitation evaporates, 33% is converted to surface runoff, and 8% percolates into the soil. In contrast, the evaporative losses in the Brahmaputra and Meghna basins are comparatively low – 33% and 32% of total precipitation, respectively; while surface runoff is high – 60% and 64% of total precipitation, respectively. The contribution of snow melt in annual river flow was substantial in both the Ganges (10%) and the Brahmaputra (17%).

The water balance in the basins in the 2050s was simulated for the three different climate change scenarios – high (A2), medium (A1B), and low (B1). Figure 32 shows the results for overall streamflow under the three scenarios compared to the baseline period. The simulations show an overall increase in average annual precipitation and surface runoff, with more marked changes in seasonality. In the Ganges basin, dry season (Dec–Mar), monsoon (Jun–Sep) and post-monsoon (Oct–Nov) flow may increase by 2–9, 9–18, and 7–22% respectively, while pre-monsoon (April–May) flow may decrease by 5–15%. In the Brahmaputra basin, flow will increase in all seasons, with a marked increase in dry season flow (10–17%) due to temperature rise and accelerated snow melt. In the Meghna basin, there is a substantial increase in pre-monsoon and monsoon flows, and a minimal increase in post-monsoon and dry season flows.

One important feature of the modelled flows is the predominance of the monsoon season flow (Jun–Sep) in the total. The results indicate an increase of 10–17%, 4–8%, and 7–10% in monsoon flow in the GBM basin under the three scenarios A2 (high), A1B (medium), and B1 (low). This could lead to more frequent flood events of higher magnitude. Frequency analysis of flood events in the 2050s under climate change showed that 50-year flood events will become 20-year events in the Ganges basin under the A2 and B1 scenarios, and 10-year events under the A1B scenario. In the Brahmaputra and Meghna basins, 50-year events will become 35-year and 20-year events, respectively.

Groundwater is important for crop production in large parts of these basins in the dry season, thus the impact of climate change on groundwater recharge was analysed based on simulated

Figure 32: **Seasonal and annual changes in stream flow compared to baseline for different climate change scenarios (A2, A1B and B1) in the Ganges, Brahmaputra, and Meghna basins**



monthly percolation. In the Ganges basin, groundwater recharge in the 2050s will remain confined mainly to the monsoon period (Jun–Sep) and may increase compared to baseline. The Brahmaputra and Meghna basins also show an increase in groundwater recharge in the 2050s, with recharge starting in the pre-monsoon period and continuing well into the post-monsoon month of October.

Climate Change and Water Availability in the Case Study Districts

The impact of climate change on local water availability was analysed in the two case study districts – Nachole in Bangladesh and Rasuwa in Nepal. The results are shown in Table 24. They indicate that surface water availability will increase in both districts in all seasons except the dry season under all emission scenarios. The change in surface water availability will be more pronounced during the pre-monsoon season in Nachole and during the dry season in Rasuwa, in other words the climate change impact varies at local level. The results reflect the recent phenomena of dry season water scarcity in the mountain districts of Nepal and increase in floods in Bangladesh, both of which will be more marked by the 2050s with likely impacts on agriculture and rural livelihoods.

The amount of recharge is also expected to increase in both districts in the 2050s under all emission scenarios, and especially the A1B scenario (Table 25). Analysis of the temporal distribution of groundwater recharge shows that most occurs during the monsoon season (Jun–Sep).

Table 24: **Changes in surface water availability in Nachole and Rasuwa districts by the 2050s**

Area	Season	Available surface water in base period (mm)	Change in surface water availability (%)		
			A2	A1B	B1
Nachole, Bangladesh	Pre-monsoon (Apr–May)	18.5	+42.9	+44.3	+38.7
	Monsoon (Jun–Sep)	440.7	+4.9	+12.5	+11.5
	Post-monsoon (Oct–Nov)	59.7	+17.5	+28.1	+17.9
	Dry (Dec–Mar)	6.2	-9.6	-17.2	-3.3
	Annual	525.0	+7.5	+15.0	+13.0
Rasuwa, Nepal	Pre-monsoon (Apr–May)	33.6	+19.4	+7.4	+26.1
	Monsoon (Jun–Sep)	541.1	+16.3	+22.2	+10.8
	Post-monsoon (Oct–Nov)	11.3	+3.2	+36.4	+10.9
	Dry (Dec–Mar)	59.6	-43.6	-54.8	-35.9
	Annual	645.7	+10.7	+14.6	+7.3

Table 25: **Changes in groundwater recharge in Nachole and Rasuwa districts by the 2050s**

Area	Annual recharge in base period (mm)	Change in recharge (%)		
		A2	A1B	B1
Nachole, Bangladesh	217	+2.6	+7.9	+7.1
Rasuwa, Nepal	1,040	+3.0	+4.8	+2.7

Climate Change and Crop Yield in the Case Study Districts

The impact of climate change on the yield of major crops was analysed for the case study districts. The crop production model DSSAT was used to simulate the yield of crops in the base period (1981–2012) and under the three climate scenarios (A1B, A2, and B1). The crops analysed were monsoon rice (transplanted aman) and dry season rice (boro) in Nachole and maize in Rasuwa. Both aman rice and maize are grown under rainfed monsoon conditions, while boro rice depends on groundwater. The simulated base period crop yields were first compared with observed yields and found to be satisfactory. The simulated average yields of transplanted aman rice, boro rice, and maize in the base period were 3,830, 6,600, and 3,560 kg/ha, respectively. The impact of climate change and water availability on crop yield by the 2050s is shown in Table 26. The projected change in temperature and precipitation will have a negative impact on yields, while the change in CO_2 will have a positive impact.

Table 26: **Changes in crop yield by the 2050s in Nachole and Rasuwa districts due to changes in temperature, precipitation, and CO_2 concentration**

Area	Crop	Scenario	Average yield (kg/ha)[a]	% Change in yield		
				TP	C	TPC[b]
Nachole, Bangladesh	Monsoon rice (transplanted aman)	Base	3,827			
		A2	3,914	-1.4	+3.9	+2.3
		A1B	3,930	-1.5	+4.1	+2.7
		B1	3,936	-1.7	+3.3	+2.8
	Dry season rice (boro)	Base	6,595			
		A2	6,337	-5.5	+2.8	-3.9
		A1B	6,370	-5.9	+2.9	-3.4
		B1	6,293	-6.0	+1.2	-4.6
Rasuwa, Nepal	Maize	Base	3,789			
		A2	3,725	-2.4	+0.9	-1.7
		A1B	3,558	-6.3	+1.5	-6.1
		B1	3,678	-3.6	+0.5	-2.9

T = temperature; P =precipitation; C = CO_2 concentration
[a] yield with changes in T, P, and C
[b] effect of simultaneous changes in T, P, and C are not a simple sum or product of the individual impacts due to the non-linear biophysical interactions between the climate variables

The yield of monsoon rice in Nachole in Bangladesh is projected to increase by about 3% under all the emission scenarios (A2, A1B, B1) as the negative impact of changes in temperature and precipitation is offset by the increase from carbon fertilization. Similar results have been found in recent studies by others on the impacts of climate change on food security in Bangladesh (Yu et al. 2010; Ruane et al. 2013). In contrast the net impact on dry season rice (boro) yield will be negative, as the negative impact from changes in temperature and precipitation outweigh the positive impact of carbon fertilization. The results indicate that dry season rice cultivation may not be sustainable in Nachole as the demand for water is projected to exceed the expected recharge and water yield.

The yield of maize in Rasuwa, Nepal, is projected to decrease by 2–6% under the different climate change scenarios. CO_2 has only a small positive impact on yield because maize is a C4 plant and little affected by CO_2 increases (Goudriaan and Unsworth 1990; Adriana et al. 1998).

Adaptation Options for Sustainable Crop Production in Nachole, Bangladesh

Three adaptation options were tested in the model simulations to reduce yield loss and crop water requirement: (1) shifting the transplantation date, (2) sowing a short duration crop variety, and (3) crop diversification. These adaptation options were tested for the base period (1981–2012), and average, wet, and dry years (20, 50, and 80% probability of exceedance of precipitation) under the A2, A1B, and B1 climate change scenarios.

The analysis indicated that transplanting monsoon rice ten days earlier than at present (11 Jul) would be the most effective way to reduce the crop water requirement and yield loss in wet, average, and dry years under all the emission scenarios. The reduction in crop water requirement and yield loss can be maximized by using short duration (135 days) monsoon rice varieties (e.g., the BIRRI dhan49 and BR 11 varieties). Continuous weather forecast information should be provided to farmers to promote these measures so that they can adjust the transplantation date to reduce risk and sustain yields with less water. Moreover, farmers should be given training to help them understand the linkages between the weather and agricultural practices, and the benefits of agro-meteorological forecasting.

Transplanting dry season rice ten days earlier (11 Jan) also helps to reduce the crop water requirement, as does introduction of short duration (140 days) dry season rice varieties (e.g., BIRRI dhan28). However, the scenario for local water availability indicates that despite the slight increase in groundwater recharge in the 2050s under all emission scenarios, there will be an irrigation deficit for growing dry season rice. Thus, dry season rice cultivation should be replaced in phases by low water requiring cereal crops such as wheat and maize, oilseeds, pulses, and winter vegetables.

Conclusions and Policy Implications

There is no single viable generic solution for sustaining crop yield and ensuring food security in the GBM basin under climate change. The findings of this research point towards the need to adopt a context-specific mix of policy interventions and preferred routes for future water resources development at multiple spatial scales. These policy implications can be summarized as follows.

- **Work towards increasing water storage in the basins** – The predominance of the monsoon season is projected to increase by the 2050s due to climate change and there is likely to be an increase in the frequency of flood events of higher magnitude in all three GBM basins. Measures to increase upstream water storage will help to address this climate-induced challenge in the future. The lower evaporation loss in the Brahmaputra basin compared to the Ganges basin suggests the possibility of constructing multipurpose water storage reservoirs in the Brahmaputra basin. However, the approach and method of water storage should be rigorously researched to identify options that can be agreed by the co-riparian countries.
- **Promote water resources development and management in the basin** – Large changes in the seasonality of precipitation and water availability are expected by the 2050s. The results indicate an increase of 10–17%, 4–8%, and 7–10% in monsoon flow in the GBM basin for all three scenarios: A2 (high), A1B (medium), and B1(low). Climate change will have a greater impact on water seasonality in the Ganges basin than in the other two basins. The possible strengthening of the spatial and temporal dimensions of water availability in the future supports the argument for identifying opportunities for water-based cooperative development and management of the basins. The prospect of two or more co-riparian countries working in cooperative, project-based water development activities in the GBM basin has been endorsed by consecutive South Asian Association for Regional Cooperation (SAARC) summits.
- **Strengthen regional hydro-meteorological and agricultural information collection and sharing mechanisms** – The nested approach adopted by this research combining a regional water model with a local crop model has been able to assess the potential impact of changing agricultural practices on crop production. In order to change agricultural practices (e.g., changing the transplantation date to reduce water stress and maintain yields), there is a critical need to provide continuous hydro-meteorological forecast information to farmers based on regional and local assessments. Special emphasis should be directed to establishing governing principles for institution building including collection of regional hydro-meteorological and agricultural information and establishing monitoring networks.
- **Increase investment in agricultural research and extension** – This study has confirmed the disruptive and uncertain nature of the future climate and water situation for agricultural production in the GBM basin. The findings call for an improved agricultural extension services to help farmers adapt quickly in terms of cropping practices, crop diversification, and irrigation, and to strengthen farmers' knowledge networks to help

broaden perspectives and awareness. For example, many farmers think that rainfed crops do not need irrigation. This may not hold true as the climate changes, and in the future previously rainfed crops may need supplementary irrigation. The government should also take the initiative to increase research and investment into the identification of new climate resilient short duration crop varieties.

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Climate Change Impact on Water Availability, and Farmers' Adaptation Strategies: Case Studies from Pakistan and Nepal

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Abstract

The agriculture and food system of countries in South Asia, including Pakistan and Nepal, will be affected by climate change. The increasing demand for food due to population growth, coupled with uncertainties introduced by climate change, as well as other drivers of change, has made it imperative for these countries to ascertain the trends in changes from the perspective of their impact on water resources and thus the agriculture and food system. This paper explores evidence of climate change and farmers' responses to what they are experiencing in two different agro-climatic locations, one with predominantly rainfed agriculture and one with predominantly irrigated agriculture. The study compared and contrasted the results of model simulations from downscaled climate scenarios with observations collected using questionnaires at community level (primary data). Future climate scenarios indicated that there may be a shift in monsoon patterns and more extreme events. This means that farmers in both areas need to be prepared to adapt to changing patterns. A number of possible climate change adaptation measures related to water management and agricultural practices were identified through in-depth analysis of the climate change scenario and the information gathered from farmers.

Introduction

Climate change has drawn international attention over the past decade, with particular concerns about the potential long-term adverse impacts on agriculture (Nelson 2009), ecosystems (Littell 2011), health (Patz et al. 2012; Malik et al. 2012), and water resources (IPCC 2007). The water and agricultural sectors are likely to be severely impacted by climate change (IPCC 2007), which has a well-recognized immense potential to markedly affect crop yields, water availability, and agricultural systems in different parts of the world (Parry et al. 2004). Some communities have already started adapting to these changes in their own ways (Pradhan et al. 2012).

Agriculture is the most sensitive of the key economic sectors to climate change, as changes in temperature, precipitation, wind speed, and atmospheric CO_2 concentration can all have significant impacts on crop productivity (Rakshit et al. 2014). Since crop performance is strongly linked to meteorological conditions (Meza and Silva 2009), agriculture is one of the main sectors to be analysed when seeking to understand the impacts of climate variability and change. Climate is the single most important factor likely to shape the future of food security (Lobell and Gourdji 2012). However, the potential impact of climate change on agriculture is crop and location specific, and much more sophisticated understanding of these dynamics is needed.

The direct and profound impacts of climate change on agriculture and the food system are of particular importance for the agriculture-based population in the developing world, where more than 800 million people are already undernourished (UNFAO 2005) and climate change is likely to cause yield reduction in most of the staple crops. South Asia will be particularly hard hit (Nelson et al. 2009). A better understanding is needed of the influence of climate on crop production in order to address likely changes in growing season climatic conditions and cope with the rising number of undernourished people, particularly in food insecure areas (Rowhani et al. 2011).

Given the importance of agriculture for human survival, and the fact that farmers have always had to deal with climate variability, there is no shortage of response strategies to changes in climate, both suggested and in use. Responses include changes to crops (alternative crop rotation, genetic development of new crop varieties), increasing efficiency in agricultural water use, altering the timing or location of cropping activities (change in cropping calendar), changes in crop management (change in input use, alternative tillage systems, and proper irrigation and drainage), changes in agricultural policy, and capacity building (Salinger et al. 2005). Irrigation is one of the possible adaptation strategies to climate change and variability, as it can address uncertainty associated with the natural precipitation regime in places that rely on rain to irrigate crops. Irrigated agriculture may be faced with a double hit, however, since not only will agriculture require more moisture in a dryer climate, but there will also be less water available. Increased temperature and decreased humidity elevates the soil moisture deficit and hence dramatically raises the irrigation water demand. It is therefore likely that warmer and drier conditions will enlarge irrigation demand in agriculture.

In order to identify and evaluate the effectiveness of different adaptation strategies, it is fundamental to first analyse the potential impact of change over the concerned area (Ficklin et al. 2009). Adaptation and impacts should be considered together for the best and most realistic assessment of climate problems (Wheaton and MacIver 1999). Without adaptation, climate change and variability is generally challenging for agricultural production, but with adaptation, benefits can be enhanced and social and economic vulnerability can be minimized (Rosenzweig and Parry 1994; Wheaton and MacIver 1999). However, potential agricultural adaptation responses will vary according to the farm types and location, climate stimuli, and economic, political, and institutional conditions (Smit and Skinner 2002). Since adaptation responses incorporate a wide range of forms (managerial, financial, technical), scales (local, regional, global), and participants (farmers, industries, governments) (Smithers and Smith 1997), they need to be carefully tailored to specific locations and situations.

With this background, this paper presents two case studies with the aim of providing evidence of climate change and its effect on water availability in two research areas, one each in Nepal and Pakistan, together with the observed responses. The study also suggests a range of responses that could be useful adaptation strategies for farmers to adopt. Due to differences in terms of topography, terrain, agricultural system, water use patterns, and socioeconomic conditions, some variations were made in the methodology followed in the two study areas. Despite these differences, the potential adaptation strategies identified were broadly the same for both locations, albeit with site-specific variations in their implementation.

Methods

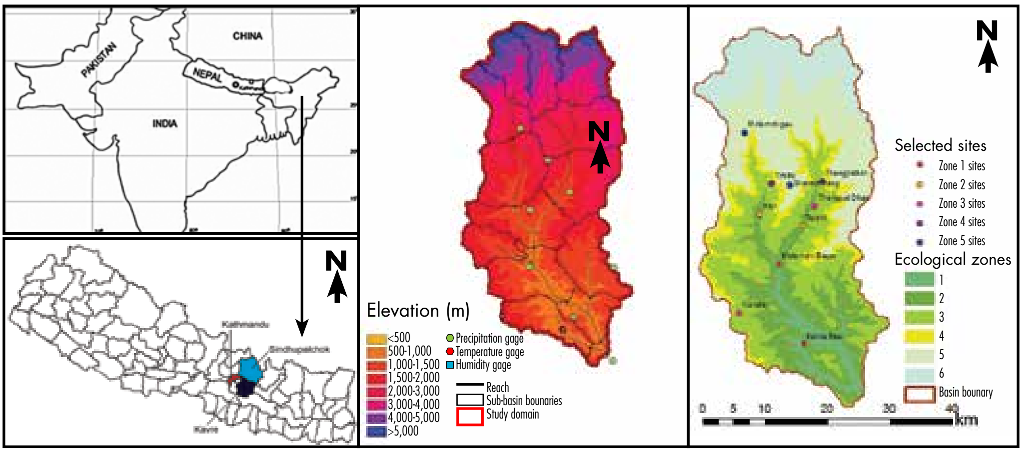
The research used a case study approach that examined and compared the impacts of climate change on water availability and the responses of farmers in a predominantly rainfed agricultural area in the Indrawati sub-basin in Nepal, and a predominantly irrigated agricultural area around the Hakra Branch Canal in Pakistan. The water requirement in both cases was essentially fulfilled by rainfall, and additional water was supplemented by irrigation canals using surface sources or electric pumps using groundwater sources.

