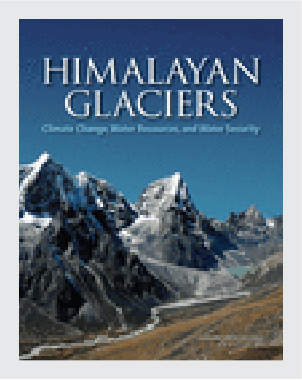

Himalayan Glaciers: Climate Change, Water Resources, and Water Security

DETAILS

143 pages | 8 1/2 x 11 | PAPERBACK
ISBN 978-0-309-26098-5 | DOI 10.17226/13449

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HIMALAYAN GLACIERS

Climate Change, Water Resources, and Water Security

Committee on Himalayan Glaciers, Hydrology,
Climate Change, and Implications for Water Security

Board on Atmospheric Sciences and Climate
Water Science and Technology Board

Division on Earth and Life Studies

Committee on Population

Division of Behavioral and Social Sciences and Education

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This study was supported by the United States intelligence community. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the sponsoring agency or any of its subagencies.

International Standard Book Number-13: 978-0-309-26098-5
International Standard Book Number-10: 0-309-26098-1

Additional copies of this report are available for sale from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; *http://www.nap.edu/*.

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Printed in the United States of America.

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Preface

Many glaciers and snowpacks around the world are receding. The rates and timing of glacial wasting, the volume of icemelt that causes a net loss of glacier volume, vary and the causes are complex. In most instances there are multiple influences that interact in complicated ways. In the early stages of glacial wasting, streamflows increase while in the later stages they may decline. Wherever glaciers are wasting continuously there are concerns about the consequences for available water supplies.

The glaciers of the Hindu Kush-Himalayan (HKH) region are among the largest and most spectacular in the world. Although there is some scientific knowledge and information about the state of the glaciers of the HKH region, with implications for future water supplies, there is also significant uncertainty. Concern has been heightened by several highly visible pronouncements which upon examination proved to be highly qualitative, local in scale, or to lack any credible scientific basis. This report, prepared by a committee appointed by the National Research Council, seeks to describe and analyze the scientific knowledge about the glaciers of the region, their impact on the regional waterscape, and likely impacts of changes in the glaciers on the population of South Asia. More specifically, the Committee addressed the following questions:

- How sensitive are the Himalayan glaciers to climate and other environmental factors?
- What are the potential impacts of changes in climate and glaciers on the timing and volume of river flows in the region and what are the likely implications for water supplies and extreme climatic events such as floods?
- What water management systems are in place to help adapt to changes in regional hydrological systems and how might those systems be strengthened?
- What are the main vulnerabilities of downstream populations to changes in water supplies, what are the prospects for conflict and/or cooperation, and what are the implications for national security?

The Committee addressed these questions from several perspectives: the physical geography of the region, the human geography of the region, and the environmental security of the region. The Committee also identifies additional scientific and data needs as well as possible means of adapting to changes in water security, and draws a series of conclusions.

To help inform its analyses the Committee hosted an interdisciplinary workshop in fall 2011 in Washington, D.C. The 2-day workshop included both invited presentations and extended discussion to explore the many issues that bear on streamflows, water supplies, and the problems of adaptation in the region. The agenda for the workshop and a list of participants comprise Appendix A. The Committee expresses its appreciation to all of the workshop participants for sharing their perspectives and wisdom. The Committee would like to thank Richard Matthew, who assisted with revisions to the report. The Committee is also grateful for the assistance of National Research Council staff Lauren Brown and Daniel Muth who served as note takers at the workshop, and Keren Charles and Zhen Liu who prepared data and graphics.

The Committee was especially fortunate in being supported by three different units of the National Research Council: the Board on Atmospheric Sciences and Climate (BASC), the Water Science and Technology Board (WSTB), and the Committee on Population (CPOP). We are particularly grateful for the help and guidance of Program Officers Maggie Walser of BASC, Laura Helsabeck of WSTB, and Malay Majmundar of CPOP. These three ably kept the Committee on task and provided many of their own valuable insights, which substantially improved the report. Shelly Freeland of BASC provided all manner of administrative support, which helped to make the Committee's efforts both efficient and pleasant. Finally, the Committee would like to thank the individuals responsible for the review of this report. Their comments were valuable and strengthened the report significantly.