Study area

Indrawati sub-basin

The Indrawati sub-basin is one of the seven sub-basins of the Koshi River. The river originates in the high Himalayas and flows south across Nepal for 59 km before meeting the Sunkoshi River at Dolalghat (Figure 33). The basin falls in the alpine and subtropical climatic zones;

Figure 33: **The Indrawati sub-basin in Nepal**



44% of the total area is covered by natural forest, 33% by agricultural land, and 12% by ice and snow (Mishra 2001). In 1998, the population density was about 175 persons per square kilometre (Bhattarai et al. 2002).

The average annual rainfall in the basin ranges from 3,874 mm at higher elevations (Sarmathang) to about 1,128 mm at the lowest elevation (Dolalghat) with high spatial and temporal variation (Mishra 2001). About 93% of the precipitation falls between mid-May and mid-October. The average annual potential evapotranspiration is about 954 mm (WECS/IWMI 2001). The relative humidity varies from 60% in the dry season to 90% in the rainy season with an average of 75%. The water flow in the river has significant seasonal variation, with 90% of the total annual river flow occurring from June to October (Mishra 2001). There is a marked variation in crops and cropping patterns within the basin with rice, maize, and vegetables in the lower elevation zones and potato, millet, and beans in the higher elevation zones. The basin is of significant national importance due to its high potential for irrigated agriculture, possibility of providing water to the capital city, and potential for hydroelectric power development, cultivation of high value crops, livestock production, and ecotourism.

Hakra Irrigation System

The Hakra Irrigation System is located in Bahawalnagar District in the southeastern part of Punjab province in Pakistan (Figure 34). The Hakra Branch Canal is a perennial channel which off-takes from the Eastern Sadiqia Canal at 74 km. (The Eastern Sadiqia Canal originates from a left bank canal of the Sulemanki headworks on the River Sutlej). The canal is about 92 km long and has a gross command area of 271,410 km^2, of which 221,544 km^2 is cultivable. The authorized head discharge is about 82 m^3/ s (cumecs). There are ten distributaries (secondary irrigation channels) originating from the right bank and four from the left bank which supply irrigation water to the command areas through a series of minors and watercourses (tertiary irrigation channels). The irrigation system is community managed and farmer organizations (FOs) are responsible for irrigation operation in consultation with the Irrigation Department. The research focused on three distributaries – 4R, 6R, and 9R – located at the head, middle, and tail of the canal (Table 26).

The average annual rainfall in the command area ranges from 125 mm to 250 mm. The groundwater in this area is generally considered unfit for irrigation, however, due to the shortage of canal water and unreliability and inequity in distribution of its supplies, farmers are compelled to rely on groundwater and rainfall. The research area is arid and designated as a cotton/wheat agro-climatic zone. There is scant variation in the annual cropping pattern. Cotton and sugarcane are the most popular cash crops in the kharif (summer) season, while wheat is the most common crop in the rabi (winter) season.

Methodological framework

A methodological framework was prepared that combined geophysical and social science perspectives (Figure 35). The framework included hydrological modelling and analysis using a

Figure 34: **The Hakra Branch Canal irrigation system in Pakistan**

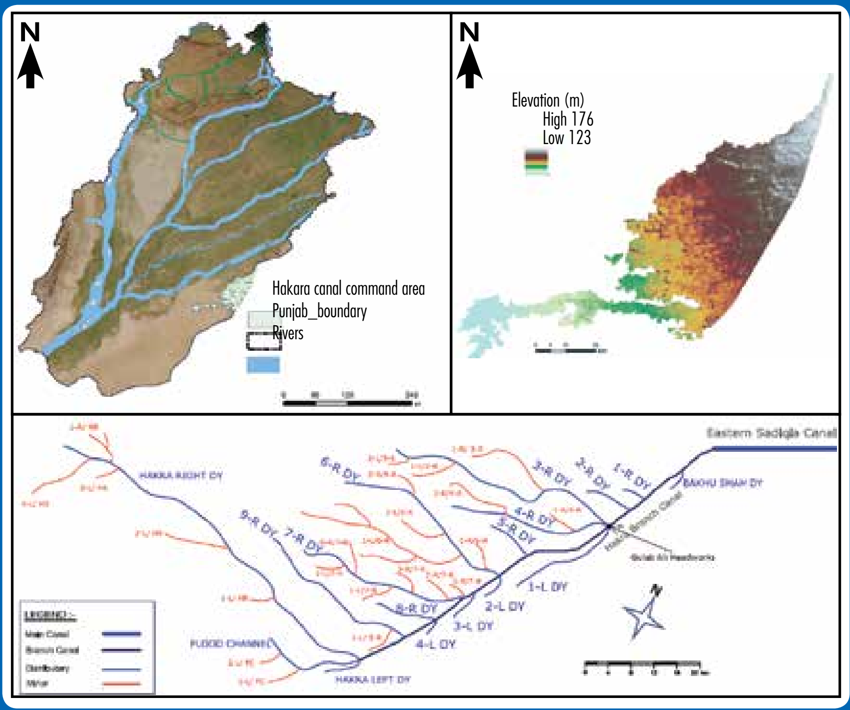
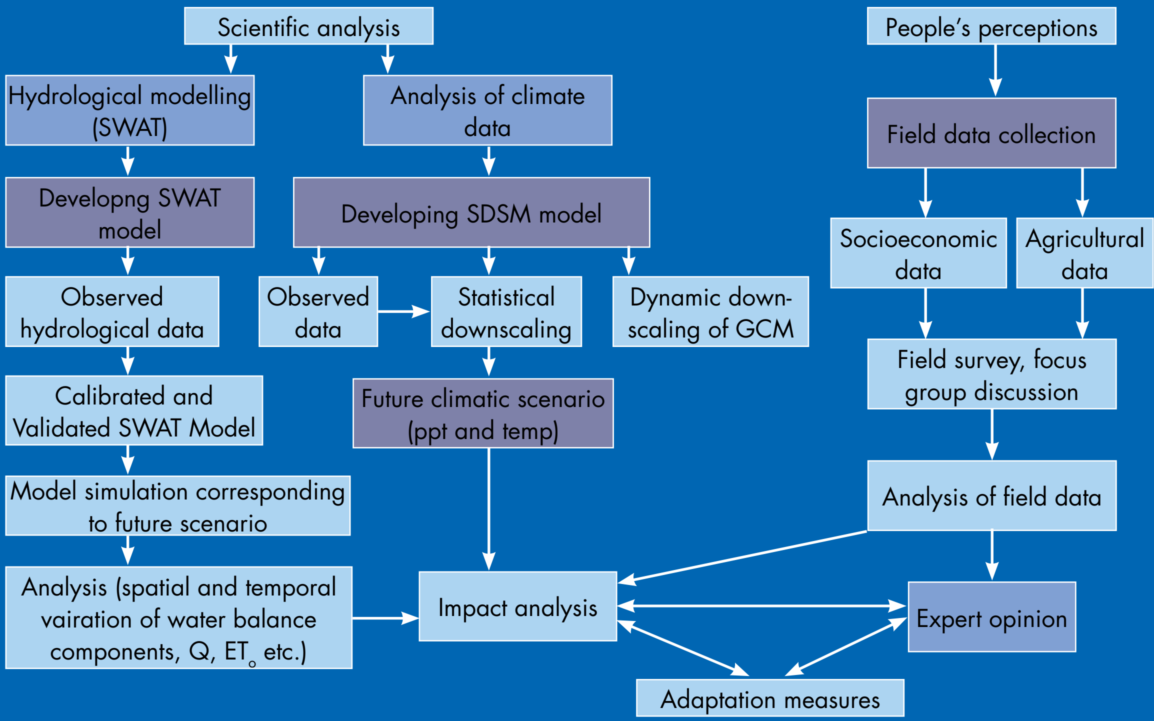


Table 27: **Salient features of the three selected distributaries of the Hakra Branch Canal**

Distributary	Parent channel	Irrigation division	Authorized discharge (m^3/sec)	Gross command area (ha)	Cultivable command area (ha)	Length (km)
4 R	Hakra Branch	Hakra	5.97	28,237	17,585	34
6-R	Hakra Branch	Hakra	15.46	49,800	41,204	45
9-R	Hakra Branch	Hakra	5.97	20,197	19,909	35

soil and water assessment tool (SWAT) and analysis of climate data using a statistical downscaling model (SDSM) to compare present and future water and climate scenarios. Farmers' interviews were conducted using semi-structured questionnaires focusing on climate parameters, prevailing agricultural practices, perceptions of change in climate parameters, and responses. The data was analysed by the research team members and verified by relevant experts working in similar fields, and the results used to develop recommendations for possible responses to the likely changes. Hydro-meteorological, socioeconomic, and agricultural production data were collected from various government offices and published literature.

Figure 35: **Methodological framework**



Trends in temperature and precipitation were analysed and used to develop an SDSM. Future climate scenarios (precipitation and temperature) were then generated by downscaling from the global climate data. The model used available data with 1981–2000 as the baseline period. The model was calibrated and validated, and the performance evaluated, using the SDSM, and was used to generate data for different future periods.

A SWAT model was used to assess the hydrological fluxes in the research areas. The model included data from a digital elevation model (DEM); the Soil and Terrain database (SOTER) for the different areas, which is based on ISRIC World Soil Information; a global land cover map for land use and land cover of each area; and daily meteorological data (precipitation, temperature, relative humidity, and others) from the respective government agencies. The SWAT model was calibrated against the observed discharge using daily and monthly data. The results from the model were used to assess both the hydrological water balance and the impact of climate change on water availability.

Data Collection in Nepal

Climate data were extracted for one grid point (latitude 27.5°N, longitude 86.25 °E; spatial resolution 2.5 x 3.75 degrees) at a daily time scale for the period January 1981 to December 2000 as a baseline. Future data from a selected emission scenario [HadCM3 A2] were generated using a statistical downscaling model (SDSM 4.2) to produce high-resolution monthly climate information from coarse-resolution general circulation model (GCM) simulations. Data from 11 meteorological/ hydrological stations were collected and processed to generate future scenarios of precipitation. The developed model was then used to obtain projections of maximum and minimum temperatures and precipitation from simulations of HadCM3. The analysis was performed on a monthly basis and all evaluations were carried out on a seasonal basis. The climate scenarios were then explained in terms of multi-decades, i.e. 2020s (2010 to 2030), 2055s (2046–2065), and 2080s (2080 to 2099).

Socioeconomic, agricultural, and farmers' perceptions data were collected using a survey questionnaire at ten sample sites selected to represent the different agro-ecological zones (two sites per zone). A total of 166 respondent households (138 male, 38 female respondents) were selected using random sampling (Table 28). Farmers were asked for their observations on changes in water availability, agricultural patterns, and rainfall and temperature patterns, as well as their perceptions of future climate change, its likely impact on their lives and livelihoods, and existing and potential adaptation measures. The data was analysed using statistical analysis. The research team used the results to identify possible adaptation measures.

Table 28: **Sample selection in the Indrawati sub-basin**

Zone	Elevation (masl)	Villages selected	Surveyed HH (no.)
1	< 900	Kunta Besi	34
		Melamchi Bazar	
2	900 – 1,200	Tipeni	34
		Kiul	
3	1,200 – 1,800	Thangpal Dhap	34
		Nangle	
4	1,800 – 2,200	Thangpal kot	32
		Timbu	
5	> 2,200	Melamchigau	32
		Shermathang	
		Total	166

Data Collection in Pakistan

Observed climate data (maximum and minimum temperature, wind speeds, relative humidity, and rainfall) from the Bahawalnagar station for the base period of 1980–2004 were collected from the respective government agencies and departments. Transient climate change scenarios were generated from the observed daily precipitation and temperature data. Three GCMs were obtained from the IPCC AR5 CMIP5 database to use in the research. GCM experiments driven by the IPCC A2 emission scenario for the twenty-first century were available when the research was carried out, these normally generate larger than average future climate change conditions.

A bias correction (BC) method was employed to analyse temperature and rainfall using the three GCMs from the CMIP5 database (CSM, CanESM2, and NorESM). The BC procedure was performed for each month, and evaluations were carried out based on seasons. The climate scenarios were explained in terms of multi-decades, i.e., 2020s (2010–2030), 2050s (2040–2069), and 2080s (2080–2099).

The crop-water requirement and irrigation scheduling of the Hakra Branch Canal command area was calculated using FAO's CROPWAT software with the physical and chemical properties of the soil and irrigation application. Rainfall data for 1980–2006 was obtained for the Bahawalnagar gauging station from the Pakistan Meteorological Department.

Primary data was collected using a survey questionnaire from 810 households located along the three distributaries '4R', '6R', and '9R' as shown in Table 29. Farmers were asked for their observations on climate change, farm yield, modes of irrigation, and groundwater contribution to analyse the socioeconomic conditions of the study area. The data was analysed using statistical analysis, and based on this, possible adaptation measures were identified.

Table 29: **Location of surveyed households in the Hakra Branch Canal area**

Distributaries	Water courses (15 each at head, middle and tail reach)	Surveyed households (2 farmers at head, middle and tail of each water course)
4R (head)	45	270
6R (middle)	45	270
9R (tail)	45	270
Total	135	810

Results and Discussion

Trends in temperature and precipitation

The residents of the Indrawati basin were asked whether they had observed any changes in temperature and precipitation over the previous decade. The results are summarized in Tables 30 and 31. The majority of respondents felt that the average temperature had changed compared to the last decade. Nearly half thought that overall temperatures were slightly higher, with close to a third saying that the hot season had become hotter, and more than a third experiencing less frost. All those who reported no change in temperature were from the lowest elevation zone (Zone 1). Precipitation changes appeared to have made a greater impression or caused more concern. Three-quarters of all respondents reported experiencing changes in the amount of annual precipitation, and most of these reported a decline. Almost all respondents noted changes in the pattern of precipitation, including a decrease in the number of snowfall days, a decrease in precipitation intensity, more erratic rainfall in general, and a delay in the arrival of the rains.

In the Hakra Branch Canal area, the majority of farmers (65%) thought that summer (April to September) temperatures had increased but not winter temperatures (Figure 36). The observed data during the baseline period confirmed that both summer and winter maximum temperatures have increased slightly over the last three decades (Figure 37).

Table 30: Perceptions of changes in temperature

Response	Yes (%)	No (%)
Change in average temperature compared to last decade	97	3
Temperature slightly higher	46	54
Hot season hotter	31	69
Cold seasons colder	19	81
Frost less common	37	63

More than half of the farmers considered that rainfall had decreased (Figure 38), however, the rainfall records did not show any clear trend (Figure 39), with some dry spells and some wet spells during the baseline period. Rainfall exceeded 300 mm in only eight of the years from 1980 and 2004, but five of these were between 1989 and 1997, and this whole period can be considered a wet spell. The farmers' observations may be based on their assessment that less rainfall is available when the crops really need it, rather than the annual rainfall. Equally they may be comparing with the relatively recent wet spell, or perceive a lack of water that actually results from higher demand rather than lower rainfall. It is also possible that the years 2005–2012 had overall lower precipitation, but these data were not available.

Table 31: Perceptions of changes in precipitation

Response	Yes (%)	No (%)	Remarks
Change in amount of annual precipitation	74	26	72% reported a decline
Change in precipitation pattern	99	1	36% reported a decrease in the number of snowfall days and 38% a decrease in precipitation intensity
Erratic rainfall	27	73	–
Delay in arrival of rains	53	47	–
Hailstorms became less frequent	28	72	–

Figure 36: Perceived change in temperature in the Hakra Branch Canal area in summer (left) and winter (right) (percentage of respondents)

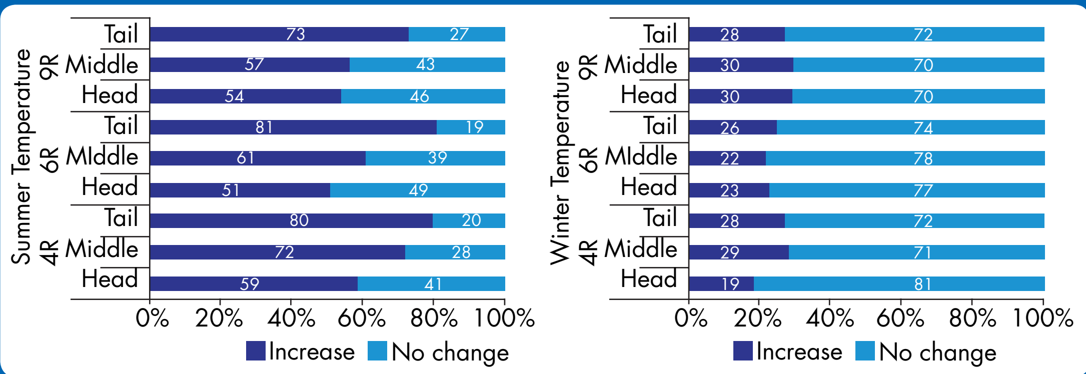


Figure 37: **Trends in summer and winter maximum temperatures in the Hakra Branch Canal area during the baseline period**

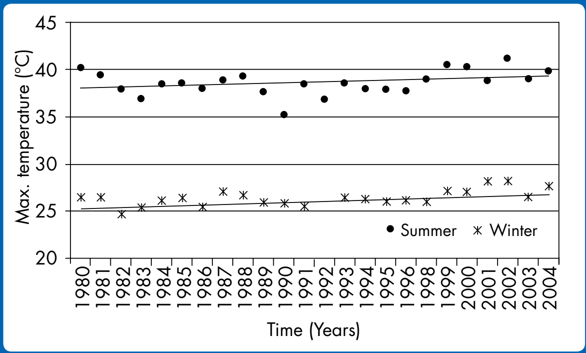


Figure 38: **Perceived change in rainfall in the Hakra Branch Canal area (percentage of respondents)**

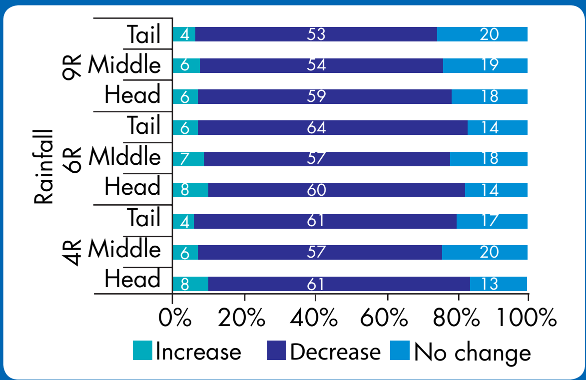
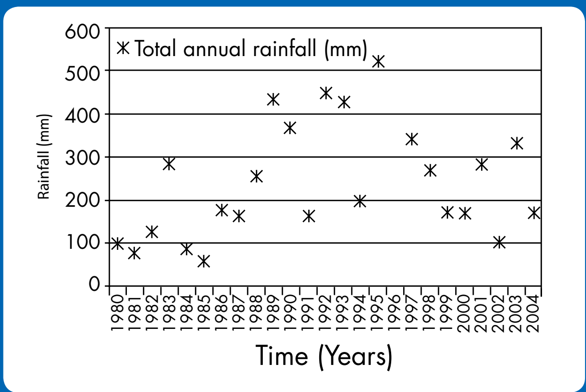


Figure 39: **Annual rainfall in the Hakra Branch Canal area during the baseline period**



Climate Change Projections

The projections for precipitation in the Indrawati basin are shown in Figure 40 and the variation from baseline is given in Table 32. The projections show a gradual slight decrease in annual average rainfall, by 0.9% of baseline in the 2020s, 1.4% in the 2055s, and 3.0% in the 2080s. There is a clear increase in rainfall during the early winter months (120% of baseline for November and 102% for December by the 2080s), a small increase in spring and early summer, but a decrease in late winter, mid-to late summer, and autumn. The results indicate that farmers will need to adapt to changing rainfall patterns.

The projections for precipitation in the Hakra Branch Canal area are shown in Figure 41 and the variation from baseline is given in Table 33. The annual rainfall is projected to decrease slightly by the 2020s (by 7.8% of baseline), but then to increase significantly (by 48.7% of baseline by the 2050s and 36% by the 2080s). In the 2020s, there is a marked decrease in rainfall in October and November (the sowing months for rabi crops), April and May (early months of the kharif season), and August and September (the monsoon period, which receives 70% of the total rainfall). Although the annual rainfall shows an increase in the 2050s and 2080s, rainfall is expected to decrease during the late monsoon (September) in the 2050 and mid-monsoon (August) in the 2050s and 2080s. As in the Indrawati, this seasonal variation in rainfall

Figure 40: **Projection of future rainfall in the Indrawati basin (HadCM3) (1–12 are Jan to Dec)**

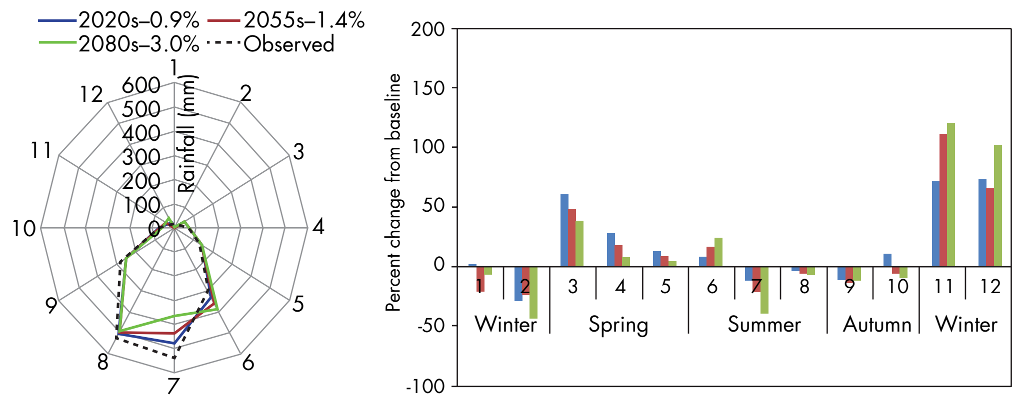


Table 32: **Projected percentage variation of rainfall from baseline in the Indrawati basin**

Season	Late winter		Spring			Summer			Autumn		Early winter		Annual
Month	1	2	3	4	5	6	7	8	9	10	11	12	
2020s	+0.8	-28.3	+60.0	+27.4	+11.9	+7.8	-11.2	-3.4	-11.3	+9.9	+72.0	+73.1	-0.9
2055s	-20.1	-23.5	+47.3	+17.5	+8.0	+16.4	-20.9	-4.8	-13.3	-5.4	+111.0	+65.3	-1.4
2080s	-6.8	-43.4	+38.3	+7.2	+4.1	+23.4	-38.9	-6.8	-11.1	-9.0	+120.7	+102.2	-3.0

patterns may have an impact on water availability for irrigation and thus crop growth. Although the primary source of irrigation is canal water, farmers in the area depend heavily on other sources, such as rainfall and groundwater. Timely occurrence of rainfall not only augments the irrigation supplies through canals but also saves the input costs of groundwater pumping. The shift in rainfall patterns projected under this scenario would have a significant impact on agriculture in the canal command area.

Future water availability and impacts on agriculture in the Indrawati sub-basin

The calibrated and validated SWAT model was used to evaluate the trends in water availability in the Indrawati sub-basin for the period 1980–2008. The trend in stream flow for the entire basin (i.e. at Dolalghat) is shown in Figure 42. The contribution of snowmelt in stream flow is not significant. The was no significant overall trend in the average annual precipitation or effective water yield in the basin over the simulation period, however, there might still be changes in the number of dry days and wet days, and the frequency and intensity of precipitation.

Figure 41: **Projection of future rainfall in the Hakra Branch Canal area (CAN ESM2) (1–12 are Jan to Dec)**

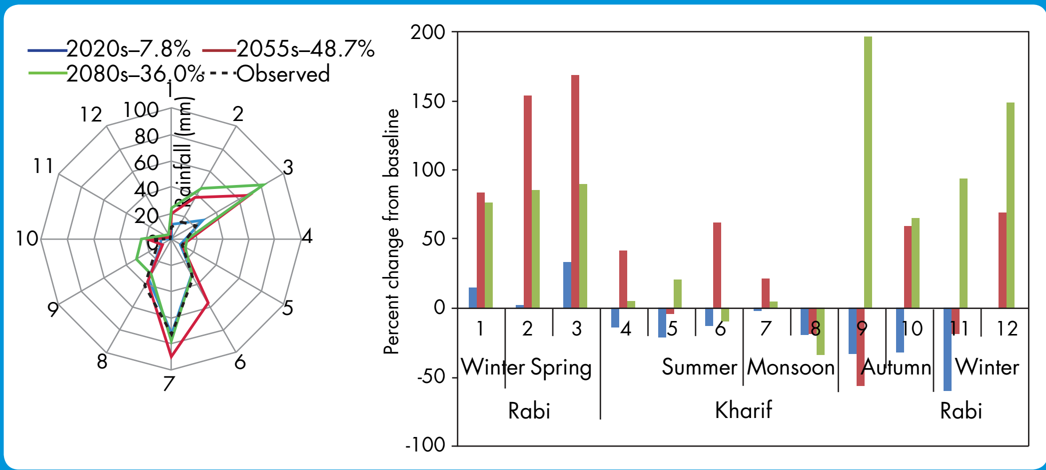


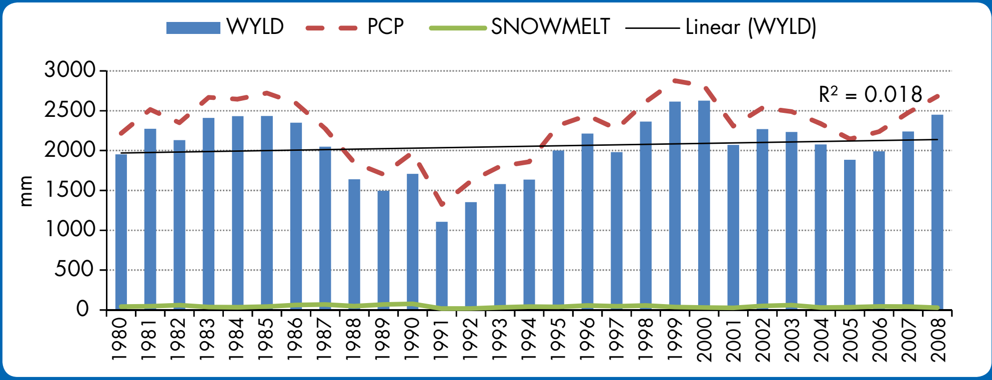
Table 33: **Projected percentage variation of rainfall from baseline in the Hakra Branch Canal area**

Season	Late winter	Spring		Summer			Monsoon		Autumn		Early winter		Annual
Crop	Rabi			Karif						Rabi			
Months	1	2	3	4	5	6	7	8	9	10	11	12	
2020s	+14.5	+1.1	+33.2	-13.9	-20.7	-12.4	-0.4	-19.2	-33.0	-32.1	-59.1	+0.5	-7.8
2050s	+83.3	+153.9	+168.7	+41.9	-3.5	+62.4	+21.3	-18.3	-55.7	+59.8	-18	+69	+48.7
2080s	+76.5	+85.2	+89.8	+5.1	+20.7	-9.1	+4.7	-33.2	+196.6	+65.1	+94	+148.7	+36

In addition to looking at the three different periods, an attempt was made to analyse trends in water availability in different seasons: winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November). No trend was identified during the simulation period in any of the seasons. However, the study did not consider the influence of land-cover changes during the simulation period when evaluating water availability. There were no long-term data available for observed discharge from the study area, thus it was not possible to evaluate trends in stream flow accurately. Farmers in the study area had a general perception that there had been a decrease in water availability for irrigation and agriculture over the last decade, with 84% of respondents experiencing a decline in water supply in the past 5 to 10 years (Figure 43).

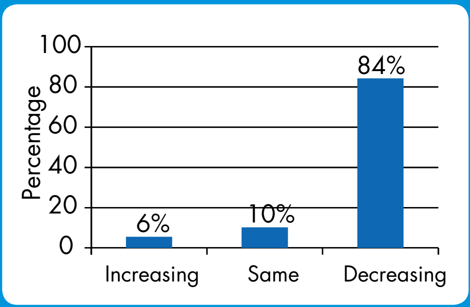
Climate change and other drivers of change affecting water availability are projected to have significant effects on crop production. Figure 44 shows the trends in productivity of different crops over the past ten years. The productivity of most crops has either remained

Figure 42: **Annual water availability in the Indrawati sub-basin (WYLD = effective water yield in cumecs; PCP = precipitation in mm)**



constant or gradually increased over the past ten years, with the exception of wheat, and to a lesser extent spring maize, which show a small decline.

Figure 43: **Perception of water availability in the Indrawati sub-basin**



Most farmers have retained the same cropping patterns but they have changed some of the crops they cultivate, abandoning some and introducing others (Figure 45). Most of the crops that they have stopped growing are pulses, especially grey pulses (gahat), black gram (mas), common beans (bodi), brown pulses (mashyang), and soya beans (bhatmas). Some cereals like barley (phaper), and in a very few cases millet (kodo), have also been abandoned, as have some root crops like tuber (pidalu) and sweet potato (shakkarkhanda). Farmers mainly keep growing millet to make alcohol for local consumption. Relatively few new crops had been introduced in place of the abandoned ones, indicating that the cropping system was becoming less diverse. Newly-introduced crops included cereals like spring rice and maize, and vegetables like onion, garlic, and cucumber. Some new cash crops like cardamom are also being tested.

The change in crops was reported to have occurred mainly about eight years ago, with reasons given including problems in cultivation like disease, lack of water for irrigation, low

Figure 44: **Productivity of different crops 2002 to 2012 in the Indrawati basin (1 muri/ropani = 0.98 t/ha) (no early data available for mustard seed as it is a recent crop)**

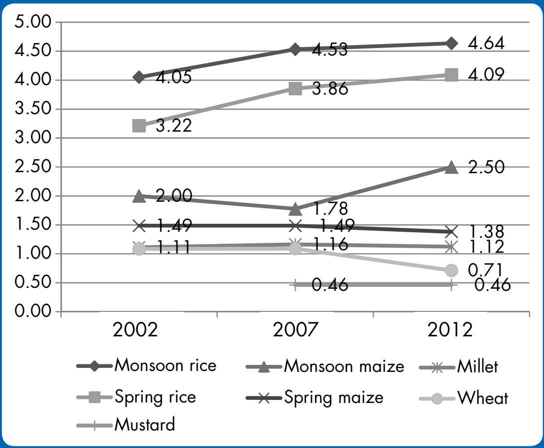
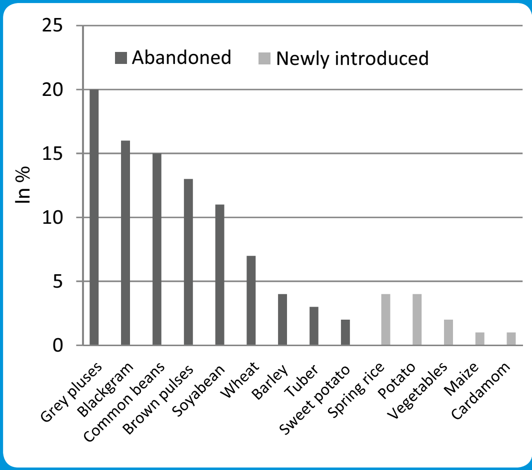


Figure 45: **Abandoned and newly-introduced crops in the Indrawati sub-basin**



production, lack of benefit, and unfavourable climatic conditions. Crops had also changed in response to the increased access to market, which encourages the production of financially lucrative crops like vegetables. The change in people's diets and development of local markets, which ensure the availability of inorganic fertilizers and the development of irrigation infrastructure, also encourage farmers to cultivate rice, which has a high water requirement. This contradiction demonstrates how many different factors are at play in influencing farmers' decisions; adaptation to changed climatic conditions is not the intuitive or obvious priority.

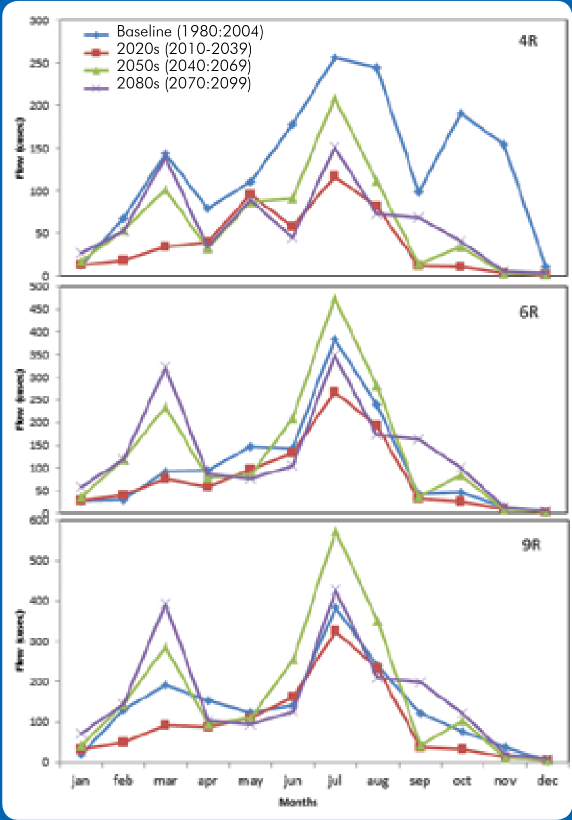
Future water availability and impacts on agriculture in the Hakra Branch Canal area

The SWAT model was used to simulate the average monthly flows at the head of the three distributaries in different time slices under future climate scenarios, the results are shown in Figure 46. Flows were reduced in all three distributaries in all three time segments, except in the 6R and 9R distributaries under the 2050s scenario in the monsoon season. The results suggest that there might be a shift in the monsoon pattern and that more extreme events might be expected in the 2050s.

The research also evaluated farmers' irrigation practices and estimated crop performance to project irrigation schedules and requirements. The monthly irrigation requirements for wheat and cotton are shown in Figure 47a as an example. The total annual requirement for wheat is about 661 mm, whereas effective rainfall in the area is about 161 mm. Similarly, the irrigation requirement for cotton is about 711 mm whereas effective rainfall in the planting season is

122 mm. The deficit (1,089 mm) is the irrigation requirement and is fulfilled from canal water and groundwater. At present, the water allowance for this canal command area is 2.85 cusec per 1,000 acre (1 cusec/acre = 0.07 cumecs/ha). The water supply from the canal is insufficient, and inequitable distribution of water at secondary (distributary) and tertiary (watercourse) levels compounds the issue of water shortage. Farmers do not depend upon the canal for irrigation. The shortage of water for crops (around 25%) is met by groundwater.