Henry J. Vaux, Jr., *Chair*
Committee on Himalayan Glaciers,
Hydrology, Climate Change,
and Implications for Water Security

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Ana Barros, Duke University
Mahendra Bhutiyani, Snow and Avalanche Study Establishment, India
Bodo Bookhagen, University of California, Santa Barbara
Abbas Firoozabadi, Yale University
Stefan Hastenrath, University of Wisconsin, Madison
Arthur Lee, Chevron Corporation
David Michel, Stimson Center
John Pomeroy, University of Saskatchewan
V. Ramanathan, Scripps Institution of Oceanography
Alan Washburn, Naval Postgraduate School
Michael White, Brown University
Aaron Wolf, Oregon State University

Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the views of the committee, nor did they see the final draft of the report before its release. The review of this report was overseen by Dr. Gerald E. Galloway, University of Maryland, appointed by the Division on Earth and Life Studies, and Dr. M. Granger Morgan, Carnegie Mellon University, appointed by the Report Review Committee, who were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring panel and the institution.

Contents

Summary

The Hindu Kush-Himalayan (HKH) region extends over 2,000 km from east to west across the Asian continent spanning several countries: Afghanistan, Bangladesh, Bhutan, China, India, Nepal, and Pakistan (Figure S.1). This region is the source of numerous large Asian river systems, including the Indus, Ganges, and Brahmaputra, which provide water for over a billion people. The surface water of these rivers and associated groundwater constitute a significant strategic resource for all of Asia. Many of the countries in this region are already experiencing physical water scarcity. Existing water stress and projections of population growth have led to concern over possibilities of negative impacts from changes in the availability of water supplies in the coming decades.

Scientific evidence indicates that glaciers in the HKH region are retreating at rates comparable to those in other parts of the world, and confirms that the rate has accelerated in the past century. In this region, conventional wisdom is that glacial meltwater is an important supplement to naturally occurring runoff from precipitation and snowmelt. The watersheds of the area each exhibit complex hydrology and the magnitude of the contribution of glacial meltwater to the total water supply in these rivers is not clear and the implications of accelerated rates of glacial retreat and the resulting increase in glacial wastage for downstream populations have not been precisely characterized. Important questions about regional water security need to be addressed in the context of incomplete science and unresolved uncertainties.

The eastern and western areas of the HKH region differ in climate, especially in timing and type of precipitation, and in glacier behavior and dynamics as well. The Sutlej Valley serves as a rough dividing line, with precipitation in the eastern end of the region dominated by monsoonal activity in summer while precipitation in the western end is dominated by the mid-latitude westerlies in winter. There is evidence of glacial retreat in the eastern and central Himalayas while glaciers in the western Himalayas appear to be more stable, and may even be advancing. The HKH region is geographically vast and complex both climatologically and hydrologically, and this complexity is dynamic and possibly changing. This large spatial variability makes it very difficult to generalize observations and findings over the entire region.

The HKH region's climate is changing. Although generally temperatures are increasing and these increases are likely to accelerate in coming decades, spatial variability and gaps in observational data mean that it remains unclear what specific manifestations of climate change will be in specific places—including where and how quickly glaciers might retreat and what the cumulative impacts on the hydrological system of the region will be. Moreover, it is difficult to separate the effects of changes in glacial wastage from other factors. These factors include changes in the timing and amounts of monsoonal rain and seasonal snowmelt, snow and ice dynamics, the effects of aerosols and black carbon,[1] and the role of tectonic activity in destabilizing glaciers. In addition, water-use changes resulting from changes in population numbers and densities, livelihoods and

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[1] Black carbon refers to particulate matter derived from the incomplete combustion of a hydrocarbon.

FIGURE S.1 The Hindu-Kush Himalayan region extends over 2,000 km across South Asia and includes all or parts of Afghanistan, Bangladesh, Bhutan, China, India, Nepal, and Pakistan. The region is the source of many of Asia's major rivers, including the Indus, Ganges, and Brahmaputra.

consumption patterns, water management decisions including groundwater pumping, agricultural water-use dynamics, and the extent of pollutants will affect water availability in the region.

Despite these important uncertainties, not everything is uncertain or unknown. The National Research Council Committee on Himalayan Glaciers, Hydrology, Climate Change, and Implications for Water Security was charged with addressing questions about four aspects of water security in the region. The Committee's overarching conclusions are that while there remains substantial scientific uncertainty, snow and glacial melt will likely continue to be important sources of water in the region and there will be several climatological, glaciological, and hydrological factors that control the rate, volume, and timing of snowmelt and icemelt. The means of adapting to change will mostly be small in nature, and adaptive solutions will be essential. Effective management institutions will also be critical and will need to operate flexibly. Monitoring systems will be critical to implementing effective adaptation solutions and improving water management systems. The following are more specific and detailed conclusions that relate to the questions in the Committee's charge (the full charge can be found in Box 1.1 of the main text of the report).