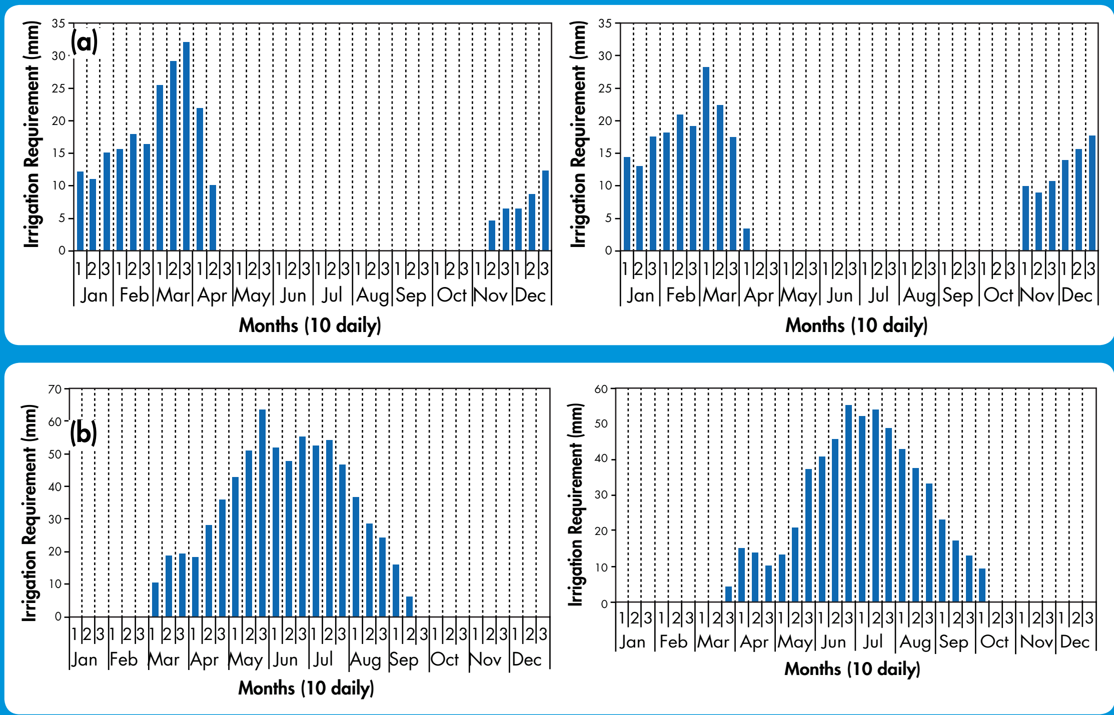
Figure 46: **Projected water availability at head of a) 4R distributary, b) 6R distributary, and c) 9R distributary in different future time periods**



According to the projections, the irrigation requirement for wheat could be reduced from 661 mm to 214 mm by 2020 with a two-week shift in the sowing date from 1 to 15 November. The future climate scenarios show that there will be more rainfall events in the monsoon months. Consequently, the irrigation requirement for cotton may also be reduced if the sowing time is shifted towards the end of May. Figure 47b shows the irrigation requirements for wheat and cotton in 2020 based on calculations using future rainfall and temperature data from 2010 to 2020.

The impact of climate change may further aggravate the prevailing water management practices as there will be more droughts and extreme events in the coming years (IPCC 2012). The results of the hydrological modelling suggest that projected flows will decrease under future climate scenarios, especially in the next two decades. This finding has significant implications for the study area, as the farmers are already facing water shortages for irrigation, resulting in a reduction in crop yields. The availability of canal water, which is diverted from the Sutlej River to the irrigation system will certainly become more critical, and farmers will be more dependent on rainfall, as well as costly groundwater pumping, which in turn will increase the input cost of cultivation. This information may help policy makers and land-use planners to anticipate and take proactive action to address the impacts of future climate conditions. The model results clearly indicate that farmers will need to adapt to the

Figure 47: a) Monthly irrigation requirement and b) irrigation requirement under the future climate scenario in the 2020s for wheat (left) and cotton (right)



changing climate to ensure sustainable crop production and food security in the project area. Shifting the timing of sowing and irrigation may be an adaptation option that can be used to maximize use of available soil moisture.

Climate Change Adaptation Strategies

A number of possible climate change adaptation measures were identified through in-depth analysis of the climate change scenario and the information gathered from the farmers in the research areas, combined with the research team's expert judgement. Some of these measures are applicable in both research areas ('common'), while others are more suitable for one or other of the areas. The main strategies are summarized in Table 34 and discussed below.

- **Rainwater harvesting and management (common):** To cope with the high seasonal variation in rainfall patterns in the research areas, in situ moisture conservation (either through conservation agriculture or construction of rainwater control and management structures) and rainwater storage for supplemental irrigation (in farm ponds, water pans, sand/sub-surface dams, earth dams, tanks, and others) can be a good adaptation strategy. Some communities still had isolated traditional methods for conserving rainwater, and there is a need to support people to restore these practices.

Table 34: **Potential adaptation strategies**

Adaptation strategy	Indrawati sub-basin	Hakra Branch Canal
Rainwater harvesting and management	x	x
Construction of terraces	x	
Construction of dikes along field boundaries		x
High-efficiency irrigation schemes		x
Adoption of biodiversity-based organic farming	x	x
Shifting crop timing and cropping patterns	x	x
Use of drought resistant crop varieties	x	x
Mixed cropping	x	x
Information system development	x	x

- **Construction of terraces (Nepal):** The farming community in the Indrawati sub-basin practises a traditional method of constructing terraces for soil and water conservation. However, some areas with slopes are being cultivated without terraces. It is imperative to make the farming community aware of the benefits of levelling land, and the way in which terraces help store water in the fields and contribute to preventing erosion of top soil.
- **Construction of dikes along field boundaries (Pakistan):** Growing trees around farm plots is a common traditional adaptation measure practised in the semi-arid conditions of Pakistan. The trees serve as a barrier to the wind, thus reducing erosion and helping to decrease evaporation. However, very few trees were seen in the Hakra Branch Canal command area. As a supplement to these vegetative barriers, construction of dikes along the field boundaries can also help to increase soil moisture content and prevent erosion of the valuable top soil layer. Other options that serve the same purpose include mulching, (i.e., covering the fields with plant residues to preserve soil moisture), and furrow irrigation (making small trenches within the field in order to increase water uptake).
- **High-efficiency irrigation schemes (Pakistan):** High-efficiency irrigation techniques, including sprinkler and drip irrigation schemes, are known to be much more water efficient than the traditional gravity-based flood and furrow irrigation techniques. The high-efficiency techniques serve as an adaptation measure to climate variability and drought due to their inherent ability to save water. There are certain constraints to the adoption of pressurized systems by farmers, the most important being the high installation costs and lack of skilled labour to operate the systems. The Government of Punjab has recently initiated the Punjab Irrigated Agriculture Productivity Improvement Programme Project (PIPIPP) with a budget of USD 250 million to address this problem. The programme has four components: (1) installation of (subsidized) high-efficiency irrigation systems, (2) improvement of community irrigation systems, (3) improved agricultural technology and practices, and monitoring and evaluation, and (4) project management, supervision, technical assistance, training, and strategic studies. This project can help the farming community in the study area to become more efficient water managers.

- **Adoption of biodiversity-based organic farming (common):** The smallholder farmers in both the research areas face financial constraints, in part due to the high costs of crop inputs like pesticides and chemical fertilizers. Some farmers rely on compost-based fertilizers and biopesticides produced locally using animal dung and weeds. These practices result in rapid improvement of soil fertility and moisture content in the fields as well as reduced input of chemical fertilizers. Such organic practices should be promoted by creating greater awareness of their benefits, and of the correct procedures for preserving maximum levels of soil nutrients.
- **Shifting crop timing and cropping patterns (common):** The climate change scenario downscaling exercise indicated that shifts could be expected in the monsoon pattern in the research areas. The farming communities are already aware of changes in rainfall patterns, and these will continue to reduce crop yield if no adaptation is undertaken. One option for coping with the variability in the monsoon is to adjust crop timing (delaying or early sowing of crops) according to the shift in the rainfall pattern. The farming communities are already using this method to a limited extent.
- **Use of drought resistant crop varieties (common):** One common practice of farmers in both research areas is to use indigenous seeds set aside from previous crops. Many farmers have reported avoiding high-yield hybrid varieties because indigenous varieties are more resistant to drought compared to hybrids. In some cases, where more drought resistant varieties have been developed, the inclination towards such varieties has also been more pronounced. In extreme conditions of water scarcity, it may even be necessary to promote crops that require less water.
- **Mixed cropping (common):** Cultivating more than one crop at a time may be a promising adaptation strategy for small-scale farmers to reduce the risk of complete crop failure. Several styles of crop mixing are found in both research areas. Although mixed fields are more labour-intensive for farmers, they do have several other advantages: they are less prone to pest attacks, allow for a diversified diet, and spread the risk of having no yields at all from failure of one crop. Thus mixed fields generate additional income in the long run.
- **Information system development (common):** In Pakistan and Nepal, the weather forecast is disseminated by the relevant government departments. Weather updates are also normally available on the Internet in English. Both the literacy rate in the research area and access to the Internet is very low, which means that the information seldom reaches the farmers. There is a need to establish a weather information system exclusively designed for the farming community in remote rural areas so that the farmers can make spontaneous decisions about sowing, irrigation, and other farm practices.

Of the different adaptation methods identified, some are already in use and need to be further promoted while others are suggestions. In terms of implementing these different measures, it will be more realistic to begin with those that already exist. Close consultation should be carried out with the stakeholders before implementation.

Conclusions

The study provided a number of insights to support understanding of the potential impacts of climate change on water availability in the Indrawati sub-basin in Nepal and the command area of the Hakra Branch Cana in Pakistan. Differences in the characteristics of the two areas necessitated the use of different approaches to assess climate change impact and identify possible adaptation strategies. This type of study can help augment the knowledge base of decision makers in agriculture and water management by highlighting potential impacts and appropriate strategies for rainfed and irrigated agriculture.

The projections generated by the different models indicated that there had been a slight increase in temperature (minimum and maximum temperatures) over the past 20 years with significant seasonal variation, but no clear trend was observed at either site in average annual precipitation and water balance. The communities had observed changes in the number of dry and wet days, and in the frequency and intensity of rainfall. Farmers had experienced climate change impacts on water availability and agricultural production and are already taking measures to address them by changing cropping patterns and abandoning some crops and introducing new ones. The research also showed that farmers' decisions were strongly influenced by increased market access, availability of inorganic fertilizers, development of irrigation infrastructure, and changes in diet, meaning that adaptation to changed climate conditions was not the immediate priority.

The future climate scenarios indicated that there may be a shift in monsoon patterns and more extreme events by 2050. This means that farmers in both the Indrawati sub-basin and the Hakra Branch Canal area need to be prepared to adapt to changing patterns, since agriculture is highly dependent on rainfall (in the Indrawati sub-basin) and the supply-based canal irrigation system (in the Hakra Branch Canal area). The communities in both areas are using traditional measures to address the changes that they have noticed, but the measures undertaken will not be sufficient given the expected changes in climate in future. The farmers require additional awareness, further institutional assistance, supportive government policies, and help to address the financial constraints to meet their needs.

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People's Perceptions of and Adaptation Strategies to Climate Change in the Koshi River Basin, Nepal

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Abstract

This paper discusses people's perceptions of climate variability and change, and their efforts to cope with the impacts, in the Koshi basin in Nepal. The study is based on primary information obtained through focus group discussions and key informant interviews in three ecological zones – mountains, hills and Terai (lowlands). People in the region have been experiencing increasing temperatures and greater variability in precipitation, with impacts in different sectors that affect their livelihood options including increasing scarcity of water, increasing risk of flash floods, decline in yield of agricultural crops, shifting of eco-zones to higher elevations, loss of biodiversity, and increasing incidence of disease. Communities have adopted different measures to cope with water scarcity such as planting trees around springs, revitalizing rotational irrigation schemes, building canals (pynes) and plastic-lined ponds for irrigation, and introducing sprinkler irrigation. Agricultural measures include changing cropping patterns and the cropping calendar, using failed crops as fodder, introducing crops with a shorter growing period, scattering ash or cow urine and using fire to kill pests, introducing integrated pest management, and constructing storage rooms to reduce post-harvest losses. Conservation of forests and biodiversity has been addressed through conservation of marginal land, planting of different species, and community management and conservation of forest. The challenge now is to improve these technologies and scale up some of the measures already adopted to manage climate change risk. It is also necessary to assess the appropriateness and effectiveness of the different strategies and practices in the context of different climate change scenarios.

Introduction

Over the past decade, adaptation to climate change has moved away from an academic and theoretical topic to become a main focus of public policy. But policy is not simply a matter of preparing a plan in the central government and expecting local communities to implement it. Although climate change is happening, the way in which the impacts are manifested is different around the world. At the same time, people have different perceptions of how urgent, important, or intense the changes are. This is not only a reflection of their political beliefs, but also of the way in which their worldviews shape these perceptions. The different perceptions can result in a high adaptive capacity, i.e., the ability to adjust comes easily and naturally, but it can also translate into barriers to adaptation. One of the ways in which this can be studied is through comparing people's perceptions of what is happening with the climate with the observed data. This study set out to understand what people think is happening and what sort of strategies they have adopted to deal with the perceived change. Improved awareness of how well people observe and respond to changes in climate helps those who provide assistance to communities on climate change understand what people's main concerns are, regardless of the physical evidence. Such an approach is particularly helpful when climate data is scarce and people's perceptions are the only information available for decision making. Since rural communities are the ones who have closely observed the local climatic patterns, local knowledge can provide important insights into a phenomenon that has not yet been documented by scientists. Patino and Gauthier (2009) demonstrate that local perspectives can be combined with scientific climate scenarios to draw policy recommendations.

Adaptation refers to responses or actions taken by individuals that enable survival of the individuals and/or the group. Coping and adaptive strategies can be tailored according to the level of vulnerability and type of risk faced by households and communities. Coping strategies are defined as 'the bundle of poor people's responses to declining food availability and entitlements in abnormal seasons or years,' while adaptive strategies 'constitute a permanent change in the mix of productive activities required to meet livelihood needs' (CIDA and CISI 1997). Adaptive strategies also constitute the plan of actions carried out over a specific time by specific groups of people to allow them to adjust to or cope with their local environment. In the climate change context, adaptation means the series of actions taken to reduce vulnerability to climate change in both the short and long term. Societies across Nepal have a long record of adapting and reducing their vulnerability to the impacts of weather and climate-related events such as floods and droughts. Nevertheless, additional adaptation measures will be required at the local level to reduce the adverse impacts of future climate change and variability.

Adaptation to climate change requires that local people first notice that the climate has altered, as this is the trigger for them to identify and implement potentially useful actions to adjust to the change (Maddison 2007).While scientific studies document how, where, and to what degree climate change is occurring, people's perceptions of these changes often have a more significant influence on their response. People's understanding of what is happening determines how they formulate strategies to cope with changes in the short term and adapt to them in the long term. However, the perception of climate change varies depending on place, time, ethnicity, culture, and socioeconomic background, and with individual experience and attitude. Several researchers and development practitioners have acknowledged the importance of perceptions in determining responses. For example, Bhusal (2009) examined how farmers' perceptions of climate change corresponded with temperature and rainfall data recorded at a meteorological station in Lumle in north-central Nepal, and documented local adaptation responses to the impacts of climate variability and change. The majority of people said that the temperature had increased and that they had experienced unpredictable rainfall patterns over the preceding ten years. The study discussed some adaptation measures in farming practices that had helped farmers to cope with the changes in climate, weather, and other environmental conditions.

The Koshi Basin Study

The study described here was a part of the Small Grants Programme project on 'Climate change adaptation through water resource management: comparative study between Yellow and Koshi River basins', carried out by Peking University and Tribhuvan University. The purpose of the project was to promote the coordinated development and management of water resources, land use, and related resources in order to maximize economic and social welfare in an equitable manner in the Yellow and Koshi River basins. The project aimed to support the development of adaptation policy and of an adaptation research agenda at the basin level.

This paper highlights the case study carried out in the Nepal part of the basin. The Koshi is an important river basin for Nepal's social and economic development. It is a dynamic river system with a high rate of erosion and sedimentation and frequent changes in river course, in an area with a relatively high population density. Significant changes in the water supply and water demand for uses in different sectors are likely to have an impact on the socioeconomic development of the basin area, especially under changing climate conditions.

The Nepal part of the basin was also selected because Nepal has a policy context that emphasizes the community level. Recognizing the challenges imposed by climate change, the Government of Nepal has developed water resource management strategies and policies. Actions have included the development of a National Water Plan (2005) and development of a Koshi River Basin Management Strategic Plan (2011-2021) by the Water and Energy Commission Secretariat (WECS) which pilots integrated water resource management (IWRM) for the basin. In addition, a National Adaptation Programme for Action (NAPA) was formulated for Nepal in 2010 in line with the UN Framework Convention on Climate Change (UNFCCC), and a Climate Change Policy was prepared in 2011. These documents emphasize community-based adaptation activities through integrated management of agriculture, watershed, water, forest, and biodiversity as the most prioritized adaptation approaches for addressing climate change issues in the country (MOE 2010).

There is a lack of high resolution, representative, long-term hydro-meteorological data in the Koshi basin, thus the experience of local people is an important source of information on climate, and also provides a basis for identifying locally acceptable and economically viable adaptation measures that have been implemented successfully. It is important to gain awareness of how local people understand the climate and how climate interacts with their livelihood activities. Unless adaptation policies and related projects address the local perceptions, it is unlikely that a community will agree to and adopt any recommended practices. There is thus a need to understand the major impacts of climate change perceived by local people in order to identify the best approaches for reducing vulnerability to these changes. This study sought to understand peoples' perceptions of climate change and identify appropriate adaptation strategies in the Koshi River basin by examining the observed trends in climate and people's views of the major impacts.

Methods

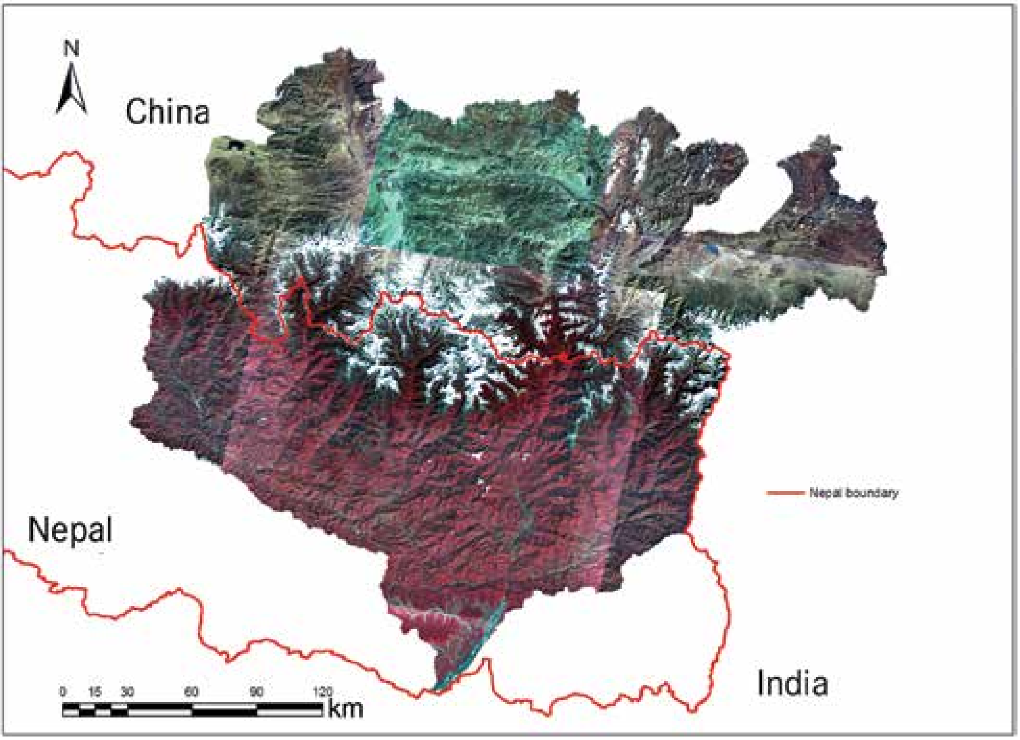
The study was based on extensive field surveys in 17 districts of the Koshi River basin in Nepal: five districts from the highest elevation mountain ecological zone (Dolakha, Sankhuwasabha, Sindhupalchok, Solukhumbu, and Taplejung), ten from the middle elevation hills (Bhojpur, Dhankuta, Kavrepalanchowk, Khotang, Okhaldhunga, Panchthar, Ramechhap, Sindhuli, Terhathum, and Udayapur), and two from the lowland Terai zone (Saptari and Sunsari). Intensive field observations were carried out by the research team to collect information from the communities. Focus group discussions (FGDs) were conducted with farmers, school teachers, local political leaders, social workers, representatives of local and international non-governmental organizations (NGOs and INGOs), and business people. Altogether, 34 FGDs were held, two from each district, with eigh to ten individuals in each group. In addition, 68 key informant interviews (KII) were conducted, four from each district. The informants included former village development committee (VDC) leaders, heads of educational institutions, representatives of government line agencies (GLAs), representatives of INGOs, members of water user groups, and members of community forest user groups. Guidelines were developed for both the FGDs and the KIIs to make the discussion more consistent. The participants in FGDs and KIIs were over 40 years old, as these people were considered to have greater experience with climate variability and sufficient memory of significant weather events. Qualitative and quantitative data on perceptions of climate change and on adaptation strategies already adopted were then analysed and interpreted.

Study area

The Koshi River is also known as the Sapta Koshi (seven Koshi) because it has seven major tributaries: from east to west the Tamor, Arun, Dudhkoshi, Likhu, Tamakoshi, Bhotekoshi/ Sunkoshi, and Indrawati. The elevation of the basin ranges from less than 70 masl in the south to 8,848 masl in the high Himalayas (summit of Mount Everest). Close to 62% of the total basin area lies above 4,000 masl. Figure 48 shows the area of the basin within China and Nepal.

The climate varies with elevation and other physical factors. Winter is the driest and summer the wettest season. In winter, the high mountain areas receive average precipitation of more than 120 mm, but the middle mountains and plains receive less than 40 mm. In summer, the high elevation regions receive more than 2,250 mm precipitation, while other parts receive between 750 and 1,500 mm.

Figure 48: **The Koshi basin**



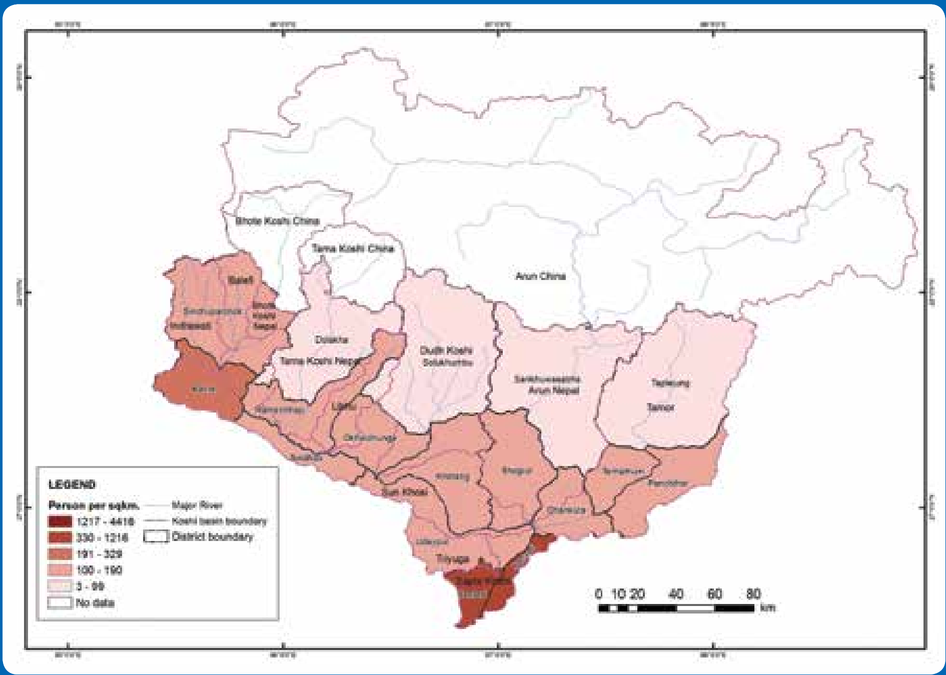
There are a total of 797 VDCs within the 17 districts in the Nepal part of the basin with a total population of just over 3 million people (CBS 2002). The population density ranges from 32 persons per square kilometre in Solukhumbu in the high mountains to 389 persons per square kilometre in Saptari District in the Terai (Figure 49).

The National Agriculture Sample Survey (2001/02) indicated that nearly 89% of the total area was owned by farm households (CBS 2002). The National Living Standards Survey 2010/11 (CBS 2012a) shows the average size of agricultural landholdings to be 0.9 ha, with nearly 60% of farmers having landholdings of less than 1 ha, and 8% owning more than 2 ha (CBS 2012b).

Results

The data and interpretations of local people's perceptions of climate change, and their adaptation mechanisms, are described in the following. The adaptation practices were identified from the data generated through the field survey. Proxy indicators were developed for climate change based on people's responses about the sort of changes they were observing, and interpretations were based on the reported impacts. The issues raised are discussed separately for the three different ecological zones: mountains, hills, and Terai.

Figure 49: **Population density in the Koshi basin, 2011**



Perceptions, Observations, and Projections of Climate Trends

Communities' perceptions of climate trends over the past 30 years are summarized in Table 35. The common feature perceived by local people in all three ecological belts was that the annual number of hot days had increased and the annual number of cold days had decreased (except in the Terai). In addition, in the Terai, the number of days with heat waves was perceived to have increased, whereas in the mountain areas, the duration of cold waves was thought to have decreased. The perceived changes were more or less consistent with the observed and projected changes in temperature. An analysis of observed temperature data in the Koshi basin shows an increasing trend in both maximum and minimum temperatures over all seasons, as well as annually, except in a few scattered places with decreasing trends in the Terai. Local people from the Terai region reported an increasing trend in cold waves resulting in loss of crops and adverse effects on both human and animal health. The decreasing trends in maximum temperature in the Terai might be the result of increased winter fog. The projections for future climate from HadRM2 and PRECIS regional climate change models indicated that 1) temperatures will increase by more than 0.01°C per year; 2) the highest increase will be in the winter (DJF); and 3) warming will increase progressively with elevation, and areas above 4,000 masl will experience the highest warming rates.

Table 35: **Communities' perceptions on climate variables within the Koshi basin area over the last 30 years**

Climate variable	Mountains	Hills	Terai
No. of hot days	Increasing and earlier	Increasing and earlier	Increasing and earlier
Heat waves	-	-	Earlier by about a week
Cold days	Decreasing and later by about a month	Decreasing and later by about a month	Increasing
Cold waves	Later by two to three weeks	-	Later by about a week
Monsoon rainfall	Later by two to three weeks	Later by two to three weeks	Later by two to three weeks
Winter rainfall	Decreasing	Decreasing	Decreasing
Snowfall	Decreasing	Decreasing	-
Frost	Decreasing	Decreasing	-
Dew	Decreasing	Decreasing	Decreasing
Hail	Delayed to May	Delayed to May	Delayed to last week of May
Thunderstorms/ storms	Decreasing and shifted by two to three weeks	Decreasing and shifted by two to three weeks	Decreasing and shifted by two to three weeks
Fogs/cloud	Decreasing	Decreasing	Increasing

Farmers considered that winter rainfall had decreased and that the start of the monsoon rainfall was two to three weeks later than previously. They also noted that the intensity and frequency of snowfall, frost, hail, and dew had decreased. However, the observations indicated that precipitation had predominantly increased in winter and pre-monsoon, and decreased during the post-monsoon. The models did not show consistent trends for precipitation, but projected an overall increase in monsoon precipitation by 7-17%, with a reduction of up to 20% over the northern part of the basin and an enhancement of up to 30% over the southern part. According to the climate change models, there is likely to be a spatial variation in the climate trends. This is also perceived by the people in the area, who were more conscious of the increased variability in weather and climate than of long-term changes.

More details of the model calculations, observational data, and farmers' perceptions are provided in the full project report (Peking University and Tribhuvan University 2013).

Observations about Climate Change Impacts

Communities made many observations about changes in the nature around them and described a number of responses to the impacts of climate changes. While everyone commented on changes, there was considerable variation among the communities regarding the intensity that they perceived. Respondents described changes related to temperature, precipitation, flora, and fauna, all of which suggest that (1) people are observant, and (2) there are many changes taking place. The observations are summarized in Box 1.

The study asked residents about changes in the cycles of specific crops. The reported changes are summarized in Table 36. According to those interviewed, the growing period of agricultural crops has been reduced, mainly due to an increase in temperature. The time of

Box 1: Observations of climate changes

Changes in temperature and seasons
- Summer is getting hotter and longer
- Winter is getting warmer and shorter

Changes in precipitation
- Increase in frequency of intense rainfall events
- Monsoon is irregular and arrival is about two-to-three weeks later than previously
- Winter precipitation and snowfall at higher elevations are erratic and decreasing dramatically
- The intensity and frequency of snowfall, frost, and dew has decreased over the last 30 years

Impacts
- Overall decrease in water availability due to dried up springs
- Increase in pests and diseases in crops and livestock products
- Fruit such as oranges and litchi now grown at higher elevations where previously not possible
- A new invasive, bad-smelling grass species (local name twake jhar) that is not eaten by cattle (causes diarrhoea) and cannot be used as fertilizer has appeared on agricultural land (in Ramechhap). The smell causes vomiting and headaches in people
- Many bird species are disappearing
- Junar (mandarin orange) flowers a month earlier than 30 years ago, peach and rhododendron are flowering earlier
- Guava trees are dying
- Lemon and orange trees are dying at lower elevations and cultivation is shifting to higher elevations (on average 100-200 m)
- Mosquitoes are found in higher areas than in the past
- There are fewer fish in the rivers

Responses
- Introduction of new crop varieties with shorter growing periods
- Seasonal farming calendar has to be changed because sowing, planting, and harvesting times of crops are about 15-30 days earlier

sowing, planting, and harvesting of agricultural crops in the Koshi basin has undergone considerable change. The sowing and harvesting time for summer crops such as rice, maize, millet, and potato are generally later by up to one month, whereas the sowing and harvesting time for the winter crops such as the wheat and barley has been shifted forward by 15-30 days.

The study also asked about timing of plant flowering and fruit ripening and wildlife behaviour, and then used these as proxy indicators of climate change. The results are summarized in Table 37. Flowering and ripening of a number of plant species were reported to be earlier than before. For example, the flowering time of rhododendron has shifted from March to mid-January, and the ripening times of fruits such as pear, jackfruit, myrica-nagi, and apricot are also earlier by about one month. Some species of wildlife and amphibians are disappearing and a few new species are appearing, also thought to be the result of climate change and migration of species to areas with a more favourable climate. For example,

Table 36: **Change in crop calendar (sowing and harvesting time) in the last 30 years**

	Crops	Rice	Wheat	Maize	Millet	Barley	Potato
Mountains	Sowing	One month later	Three weeks earlier	Two weeks later	Three weeks later	Two weeks earlier	–
	Planting	One month later	–	–	Three weeks later	–	Rainy season: two weeks later Winter: two weeks earlier
	Harvesting	One month later	Two to three weeks earlier	Two to three weeks later	No change	Two to three weeks earlier	Rainy season: same as before Winter: two to three weeks later
Hills	Sowing	One month later	No change	Two to three weeks later	Four weeks later	Three weeks earlier	–
	Planting	One month later	–	–	Two weeks later	–	Rainy season: two to three weeks later Winter: two to three weeks later
	Harvesting	Three weeks earlier	One month earlier	Two to three weeks later	Two weeks earlier	Three weeks earlier	Rainy season: two weeks earlier Winter: two weeks earlier
Terai	Sowing	One month later	Three weeks earlier	Three to four weeks later	–	–	–
	Planting	One month later	–	–	–	–	One week earlier
	Harvesting	One to two weeks earlier	Two weeks earlier	Three to four weeks later	–	–	Two weeks earlier

falcon, vultures, and parrots are decreasing in number in all three ecological zones, whereas green and red snakes and red monkeys have become more frequent in the hills and Terai.

Table 38 shows the perceived changes related to the sectors of water resources, agriculture, forest and biodiversity, and human health. Some farmers' observations are also given in Box 2. The major changes related to water resources reported in mountain areas were the retreat of glaciers and lowering of the snowline, which in the long run may result in less water being available in the dry season and an increase in the likelihood of glacial lake outburst floods. The major change in hill and Terai areas was the increase in unpredictable river flow, which may lead to an increase in floods. The reduced volume of water in rivers and siltation in river beds will also lead to a decrease in the capacity for hydroelectricity. Farmers considered that the frequency and intensity of droughts and floods had increased over the past 30 years. In the agricultural sector, there had been an increase in potato and vegetable yields which had a positive impact on household income. Several changes had been observed related to human health. Increased prevalence of mosquitoes is often cited as a direct consequence of

Table 37: Seasonal changes in biophysical aspects (proxy indicators) over the last 30 years

Indicator	Mountains	Hills	Terai
Plant flowering			
Rhododendron	One month earlier	One month earlier	–
Painu	One month earlier	One month earlier	–
Mango		Two weeks earlier	Two weeks earlier
Fruit ripening			
Pear (aru)	Two weeks earlier	One month earlier	–
Jackfruit (rukh kathar)	One month earlier	Two to three weeks earlier	One month earlier
Mirica-nagi (kafal)	–	Two weeks earlier	–
Apricot (khurpani)	One month earlier	One month earlier	
Animal/birds/fish appearance/disappearance			
Falcon (malchara)	Disappearing Disappearing	Disappearing Disappearing	Disappearing
Parrot	Disappearing	Disappearing	Disappearing
Green/red snakes, lokharke, lampuchhre, red monkey		Appearing	Appearing
Salak, todke, wolf	Disappearing	Disappearing	Disappearing
Vulture	Disappearing	Disappearing	Disappearing
Sparrow	Disappearing	Disappearing	Disappearing
Frog	Disappearing	Disappearing	Disappearing
Tiger	Disappearing	Disappearing	Disappearing

warmer weather, and people in both hill and mountain regions mentioned that mosquitoes had become common even in winter in contrast to a few years ago. The increased presence of mosquitoes and other insects was accompanied by an increased incidence in vector-borne diseases, and local people linked the increased incidence of such diseases to rising temperatures. Previously unknown diseases were also appearing in livestock. These diseases can affect quality of life, supply of labour, household income, and other aspects of rural livelihoods.

Box 2: Farmers' observations on changes in climate

Indra Khadka, local farmer, Sindhupalchok: 'We used to feel much cold for many days in the past. These days we hardly feel cold for long times. Whenever it is cold, it lasts only for a couple of days. There used to be a week-long precipitation during winter. However, in recent years we rarely see such rains in the winter. Only very short winter rains occur these days. Sometimes we have to wait until March for rain.'

Yuba Raj Pandey, senior agriculture officer, Dolakha: 'Little rain during winter has seriously affected winter crops. The yield of wheat and other winter crops has significantly reduced; the grain is often wrinkled and less tasty. There are more insects and pest attacks on winter crops.'

Ramesh Bahadur Thapa, local farmer, Ramechhap: 'In the past, Manthali Phant valley used to be totally covered by fog in December and January. Now, the Phant is not fully covered even in January.'

Table 38: **Perceived impacts of climate change on different sectors**

Sectors	Mountain		Hills		Terai	
	Perceived change	Likely consequence	Perceived change	Likely consequence	Perceived change	Likely consequence
Water Resources	- Retreat of glaciers - Drying up of ponds and springs - Frequent floods and droughts	- Floods - Reduced water supply - Water shortage and destruction of irrigation canals	- Unpredictable river flows - Drying up of ponds and springs - Reduction in stream water - Frequent flood and drought events	- Floods and siltation - Reduction in water supply - Less hydropower generation - Water shortage and destruction of structures	- Unpredictable river flows - Decrease in level of surface water - Frequent flood and drought events	- Floods - Reduction in water supply - Desertification
Agriculture	- Increased potato farming - Low production of food crops - Changes in growing season - Reduced grazing land	- Increased income - Food scarcity - Change in crop calendar - Decreased number of livestock - Decline in production	- Increased potato farming - Low production of food crops - Changes in growing season - Reduced grazing land - Increased pests and diseases	- Increased income - Food scarcity - Change in crop calendar - Decreased number of livestock - Decline in production	- Increase in vegetable and fruit farming - Increased production due to use of hybrid seed - Maximum use of fertilizer and pesticides - Increase in goat and buffalo farming	- Increase in income from vegetable and fruit farming - Food sufficiency - Soil pollution - Increased production and income
Forest and biodiversity	- Decrease in varieties of trees and fruit - NTFPs and medicinal herbs disappearing	- Losses in biodiversity and supply of fruit - Negative impact on income and human health	- Decrease in varieties of trees and fruit - NTFPs and medicinal herbs disappearing	- Losses in biodiversity and supply of fruit - Negative impact on income and human health	- Decrease in varieties of trees and fruit - NTFPs and medicinal herbs decreasing	- Losses in biodiversity and supply of fruit - Negative impact on income and human health
Human Health	Prevalence of kalazaar, Japanese encephalitis, diarrhoeal diseases, infectious diseases, and respiratory diseases	Decrease in quality of life and increase in costs for treatment	Prevalence of kalazaar, Japanese encephalitis, diarrhoeal diseases, infectious diseases, and respiratory diseases	Decrease in quality of life and increase in costs for treatment	Prevalence of kalazaar, Japanese encephalitis, diarrhoeal diseases, infectious diseases, and respiratory diseases	Decrease in quality of life and increase in costs for treatment

Forecasting Indicators Used by the Local People

People know about the causes of flash floods of different types which they have experienced in the past – glacial lake outburst floods, landslide dam outburst floods, and floods due to heavy precipitation. Based on past experience, people reported some indicators that they used to forecast rainfall, landslides, debris flows, and floods. These are traditional beliefs, most of which have scientific explanations and can be used as indicators of change in precipitation. The main indicators reported are shown in Box 3.