How sensitive are the Himalayan glaciers to changes in temperature, precipitation, and the surface energy budget?

The climate of the Himalayas is not uniform and is strongly influenced by the South Asian monsoon in the east and the mid-latitude westerlies in the west. Evidence suggests that the eastern Himalayas and the Tibetan Plateau are warming, and this trend is more pronounced at higher elevations; however, the long-term significance of this trend is not clear. Absorbing aerosols such as desert dust and black carbon may contribute to the rapid warming of the atmosphere, and model results indicate this may in turn contribute to accelerated melting of snowpack and glacial retreat.

The rate of retreat and growth of individual glaciers is highly dependent on glacier characteristics and location. In the eastern and central Himalayas, there is evidence of glacial retreat with rates accelerating over the past century. Retreat rates are comparable to other areas of the world. Glaciers in the western Himalayas appear to be more stable overall, with evidence that some may even be advancing.

What does current glaciological and climatological knowledge imply about potential changes in climate on downstream flows? What are the likely major impacts on water supplies and flood regimes?

Surface water flow is highly seasonal and varies across the region, as does the relative importance of glacial meltwater. In most instances, the annual contribution of snowmelt and rainfall to streamflow exceeds that of glacial wastage. The contribution of glacial wastage can be more important when the glacial wastage acts as a buffer against hydrological impacts brought about by a changing climate. Overall, retreating glaciers over the next several decades are unlikely to cause significant change in water availability at lower elevations, which depend primarily on monsoon precipitation and snowmelt. However, for high-elevation areas, current rates of glacial retreat, if they continue, appear to be sufficient to alter the seasonal and temporal streamflow in some basins.

Uncertainties in the role of groundwater in the overall hydrology of the region are even greater than those of surface water. Evidence suggests that sizable and extensive overdraft in the central Ganges Basin is likely to have an earlier and larger impact on water supplies than foreseeable changes in glacial wastage. For upstream populations, glacial lake outburst floods and landslide lake outburst floods are the dominant physical hazard risks. For downstream populations in the central and eastern Himalayas, floods from changes in monsoon dynamics are more likely to be important, along with changes in the timing of extreme events.

What management systems (including water supply, water demand, land use, and other institutions and infrastructure) are in place to manage climate-induced changes in regional hydrology, and how might they be strengthened?

Water resources management and provision of clean water and sanitation are already a challenge in the HKH region. The adequacy and effectiveness of existing water management institutions is a reasonable, if coarse, indicator of how the region is likely to cope with changes in water supply. Changes in seasonal streamflow could have significant impacts on the local populations by altering water availability patterns and affecting water management decisions and policies for irrigation, municipal, industrial, and environmental use.

Current efforts that focus on natural hazards and disaster reduction in the region can offer useful lessons when considering and addressing the potential for impacts resulting from glacial retreat and changes in snowmelt processes in the region. Water management assessments have advanced over the past 5 to 10 years, though their implementation in water policies and programs is less clear; to date, there is limited penetration to lower levels of governance or support for local water managers who are most at risk. Changes to the hydrological system are inevitable and adaptation is needed at all levels of governance and throughout societies from rural household to city level. Adaptation approaches need to be flexible enough to change with changing conditions, for example, smaller scale and lower cost water management systems, because of uncertainty in impacts and the dynamic nature of future changes.

What are some of the main vulnerabilities to adjusting to changes in water supply in these downstream areas? What are the prospects for increased competition, or improved cooperation, between different downstream water users? What are some of the implications for national security in the region?