Responses

Climate-related changes are already having a severe impact on people's livelihoods, particularly where people are highly dependent on agriculture and animal husbandry. Water scarcity or overabundance, drastic reductions in crop yields, and increases in crop pests are some of the challenges that rural communities are facing.

People residing in the Koshi basin have adopted different strategies in response to climate change risk (Table 39). These include planting trees around springs to protect the catchment area, revitalizing rotational irrigation schemes, and building canals (pynes) and plastic-lined ponds for irrigation. Other adaptation strategies include shifting the agricultural calendar, using stalks of failed crops as fodder, introducing improved seeds that promise high yields even under dry conditions, growing crops at higher elevations, and cultivating more than one crop per year. Conservation of marginal land and forest, planting of different species, and management and conservation of forest by communities have also been practised to conserve forest and biodiversity. People are applying integrated pest management strategies such as scattering ash or cow urine, and setting fires in fields to kill pests, as well as using chemical

Box 3: Indicators used by local people for forecasting water-induced disasters

- Black clouds in the sky mean rain of long duration in the watershed area.
- Sunny days follow rainfall of long duration.
- Downward movement of snakes means rain ('when large snakes are seen on the ground, it may rain').
- Movement of crabs from river to land means risk of flooding.
- Regular crying of crows and thirsty birds means rain (kakakul) ('When a kakakuli cries in the sky, it will rain.')
- Active landslides in upstream hillsides mean disastrous floods in downstream areas.
- When a person feels laziness at mid-day, it will rain in the evening.
- When dry leaves become moist, there is a high chance of rain.
- When ants carry their eggs from their home (hole), it is more likely that it will rain.
- When a long cloud belt appears over the ground, there will not be rain for many days, and there may be a drought.
- Good flowering of sal forest means good seasons all year.
- Heavy rainfall in May/June indicates a drought in July.
- Rainfall at the beginning of the third week of January is a good indicator for agriculture throughout the year.

Table 39: **Responses to climate change in the Koshi Basin**

Sector	Mountains	Hills	Terai
Water Resources	▪ Planting trees around springs to protect the catchment area ▪ Revitalization of rotational irrigation, a traditional mechanism in the study area where water is shared through canals (pynes) ▪ Construction of canals (pynes) and plastic-lined ponds for irrigation ▪ Sprinkler irrigation ▪ Re-use of waste water	▪ Rainwater harvesting into tanks; water used for cattle, household, and vegetable irrigation ▪ Planting trees around springs to protect the catchment area ▪ Construction of canals (pynes) and plastic-lined ponds for irrigation ▪ Re-use of waste water ▪ Sprinkler irrigation	▪ Investment in electric pumps to get spring water from nearby streams at lower elevations ▪ Construction of canals (pynes) and plastic-lined ponds for irrigation ▪ Re-use of waste water
Agriculture	▪ Changing to crops that can cope with water and temperature stress (e.g., millet replacing rice, mustard replacing wheat) ▪ Introduction of improved seeds that promise high yields even under dry conditions ▪ Growing crops at higher elevations and cultivating more than one crop per year ▪ Mixed cropping of beans with maize to protect the maize plants from strong winds ▪ Introducing new crops such as ginger and turmeric that fetch higher prices and can better withstand water and temperature stress	▪ Changing to crops that can cope with water and temperature stress (e.g., millet replacing rice, mustard replacing wheat) ▪ Starting to cultivate off-season vegetables ▪ Introduction of improved seeds that promise high yields even under dry conditions ▪ Using stalks of failed crops as fodder ▪ Mulching to increase soil moisture ▪ Introducing new crops such as ginger and turmeric that fetch higher prices and can better withstand water and temperature stress ▪ Mixed cropping of beans with maize to protect the maize plants from strong winds. ▪ Planting trees around farmland	▪ Changing to crops that can cope with water and temperature stress (e.g., mustard replacing wheat) ▪ Starting to cultivate off-season vegetables ▪ Introduction of improved seeds that promise high yields even under dry conditions ▪ Using stalks of failed crops as fodder ▪ Mixed cropping of beans with wheat to protect the wheat plants from strong winds ▪ Planting trees around farmland
Forest and biodiversity	▪ Focus on non-timber forest products ▪ Conservation of marginal land and forest ▪ Planting of different species	▪ Focus on non-timber forest products ▪ Conservation of marginal land and forest ▪ Planting of different plants ▪ Management and conservation by communities	▪ Focus on non-timber forest products ▪ Conservation of marginal land and forest ▪ Management and conservation by communities
Pests and disease	▪ Applying traditional pest management strategies such as scattering ash or cow urine and setting fires in fields to kill pests ▪ Use of chemical pesticides ▪ Construction of specific storage rooms to reduce post-harvest losses	▪ Applying traditional pest management strategies such as scattering ash or cow urine, and setting fires in fields to kill pests ▪ Crop rotation and planting of different crops every season to limit infestations of the same pests as well as provide nutrients to the soil ▪ Construction of specific storage rooms to reduce post-harvest losses ▪ Use of chemical pesticides	▪ Promotion of organic pest control mechanisms ▪ Construction of specific storage rooms to reduce post-harvest losses ▪ Use of chemical pesticides ▪ Applying traditional pest management strategies such as scattering ash or cow urine and setting fires in fields to kill pests

pesticides and constructing specific storage rooms in households to reduce post-harvest losses. However, these responses, which enable farmers to cope with the adverse impacts of climate change, are still limited in scale and use and need to be improved and scaled up to the basin level.

Discussion

The study shows that even people in remote rural areas are engaged actors trying to mitigate the way in which unexpected climate variability – a manifestation of climate change – is affecting their lives and livelihoods. The observations of how temperature and precipitation changes have transformed approaches to farming, and the list of actions taken, indicate that people are already responding to the changes, albeit often through coping strategies that may eventually lose their potential. The key is to foster responses that are sustainable, at least in the medium term, and enable people to have a sufficient safety net to survive additional unexpected occurrences. The present study did not attempt to evaluate the responses, but this is an important next step.

There was considerable spatial variation in the types and magnitude of climate change reported and how these are being experienced. People living in the Terai region, who are downstream in a warmer environment, are more worried about the increasing risk of flash floods as a result of the increasing number and intensity of extreme precipitation events, as well as about the increasing frequency and intensity of cold waves in winter. People in the mountains and hills are more worried about the increasing scarcity of water in winter and spring and increasing risk of landslides, soil erosion, and flash floods in the summer during the monsoon.

Major responses adopted by the people living in the Terai include the use of electric pumps for groundwater irrigation, construction of plastic-lined ponds, changes in cropping patterns, planting trees around farmland, and conservation of marginal land and forest. Major responses in the mountain and hill regions include adoption of sprinkler irrigation, afforestation, introduction of micro-hydro dams, revitalization of rotational irrigation, construction of plastic-lined ponds, changes in crop species and cropping patterns, rainwater harvesting, afforestation, and mulching. However, these responses still require some technological improvement before they can be scaled up to watershed level. Improvements in existing technology and introduction of climate resilient crop varieties should be based on research and development of the responses already adopted by the people who are dealing with climate variability in their everyday lives. Furthermore, people in the area should be made aware of the results of research, of recommendations for scaling up existing measures, and of new innovations for long-term climate risk management.

Climate change risk management approaches and strategies in Nepal such as the National Adaptation Programme of Action (NAPA) (MOE 2010) and climate resilient planning (ADB/UNDP 2010) are focused predominantly on sectoral approaches. This ignores the spatial variation in the types, magnitude, and intensity of climate change and its impacts in the different eco-zones of Nepal. The present study in the Koshi basin with different spatial contexts suggests that spatial variation should also be considered when formulating national policies and strategies for climate change risk management.

Additional questions that emerge from this work include whether some of the responses mentioned might work well in the short term but have opportunity costs in the medium or long term. This includes strategies like planting a different cash crop; if everyone adopts the same crop, prices could fall leaving farmers worse off than before. It would also be interesting to know whether people prefer to stay with their traditional livelihoods or whether they are more inclined to abandon these when the situation is changing. Finally, what is the best way to raise awareness of changes in weather without compromising people's own ability to observe and 'own' what is happening so that they feel empowered to take action themselves? This does not assume that all actions represent sustainable long-term adaptation, rather it acknowledges that some of the actions may actually be maladaptive, i.e., actually increase vulnerability (inadvertently) or undermine future opportunities. However, the act of undertaking some sort of response is an important dimension in its own right.

Conclusions

The study looked at the perceptions of people in the Koshi basin of changes in climate, and their adaptive strategies. A majority of respondents had perceived changes in climate and were aware of the impacts in different sectors. They have been adopting different measures at the household and community levels to cope with the impacts of climate change. However, the major challenge is to improve the technology and scale up some of the measures already adopted by local people, such as micro-hydro dams, sprinkler irrigation, and rainwater harvesting. It is also necessary to assess the appropriateness and effectiveness of the different strategies and practices in the context of different climate change scenarios. Future efforts should also focus on improving the hydro-meteorological data and developing reliable climate change scenarios. The concerned government line agencies should focus their activities on seasonal weather forecasts, and assist rural households to design their crop calendars in accordance with these forecasts.

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Benefit Sharing Mechanisms in Hydropower Projects: Lessons from Nepal and India

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Abstract

A study was carried out to assess the modalities of the benefit-sharing mechanism and implementation in the Kulekhani hydropower project in Nepal and Teesta V hydropower project in Sikkim, India, and to analyse and suggest appropriate policy formulation for effective implementation to benefit both hydropower developers and local communities. The information and data for the study were generated from primary and secondary sources, including field studies. Hydropower policy in India and Nepal focuses on sharing of benefits from the use of local natural resources, in India through rehabilitation and resettlement, and in Nepal through local development activities. The study findings suggest that there is a need for clear policy and legal provisions that define the concepts of benefit and benefit sharing as well as the purpose of providing royalties from hydropower projects, together with a strong institutional mechanism for administration.

Introduction

Hydropower is a renewable energy source with a great deal of untapped potential worldwide. However, hydropower projects have often been controversial due to adverse social and environmental impacts, for example displacement of communities, loss of livelihoods, and ecological changes both in the area inundated by the reservoir and downstream. As a result, international and national guidelines have been developed to aid sustainable development during both the construction and operational phases. Sustainability is of importance to hydropower because project operation requires management of the catchment area to maintain hydrological quality and minimize erosion that may lead to siltation of the reservoir. These concerns have led to the creation of benefit-sharing mechanisms in which both upstream and downstream communities receive compensation from hydropower developers and operators. In particular, hydropower offers the opportunity for 'payment for ecosystem services' (PES) schemes under which communities or landowners in the catchments can receive payments in return for land management practices appropriate for long-term operation of the hydropower project. This study examined two projects, one in Nepal and the other in the state of Sikkim in India, in order to assess how benefit-sharing schemes have been applied in practice.

In Nepal and India, governments, and more recently the private sector, are lead agencies for hydropower development. In Nepal this is the Electricity Development Authority, a government subsidiary for power development; in Sikkim it is the National Hydro Electric Power Corporation (NHPC), together with private sector developers. Benefits from the hydropower generated are shared between the power developers and government in the form of profits and royalties, respectively. Watershed management is vital for sustained benefit as most of the projects are located in hill regions, the slopes of which are used for farming and forestry. Both 'run-of-the-river' (ROR) and reservoir storage hydropower projects are vulnerable to alterations in catchment hydrology, landslips, and siltation. As a result, government policy encourages participation of local communities in watershed management, as these communities are directly or indirectly dependent on the natural resources available in their vicinity and have a claim on the ownership of the resources. Land, water, and forest resources contribute to the livelihoods of the local population, as the majority engage in subsistence farming, with traditionally established irrigation systems and community forest management as examples. However, benefits from hydropower projects are largely obtained by users outside the watershed and, in the absence of an appropriate mechanism for redistribution of benefits, local populations are deprived of compensation for the use of water resources that they manage directly or indirectly. The government of Nepal has introduced a benefit-sharing mechanism in the Kulekhani hydropower project to compensate upstream users for the ecosystem services that they provide (Upadhyay 2005). The mechanism involves sharing a percentage of royalties accrued by government and has been in operation for five years. Similarly, there are provisions for royalty sharing from the hydropower development in Sikkim, North East India.

Analysis of the two hydropower projects is presented in this paper as a contribution to designing appropriate policy provisions to benefit both the local communities and hydropower developers. As an important source of renewable energy, promotion of hydropower development by both government agencies and the private sector needs to be carried out with local community involvement to ensure long-term sustainability. Lessons learned from the study have more than regional relevance, as hydropower is a resource of global significance.

The overall objective of the study was to assess existing benefit-sharing mechanisms and their implementation in hydropower projects in Nepal and India. The aim is to develop policy-level recommendations for effective implementation of benefit sharing for sustainable of watershed management to benefit both hydropower developers and local communities.

Benefit Sharing Concepts

Benefit sharing in hydropower projects is based on the concepts of equity and sustainability. Guidelines and best practice have been produced by the World Commission on Dams (WCD 2000) and International Hydropower Association (IHA 2010) among others. These focus on equitable distribution of project benefits and improving conditions in riparian communities affected by the project or those dependent on the resource beyond the immediate project area. The guidelines are not mandatory but serve as a basis for creating benefit-sharing mechanisms within broader policy and legal frameworks. Methods that have been devised and practised in order to create a rational basis for benefit sharing from hydropower projects are discussed below.

The amount of energy that can be generated by a hydropower project is determined by the flow of water and storage capacity of the reservoir. Social and economic activities in the project catchment, such as construction of roads, houses, factories, deforestation, and cropping patterns, affect water production and siltation in the reservoir. Payments to the community can be used to provide incentives to ensure that land use in the catchment is compatible with operation of the hydropower project by regulating runoff and reducing landslides and erosion. This type of benefit-sharing mechanism is termed 'payment for ecosystem (or environmental) services' (PES).

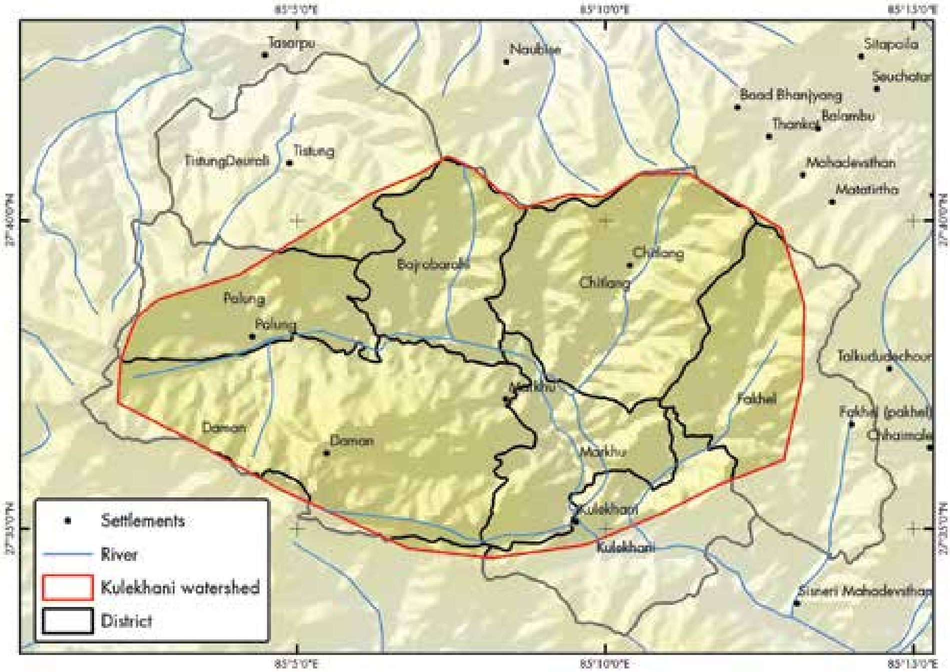
Analysing resource ownership is a prerequisite for establishing a system of equitable payments. Owners often have legally enforceable claims on the use of resources. Questions then arise over who owns the water resource. Is it something that can be owned by an individual, community, or corporation to the exclusion of others? This becomes particularly problematic when large catchments cross political boundaries. Allocation of compensation payments is complicated by the widely accepted concept that natural resources, such as water, are a gift of nature and not an object created by human society, and so should not be under the jurisdiction of an individual or a corporation. Therefore, water in most countries is owned by the state. However, prior user rights on water are customarily accepted, for example, water use for irrigation where local communities have invested in the development and operation of an irrigation system. In this case, local community members are direct stakeholders and can legitimately claim shares in the benefits. Any other use of the water, such as for hydropower, that affects the rights of existing users is regarded as an encroachment on property rights.

Methods

Study areas

The 124 km^2 Kulekhani watershed (85°00'00" to 85°12'30"E, 27°12'00" to 27°45'00" N) is a sub-basin of the Bagmati in Makwanpur District in Nepal. The catchment area of the Kulekhani Hydro Electricity Project (KHEP) covers eight village development committee areas (VDCs, the smallest administrative unit in Nepal): Tistung, Palung, Bajrabarahi, Chitlang, Phakhel, Daman, Markhu, and Kulekhani (Figure 50). The water drained from the watershed

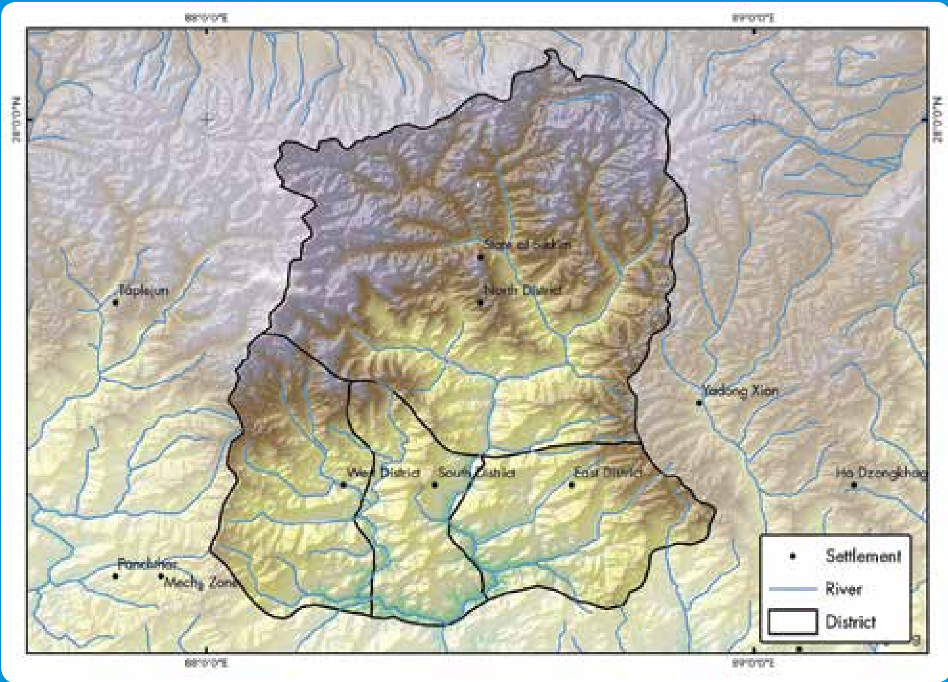
Figure 50: **village development committees (VDCs) in the study area in the Kulekhani watershed, Nepal**



accumulates in a 7 km long reservoir bound by a 114 m high rock-filled dam, and produces 92 MW of electricity in three cascades.

The Teesta basin in Sikkim India (88°00'58" to 88°55'25"E, 27°00'46" to 28°07'48"N) contains the Teesta River and its major tributaries, the Rangit and Rangpo rivers. It is about 100 km long and ranges in elevation from 213 m to 8,598 m. The project area extends downstream for about 54 km from Dikchu, in the upper Rangphu basin, with study sites at Tumin, Dikchu, Singbel, Ralap, Makha, Lingee, Lower Lingmoo, and Lower Khamdong in the upstream section (above DipuDara); and at Rashyap, Sirwani, Manpari Busty, Lower Tokal-Bermoik, Namphing, Singtam, Mazitar, Mining, and Rangphu in the downstream area (Figure 51). The Teesta V hydropower project, with a capacity of 510 MW, is a run-of-the river project along cascades. It was commissioned in 2008 by the National Hydroelectric Power Corporation (NHPC), a Government of India enterprise, and was one of the first run-of-the river hydropower projects for this public sector organization. Residential colonies were established for NHPC employees in 2003/04 in Balutar, East Sikkim, approximately 5 km from Singtam Bazar; Raley in Middle Samdung, East Sikkim, approximately 20 km from Singtam; and Lower Daring, South Sikkim, approximately 8 km from Singtam. In addition the private power producer LANCO (Lagadapati Amarappa Naidu Company/ LANCO Infratech Limited) was in charge of a further site in Samardung, but at the time of the survey, this project was on hold and there was a lack of clarity about its future.

Figure 51: **Study sites in East and South Sikkim, India**



Data Gathering

Information and data was gathered from both primary and secondary sources. Secondary data was obtained from government documents, study reports, and existing research studies. Primary data was obtained from a field study using a common methodological approach at both study sites, but modified to suit the different field conditions. The study was conducted in stages: reconnaissance visit; field visits; inception workshop; desktop review; information from geographical information system (GIS) analysis; rapid assessment and selection of field study site (India); household survey with proportionate representation from affected VDCs; key informant surveys consisting of past elected representatives of VDCs; focus group discussions with VDC secretaries and assistants, community forest user groups (CFUGs), and users from upstream and downstream in the watershed; data collection from secondary sources; stakeholder workshop; experts meeting; and final consultation workshop. Separate survey questionnaires were prepared for stakeholders from upstream, downstream, and surrounding areas in Nepal; and local and project institutions and officials in India. Involvement of local stakeholders in information generation, and use of their knowledge through interaction, was at the core of information gathering.

In Kulekhani, the study area was divided into four clusters (two upstream, one downstream, and one in the surrounding area) in order to obtain representation from households in each of the VDCs benefiting from the project, with sampled households benefiting from all of the activities in that cluster. The total number of households in each cluster was very large (5,084 total in all clusters); 4% of the total households in each cluster were included in the sample (200 households in total). Focus group discussions were organized in each of the clusters. Separate discussions were organized with CFUGs, VDC officials, and the Local Development Officer of Makwanpur District Development Committee (DDC).

In Teesta V, the target population for the survey included stakeholders upstream and downstream in the immediate vicinity of the power project, and local institutions within the Rangphu-Dikchu stretch of the Teesta River. Due to time and resource constraints, and considering the sparse population of 366 households in the vicinity of the project, a sample of 46 stakeholders (12%) was selected to fill in the questionnaires. Representative samples were selected at random from among affected households in order to identify and assess such matters as the benefits being provided by the power developers, changes in living standards, changes in agricultural yields, and land price before and after project implementation. A separate questionnaire was prepared to survey representatives of local institutions in the project affected areas to identify key issues related to the Teesta River and its utilization by the power developers; the role of the institutions in the decision-making process; their functional linkages with the public and private sector companies NHPC and LANCO and other power developers; the policy of the private power developers; legal issues; and others. A further questionnaire was prepared for interviews with officials of the project institutions NHPC and LANCO and other power developers in order to understand their perceptions; list direct and indirect benefits provided to individual households (HHs) or communities, gram panchayat units (GPUs), or GPU wards; to understand the benefit-sharing policy/mechanism; resettlement and rehabilitation (R&R) policy of the project(s); affected upstream and downstream communities covered through the benefit-sharing mechanism process; and challenges for the independent power producers (IPPs) and state government in the near future.

Results

Policy, legal, and institutional provisions

The concept of benefit sharing is intrinsic to the hydropower projects at both study sites. Sharing is done either directly or indirectly among stakeholders and the state. Non-government organizations (NGOs), community-based organizations (CBOs), and other local institutions play important roles as intermediaries for facilitating implementation and administration of the benefit-sharing mechanism. Benefit sharing was thus analysed from both a national level policy perspective and at a local level.

The Water Resource Act, 1992 of Nepal has vested ownership rights to water in the Government of Nepal. The legal regime created by this act makes a clear difference between ownership and user rights and makes water use a prescriptive right. However, in certain cases it also recognizes traditional rights, such as traditional community irrigation and limited individual use rights for household use. Under the 1992 Community Forest Act, Nepal embraced participatory forest management and encouraged local communities to participate in forest management and conservation. Improvement in forest cover is likely to affect the hydrological cycle due to increased evapotranspiration and changes in micro-climate.

In the case of India, legal provisions on water resource development are decentralized to the respective states. As a resulty, each state in India is responsible for water resources development and has its own guidelines pertaining to hydropower development and benefit sharing with the local communities.

The 2001 Hydropower Development Policy in Nepal provides for the provision of 10% of the royalties received by the government to the DDC in whose territorial jurisdiction the dam, reservoir, and powerhouse fall. The Local Self Governance Rules (LSGR) 1999, based on the Local Self-governance Act (LSGA) 1999, provide for the allocation of 50% of the royalties received by the government from any hydropower project to the concerned DDCs. The benefit sharing provisions in the LSGR 1999 are for implementation in the absence of a legal framework for implementation of the hydropower policy provisions on benefit sharing, because the legal provisions are enforceable whereas policy provisions may not be. Under the LSGR 1999, 12% of the royalties go to the DDC in whose territorial jurisdiction the powerhouse is situated and the remaining 38% is divided among all the DDCs in that development region. The LSGR 1999 also provides for disseminating benefits at the local level. This is mainly confined to the exemption of royalties on energy consumption for 15 years of commercial operation. In addition, 1% of the royalty received by the government is allocated to the directly affected VDCs for rural electrification and establishment of a rural electrification fund. The licence for hydropower development prescribes the amount of water allocated for the particular hydropower project. Prior to issuing the licence, the licensing authority conducts studies to ensure that award of the licence will not have a detrimental effect or create a situation of conflict in existing water use, or any possible future use during the period of the licence. The policy in Nepal does not cover resettlement and rehabilitation, presuming this will come under legislation designed to compensate for loss of property and assets due to government projects.

In India, hydropower development falls into the concurrent list; under the 2007 Government of India hydropower policy, the power developer has to pay 12% of the benefits as royalties to the state and 1% to the community. The 1% is in the form of free power earmarked for local area development with a matching 1% to come from the state government's 12% share of free power. Moreover the policy places emphasis on resettlement and rehabilitation (R&R) for communities affected by hydropower development. The R&R policy goes beyond compensation and covers loss of assets and livelihoods. The policy aims to provide a higher living standard to 'project affected people' by making them long-term beneficiaries and stakeholders in the project. In Sikkim, the policy of providing higher living standards to project affected people is addressed through provision of basic amenities for families leading to improvement in quality of life, alleviation of poverty by generating work opportunities, and providing vocational training. In Teesta V, as per Government of India rules, compliance with safeguards and actual monitoring is done by monitoring committees formed in a three-tier system at the centre, state, and project levels that involve people from different ministries such as those for water resources, environment, rural development, and social welfare.

Thus, administration of benefits is decentralized in both countries from ministry level down to the district and local level, and spending of funds is not confined to electrification activities, as other development activities are also the priority of the local communities. Hydropower policy in both Nepal and Sikkim provide benefits in the form of electricity to the local communities.

People's perceptions of impacts and benefit sharing

Local stakeholders view the Kulekhani hydropower project as a 'pride project', and they expect to receive benefits. As a result, they have been involved in implementation of the project from the beginning, as well as later in the project cycle as beneficiaries of the royalties received. No one interviewed in the local community was against the project. However, there were different opinions, firstly on the risks they would have to bear if the dam collapsed, and secondly about inequality of benefits received by stakeholders upstream and downstream. Similarly, in the Teesta V project, stakeholders were strongly of the opinion that projects, and infrastructure associated with projects (such as dams and tunnels, power houses, and protection measures), needed to be technically sound, economically viable, environmentally friendly, and socio-culturally acceptable. They also expressed concern that the river should not dry up due to the hydropower project.

Soil erosion and hazards

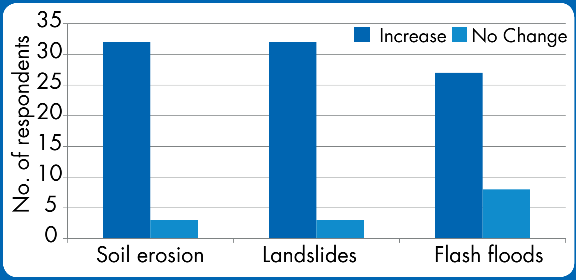
The 'reasons for soil erosion' given in 150 responses from upstream VDCs in the Kulekhani project were deforestation (64%), road construction (28%), don't know (6%); unmanaged cropping patterns (1.3%); and river bank erosion (0.7%). However, the opinions depended on residential location. For example, the surrounding VDCs of Palung and Bhimphedi and the upstream Phakhel reported construction of roads as the main reason for increased soil erosion. Similar variation was observed for flooding and landslides. Whenever landslides took place, the perceived harm was high for farmland and not for houses.

In Teesta V, the hazards (landslides, soil erosion, and flash floods) related to construction activities (road construction, dam construction, and others) have resulted in economic loss and damage to houses and agricultural land belonging to the communities in the project areas. Of the 35 responses to the survey, almost all (91%) noted an increase in the number of landslides and amount of soil erosion, and three-quarters considered that the frequency of flash floods had increased owing to frequent release of water from the hydel dams (Figure 52).

Water Resources

There is evidence that the increase in forest cover and other soil conservation activities have led to reduced sedimentation and increased dry-season water flow into the Kulekhani reservoir, however, people have observed a reduction in the downstream flow. Some respondents expressed concern about the impact on livelihoods due to loss of irrigation water downstream. Other conservation activities of upland people such as terracing of their private agricultural land have also helped to enhance ecosystem services. Almost all households know about soil erosion and considered deforestation and road construction to be the major causes. Recently, VDCs with rapid road construction activities (Bajrabarahi) have been reported as contributing to a deterioration in water quality, as there is no obligation to practice soil conservation to be eligible for royalty payments. According to the officer-in-charge of KHEP in Kulekhani, road construction activities may be the major factor contributing to siltation of the reservoir.

Figure 52: **Respondents' perceptions of the impact of project activities in Sikkim**



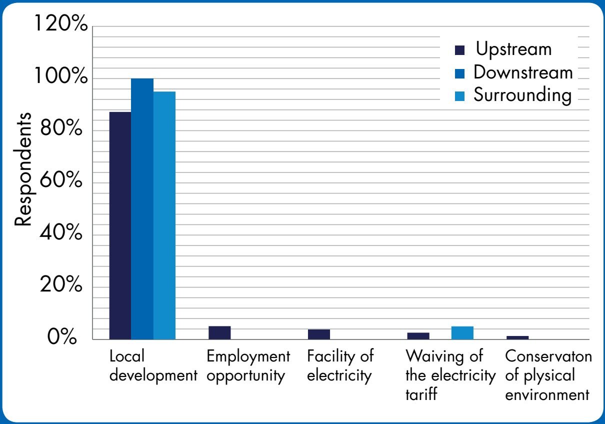
All respondents of both upstream and downstream communities in Teesta V indicated a serious decline (by 35–40%) in the number and volume (average annual flow) of water resources such as springs, rivulets, and streams. About 80% of respondents from Singbel, Dikchu, Samdung, Dipudara, Sirwani, Dochum, Namgeythang, Namphing, Burdang, MazitarJholungey, and Rangphu expressed concern that local water sources, particularly rural springs and streams, have disappeared completely over the last five years, and attributed this to extensive tunnelling and explosions associated with construction. Respondents perceived that groundwater is being lost due to leakage from the tunnels (e.g., tunnels along the Dipu Dara stretch and Rashyap, Jholungey). The respondents also expressed concern that agricultural yields have declined significantly over the last five to six years.

Benefit Sharing

The majority of the Kulekhani respondents (81%) did not know about the royalty benefit-sharing arrangements, although they were positive towards the KHEP project as it had brought them electricity, which made their lives easier. Those who knew about the benefit-sharing mechanism obtained the information through VDCs, DDCs, political parties, and friends. This indicates that knowledge on royalty benefits is not being communicated to the general public, but rather was confined to local political leaders and elites in the community.

The Kulekhani respondents had varied expectations from implementation of benefit sharing in their VDCs (Figure 53). The great majority preferred the royalty money to be utilized for local development, with a very minor second preference of waiving the electricity tariff. Environmental conservation was the least preferred choice for investing the royalty money (favoured by less than 5% of upstream respondents and no one in the other groups), even though upstream residents are responsible for providing environmental services to the hydropower project through appropriate land management. This effectively contradicts the concept of benefit sharing via payment for ecosystem services and is in contrast to the view of the local development officer of Makwanpur District, who considered the objective to be watershed conservation. This could be due to the local understanding of benefit sharing, in which they regard their share of royalty as a right for using resources under their ownership and wish to exercise the right for implementation of development activities rather than fulfilling environmental obligations. There is no legally binding component in the royalty for performance-based ecosystem service payments, and so the royalty becomes more of a direct financial transfer for implementing local development plans, than a means of maintaining ecosystem services from the upland watershed.

Figure 53: **Community expectations for expenditure of royalty money in the Kulekhani project area**



Sharing of benefits in Kulekhani was recorded from 2010 to 2013. Allocations to the VDCs are divided equally by the DDC. The four major royalty investments were road construction (64%), electrification (22%), education (9%), and drinking water (4%). Decisions on investments are made by representatives of the local political parties as there are no elected officials in the VDC at present. Rural electrification is given first priority in the royalty distribution directive, but criteria for selecting projects is needs-based, and almost all VDCs have given first priority to road construction, except Bhaise VDC where the major part went to education.

In Teesta V, 57% of respondents were unaware of the provision of royalty money and/or a benefit-sharing mechanism by the project developers. Only 43% knew about the benefit-sharing programmes (especially the CSR-CD programmes) of the hydropower companies, although they were all aware of the resettlement and rehabilitation compensation.

Respondents in the Teesta V project had mixed responses to the royalty/benefits provided by the NHPC power projects in the different areas, and considered that benefits have been focused on areas where there is a colony that belongs to NHPC or where there is a high level of disturbance. The responses suggest that sharing of benefits to GPUs (wards) on a periodic time scale or frequency is not uniform. The benefits currently provided to beneficiaries are needs based and/or demand based. The power developer NHPC has provided maximum benefits to the indigenous communities in Lower Samdung, Raley, and Dikchu in the form of infrastructural development (construction of schools, project hospitals, a computer institute), health camps, training, and capacity building. About 43% of the upstream/downstream respondents mentioned that hydropower developers had carried out road construction and electrification in the project areas, especially in the project-owned areas (NHPC colony in Raley and LANCO in Samardung Byasi) after repeated requests by the local communities.

Sharing of benefits in Teesta V by NHPC among the communities was recorded from 2006 onwards. Allocation of compensation and benefit sharing were both needs-based (contingent upon impact to households or other owned lands and/or impact due to natural disasters such as landslides and earthquakes), and demand driven (from the communities/government agencies/local NGOs). NHPC officials stated that monetary support/benefits provided by NHPC in 2011/12 included compensation for damage to households and private lands/farms; financial assistance for infrastructural development; contribution to Chief Ministers Relief Fund for people affected by earthquakes (for example, that on 18 September 2011); and allowances/ex-gratia payments (e.g., vibration allowance) to a limited number of households.

Community benefits have mainly been allocated in Lower Samdung, Raley, Dipudara, Dikchu, and Tumin. The priority order of sharing or allocation has changed over the years. NHPC Teesta V works in collaboration with local NGOs (Yuva Jagriti Sangh, The Green Point), the Member of the Legislative Assembly (MLA), and local government (gram panchayats) in the selection, planning, and implementation of activities in the affected areas. There are several community-based organizations, both formal and informal, which could be consulted and involved in the process, however, currently only a few have been involved in developmental activities such as laying of water pipelines, medical camps, support to school children, tree planting, building road networks, police check posts, and foot bridges.

Policy, Legal, and Institutional Provisions

In Kulekhani, most respondents at the household level had no understanding of the policy, legal, and institutional provisions of benefit sharing, with only a few respondents from upstream and surrounding areas noting that they had any understanding (Figure 54).

In Teesta V, 77% of respondents from local institutions and affected households did not fully understand the policy and legal provisions for royalty collection and administration by the power developers, and only 42% were satisfied with the existing policy and legal provisions, whereas 49% were not satisfied, and 9% didn't know (Figure 55). The majority complained that the existing policies, legal provisions, and allocation of benefit sharing were not community-focused and were demand-based. They also reported that allocated funds were not utilized evenly in all project-affected areas, but were concentrated in project-owned areas.

Figure 54: **Knowledge about policy and legal provisions in the Kulekhani project area**

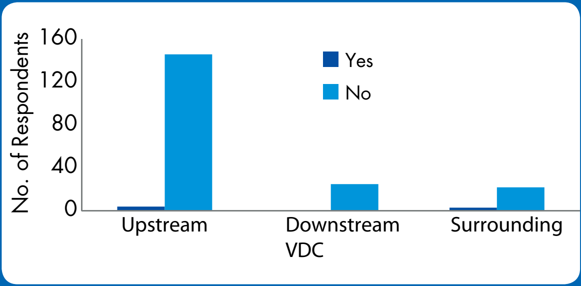
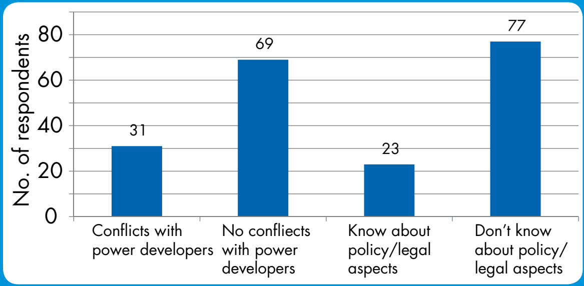


Figure 55: **Perceptions of conflicts and policies in the Teesta V project area**



Key issues raised

The issues that emerged out of the household survey, key informant interviews, and focus group discussions are summarized in the following. The key issues raised by informants encompassed a wide range of subjects, and were not only concerned with benefit sharing and its administration. The issues were felt to be more pressing in the Teesta V area.

Livelihoods

Loss of livelihoods was a common community concern, especially lack of irrigation water for the planting season in KHEP, as was non-availability of sand for those involved in local mining as a result of irregular river flow in Teesta V due to construction and inundation. In Teesta V, the livelihoods of many families dependent on wage labour in quarries along the river banks, of truck drivers, and of fishermen have been severely impacted. The majority of upstream and downstream stakeholders in Teesta V were strongly against the dam projects and stated that no project would be acceptable even with only a small negative impact, especially if it affects local livelihoods.

Decision Making

In both KHEP and Teesta V, participation of local communities in the decision-making process in the initial phase of project development was minimal. At the time of the survey, the majority of the affected communities were not being directly consulted and were not satisfied with project selection, fund allocation, or fund administration. Similarly, most local institutions (NGOs/ CBOs/ VDCs/ panchayats) were not satisfied with the institutional arrangements and roles for the selection and implementation of activities at local level, and considered that benefit sharing was not distributed equitably among the affected communities.

Health

Discussion with health officials from health centres in Teesta V revealed a serious concern over health impacts. New diseases are emerging due to the large migration of people from the plains to Sikkim. According to the locals, cases of dengue fever, malaria, and HIV-AIDS have become common in Sikkim; however, this needs to be substantiated by further study.

Environmental

Local communities in both areas had major concerns about lack of water downstream for irrigation and maintaining the ecological flow. Perceptions of environmental problems were more marked in Teesta V, including environmental damage, dam construction and flooding, irregular water release, landslides and soil erosion, flash floods during the monsoon, and drying up and disappearance of water resources (particularly rural springs and streams), which was considered to be associated with the extensive tunnelling. Respondents in both KHEP and Teesta V reported pollution, traffic congestion, and accidents due to the construction of the road, as matters of concern. Moreover, temperature rise (less wind blowing due to low volume of water), and lack of protection measures (wall) in reservoir area and along the river belt and inhabited areas were also reported. Respondents in Teesta V also reported a decline in agricultural productivity in the river belts, deteriorating quality of forests and loss of biodiversity, and conflicts between the power developers/government and the communities over land and jobs.

Institutions

Neither of the organizations responsible for overseeing the implementation of environmental activities to the benefit of the projects – the Special Fund Operation Sub-committee of Makwanpur DDC for KHEP and the Multidisciplinary Environmental Monitoring Committee (EMC) constituted by the Ministry of Water Resources and Environment Management for Teesta V – were considered to be functioning effectively. In KHEP, the Electricity Royalty Allocation and Use Directives 2062 (2006) and Environment Management Special Fund Implementing Procedures 2063 (2007) have not been implemented and the royalty is used as a financial transfer for implementing local development plans. Implementation of existing guidelines and procedures would have ensured environmental safeguards simultaneously with local community involvement, and most of the local concerns would have been addressed by ensuring participation in the decision-making process. In Teesta V, compliance with safeguards and actual monitoring by the three tier system of monitoring committees was very poor or negligible. When public hearings are held, they are not well publicised and the list of attendees doesn't adequately reflect the diversity of stakeholders.

Transparency

There is a clear requirement for a monitoring and verification mechanism to ensure that the benefits distributed are related to power generated and are in line with the project documents and policy. In KHEP, respondents were concerned by the lack of transparency with respect to the actual amount of royalty collected from the Nepal Electricity Authority (NEA) by the government, and the amount received by the DDC from the government. The royalty should be based on the power generated and not decided on an ad hoc basis by NEA. In the absence of information on power generation, local communities are not aware of the benefits they are entitled to. Moreover, they have only a minimal say in the administration of royalty payments. In order to improve transparency, local communities demand the establishment of a clear benefit-sharing mechanism and a role for local elected institutions in the administration and monitoring of royalty expenditure.

In Teesta V, the MOUs or agreements between power developers and the government also lack transparency, and the benefits that the local communities are entitled to are not clear. When this topic was discussed with the officials of NHPC Balutar, they argued that water availability (river volume) during the peak lean season was the biggest issue. Secondly, conflicts between the power developer and local communities both on acquiring land and on employment in the project emerged prominently during interviews with different project institutions. Allocation of incentives and benefits among people affected by the project, their identification, and development of benefit-sharing mechanisms were all a cause for concern.

In Teesta V, the lack of adherence by the power developers to compliance with the policies and legal framework with respect to environmental safeguards and benefit sharing with the local communities has given rise to a lot of discontent and a sense of alienation between the people and the power developers. The discontentment keeps erupting in the form of protests and agitation. Conflicts in the past were mostly triggered by low compensation for land, the lack of, or type of, employment (contractual and regular) offered by the power developers to the affected households, and damage to landholdings that took place in Singbel, Rashyap, Namphing, Dikchu, Jholengey, Sirwani, Lower Dochum, and Mazitar. Conflicts also occur due to concerns about the changing fabric of local culture. The same issues continue to haunt the people of the area, but in addition there are new issues such as smoke pollution from the steel and beer factory located in the vicinity of the project areas, disposal of waste along the river banks by the allied industries, and damage and loss of life due to increased traffic and accidents.

Conclusions and Recommendations

The study was carried out to help understand the dynamics of the benefit-sharing mechanism from a policy, legal, institutional, environmental, and economic perspective using case studies in two countries: India and Nepal. Analysis of the policy and legal provisions reveals a disjunction between the concepts of benefit sharing and actual implementation in the hydropower projects. Neither country had included a 'payment for ecosystem services' mechanism in policy. Social safeguards were given higher priority than environmental safeguards. One possible explanation for this is that complex procedures are required to assess ecosystem services and determine values that can be used to provide levels of benefit and increase transparency and accountability in the allocation of royalty payments.

Benefit sharing in both countries has made provision for allocation of a percentage of royalties to the local level, with the emphasis on free electricity. Allocation of royalty money for local development is realized through the DDC in Nepal, and through the government in Sikkim. In Nepal, provision of funds for development from royalties is mandatory, and locally elected institutions, the DDC and VDC, play an important role in its administration. In Sikkim, allocation of 12% royalty to the state government and 1% to the local community is prescribed by the national hydropower policy. However, the royalty paid to the state government is spent on general developmental activities of the state, and may not be concentrated in communities affected by the project. The 1% revenue for the community is expected to provide a regular stream of resources to support activities for income generation and welfare schemes to create additional infrastructure and facilities on a sustainable basis.

Administration of royalties in Nepal is influenced by the 1999 Local Self-governance Act and associated Rules and is done through the DDC based on its directives, principles, and priorities. Allocation of funds from the central to the district and local levels is not transparent, and guidelines developed by the DDC, which emphasize environmental protection, are not implemented. Royalty money is shared equally among the affected VDCs, and a major share is spent on road construction, which is perceived to cause environmental harm and reservoir siltation.

In India, compliance with the environmental safeguards, holding of public hearings and public consultations, and a participatory approach were supposed to be an integral part of the implementation process. However, in the initial phase of the project (up to 2006), these guidelines appear not to have been followed. Public protests resulted in benefits being directed to communities and local people affected by the project. National hydropower policy provides the minimum requirement that needs to be followed by all hydropower developers, even though development is under state control. Provision for allocation of benefits is clear, but the problem lies in implementation. Moreover, there are policy provisions for compensation with a long-term perspective on rehabilitation and resettlement. Benefits over and above the royalty prescribed by the national hydropower policy and compensation prescribed by the rehabilitation and resettlement policy are state matters and are addressed on a project basis, leaving much to negotiations between people affected by the project and the license holder/power developer.

In conclusion, the results of the study show that there is a benefit-sharing arrangement through allocation of royalty payments by the governments from the hydropower projects, but it is not based on the premise of compensation for ecosystem services, or of redressing negative impacts on communities. The research reveals a lack of information flow on royalty payment policy to the general public, and suggests that knowledge is confined to local political leaders and elites in the community. In essence, royalties are treated as a fund to be used to meet development needs. Local communities are not satisfied with the administration of the royalties as it does not take into consideration the relative environmental location of the recipients, for example, whether they are upstream or downstream; the identification of communities that are most affected; or the selection of activities that address issues related to livelihoods and negative externalities created due to the project in the form of noise, pollution, and loss of natural resources.

The following recommendations provide suggestions for effective implementation of benefit-sharing mechanisms in hydropower projects based on the research findings:

- There is a need to formulate uniform policy and legislation on benefit sharing encompassing compensation, rehabilitation, acquisition of property, and royalty sharing. The local community should be made aware of the provisions, and transparency should be maintained among stakeholders.
- Clear procedures should be applied in the administration of royalty sharing, so that the benefit allocation is equitable under a strong institutional mechanism and the intended objectives are addressed.
- The roles and responsibilities of local communities need to be associated with the benefits they receive, in particular the provision of ecosystem services.
- Clarity is needed in policy and legal provisions to define the concepts of benefit and benefit-sharing and the purpose of royalty provision, and support is required in the form of a monitoring and verification protocol.
- Community participation is needed throughout the entire project development and implementation process. In principle this has been acknowledged; in reality there is little compliance.
- When the private sector is the primary development agent, their benefit-sharing role needs to be clearly defined as they may focus on the economic/financial viability of the project rather than the long-term interests of the region.
- There is a need for allocation of hydropower royalties to be based on the compensation of activities that maintain the long-term sustainability of the watershed and the livelihoods of the population living in the vicinity of the hydropower projects. Effective monitoring systems need to be developed so that effective social environmental safeguards are in place to make the royalty payments more effective and sustainable.

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Research Note

A Preliminary Investigation of Spatial Variability and Stable Isotope Content of Monsoon Rainfall in the Lesser Himalayas, Northern India: A Microwatershed Perspective

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Aim of the Research

High mountain basins are complex, and it is essential to first understand the impacts of conservation and development interventions at the smaller microwatershed scale. Catchments, as the unit of conservation and development, comprise a complex association between topography, geology and soil, types of vegetation, and other factors; thus, to be useful, investigations should follow an integrated multi-disciplinary approach. Investigations into the short- and long-term impacts of interventions in the Indian Himalayan region are generally fragmentary. There are few reports describing the spatial variability of rainfall and surface temperature patterns at the finer watershed scale (between 5 and 10 km^2) in the complex Himalayan terrain, although significant variability in these regimes at fine scales have been reported from other parts of the world (Wilm et al. 1939; Loukas and Quick 1993; Buytaert et al. 2006; Lookingbill and Urban 2003; Fridley 2009).

Springs, locally known as 'dhara' or 'naula', and spring-fed streams are the most assured sources of fresh water for the rural population in the remote microwatersheds of the Himalayas. Proper identification of the recharge areas for these key water resources is vital for their protection and implementation of groundwater augmenting interventions.

The purpose of the research was to investigate the spatial variability of two topographically dependent key regimes – rainfall and surface air temperature – within an elevation change of

700 m, and to analyse the isotopic lapse rate (altitude effect) using the stable isotope compositions of rainfall for the four monsoon months in 2013 in a small basin (micro watershed) located on the southern slopes of the lesser Himalayas.

Methodology

A small elongated micro watershed roughly 2 km wide and 5 km long was selected for the investigations. The microwatershed is located between latitude 30°02′ and 30°06′N and longitude 78°45′ and 78°50′E in Uttarakhand State in India. The outlet of the watershed is at Paidul, approximately 20 km from the district headquarters, Pauri. Rain gauges and temperature and humidity loggers with appropriate sunscreens were installed at 1,330, 1,470, and 1,880 masl. These three elevations represent the three major topographic divisions in the watershed – valley, mountain slope, and mountain summit – and the instruments enabled measurement of the microclimate at these locations. An automated weather station was installed at 1,620 masl to record air temperature, humidity, wind speed, wind direction, rainfall, and solar radiation. It was placed in the northern part of the watershed where land cover patterns were similar to that in the other areas, but there was less possibility of rainfall sampling being influenced by forest cover (DeWalle et al. 1988; Kendall and McDonnell 1993).

The ratio of rainfall at different elevations to rainfall at the base station was used as a basis for understanding the variability of rainfall with increase in elevation (Loukas and Quick 1996).The base station was the valley rain gauge at 1,330 masl, close to the outlet of the watershed. The spatial variability of rainfall was investigated by comparing the daily rainfall amounts at six different locations with variable aspects and elevation for 33 comparable rainfall events between June and the end of September in 2013. The mean rainfall amount and the percentage of coefficient of variation of different groups of stations were plotted to gain an insight into the overall spatial rainfall variability during the normal summer monsoon.

The monthly characteristics of mean surface air temperature, relative humidity, wind speed, wind direction, and short wave solar radiation were also compared in the four monsoonal months, as hydrometeorology has an impact on rainfall patterns and isotopic composition of rain. The monthly wind rose and day and night time wind directional variability were also investigated. The surface temperature lapse rate (or topographic lapse rate, TLR) was examined for the four months using the mean monthly surface temperature data recorded at four stations at different elevations. The aspect and slope maps were prepared using a digital elevation model prepared from high resolution stereo data (Cartosat-1).

Daily rain samples were collected following the IAEA guidelines for rainfall sampling and mixed thoroughly to prepare a composite of weekly rainfall at each of the four elevations. The samples were used for stable isotope analysis, and for investigations of variation in stable isotope content with elevation (altitude effect). The isotope analysis was carried out at the National Institute of Hydrology (NIH), Roorkee, using an isotopic water analyser (LGR) for measurement of $\delta^{18}O$ and $\delta^{2}H$ based on VSMOW (Vienna Standard Mean Oceanic Water).

First Analysis and Scope of Future Work

Initial findings

The main findings on altitudinal variability of rainfall, surface air temperature, and stable isotopic content of rainfall in the microwatershed during the monsoon period were as follows.

A large spatial variability over small distances was observed in rainfall, with a strong ridge to valley gradient. Topography had a marked influence on spatial distribution of rainfall.

- The findings indicate that in Himalayan basins or microwatersheds, the sparse distribution of rain gauges might lead to under or over representation of rainfall as a result of the high spatial variability.
- The meteorological data was investigated from June to September 2013 to enable understanding of the overall pattern as well as of the local climatological systems. The study site showed a day and night monthly lapse rate of 0.6°C (100 m^{-1}), which is very similar to the observed temperature lapse rate reported for the Himalayas during the monsoon.
- The isotopic lapse rate ranged from -0.3‰ to 0.4‰ per 100 m (r2>0.6), which matches well with observations from other parts of the western Himalayas.
- The observations from the weather station suggest that a topographically controlled regional wind system also dominates the smaller watershed.
- The study also tried to look into the reasons for inconsistent results in the observed altitude effect, which need further research.

Scope of future work

- It will be important to develop a baseline database for water resource availability, as this is fundamental for the assessment of gaps in supply and demand, which in turn helps in making the harnessed data useful for designing local adaptation measures.
- Ensuring long-term water resource sustainability of rural microwatersheds in the Himalayas will largely depend on the understanding emanating out of scientific investigations carried out on the hydrology and geohydrology of the mountain watersheds.

Limitations and Future Research

The stable isotope method enables identification of the altitude effect at regional, basin, and sub-basin scales. The underlying question is whether the application can be demonstrated at a local microwatershed scale, as the interaction between the monsoonal cloud mass and surface topography and microclimates can become complicated at this scale.

Disaggregated socioeconomic data and information on current public and private interventions and the scale of investments could help in the design of future research into how current policy and practices are influencing the sustainability of microwatershed management, what learning needs to be generated to negotiate climate and water governance issues, and how best to generate such learning.

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