Rural and urban poor may be most at risk, in part because the poor are least likely to be able to retrofit, move, or rebuild as needed when faced with risks. Social changes in the region have at least as much of an effect on water use as environmental factors do on water supply, leading to stress. Among the most serious challenges, even in the absence of climate change, are the magnitude of conflicting demands for limited water resources, the lack of corresponding institutional capacity to cope with such conflicts, and the current political disputes among regional actors that complicate reaching any agreements on resource disputes. Although the history of international river disputes and agreement in this region suggests that cooperation is a more likely outcome than violent conflict, social conditions may have changed in ways that make historical patterns less informative about current and future challenges; populations are larger, the number of state and nonstate actors has increased dramatically, patterns of economic growth have changed, and the resource challenges are more complex. Changes in the availability of water resources may play an increasing role in political tensions, especially if existing water management institutions do not evolve to take better account of the social, economic, and ecological complexities in the region. Agreements will likely reflect existing political relations more than optimal management strategies. The most dangerous situation to monitor for is a combination of state fragility (encompassing, e.g., recent violent conflict, obstacles to economic development, and weak management institutions) and high water stress.

A WAY FORWARD

When considering the link between humans and the environment within the context of water security in the HKH region, four themes emerge: (1) there is significant variability in the climate, hydrology, and glacier behavior as well as the demographics and water-use patterns within the region; (2) uncertainties exist and will continue to exist in both the physical and social systems; (3) to reduce and respond to this uncertainty there is a need for improved monitoring of both the physical and social systems; and (4) in the face of this uncertainty, the most compelling need is to improve water management and hazard mitigation systems.

Theme 1: There is significant variability in the climate, hydrology, and glacier behavior as well as the demographics and water-use patterns in the region. The retreat rates of Himalayan glaciers vary over time and space, with the rate of retreat being higher in the east than the west. There are confounding factors such as dust and black carbon that could affect glacial melt and in some cases increase glacial wastage. Changes in the monsoon will probably be more important than changes in glacial wastage at lower, downstream elevations. Rates of urbanization vary across the region, as does the portion of the population with access to improved water and sanitation.

Theme 2: Uncertainties exist and will continue to exist in both the physical and social systems. The impact of future climate change is uncertain but will probably accelerate rates of glacial retreat. Accelerated glacial retreat rates will have significant impacts in local, high-mountain areas but may not be important downstream unless the seasonal contribution of glacial meltwater to rivers is high or dense populations are dependent on historical flow rates. As the region's population becomes more urbanized and standards of living change, water-use patterns will also change in ways that will be difficult to predict. Existing demographic methods also do not allow for projections at a sufficient spatial resolution to determine whether, for example, certain river basins and elevation zones will experience higher rates of population growth than others and how the demographic composition of those specific areas will change. In both the physical and social systems, stationarity—the assumption that the systems will fluctuate within a known range of variability—will no longer apply. In other words, the past is not a good basis for prediction, and past trends in the climate, hydrology, glacier behavior, population, and water use of the region will not be a viable guide for the future.

Theme 3: To reduce and respond to this uncertainty there is a need for improved monitoring of both the physical and social systems. Monitoring will need to occur on a more extensive and consistent basis. Without enhanced monitoring, the information needed to respond to changing environmental and social conditions will be unavailable. Monitoring and research will advance understanding of both the physical and social systems in the region, and identify the various options available to respond to change in the face of uncertainty.

Theme 4: In the face of this uncertainty, the most compelling need is to improve water management and hazards mitigation systems. Existing patterns of water use and water management need improvement. Some progress has been made in improved assessments in the recent past. Going forward, improved implementation of lessons from these assessments in water policies and programs will be necessary. Options for adapting to climate change and hydroclimatic hazards are discussed in greater detail in the report. However, the people most likely to be affected by changing water security in the region are the rural and urban poor who have the least capacity to adapt to changing environmental and social conditions and hazards. Management of groundwater and demand-side management are among the areas where improvements can be made.

1

Introduction

Many glaciers and snowpacks around the world are receding. This recession results from glacial ablation (melt and sublimation) rates that exceed the rates of glacial formation and accretion from precipitation over time. The rates and timing of glacial retreat vary across hemispheres, regions, and locales. The causes of such retreat are complex and although climatic warming is an important cause, care must be taken to recognize that in most instances there are multiple influences that interact in ways that are difficult to predict.

Initially, glacial wasting increases the volumes of glacial meltwater in downstream waterways. As a glacier continues to waste, a point will be reached at which the volumes of meltwater begin to decline and ultimately become zero when the glacier has disappeared (although precipitation falling on the land area previously occupied by the glacier will continue to contribute to downstream flows). Wherever glaciers are wasting continuously, there are concerns about the consequences for available water supplies.

Mountains are the water towers of the world and in many regions, the volume and timing of streamflow from glacial and snowmelt are critical for agricultural production, hydropower generation, water supply, and the functioning and health of ecosystems. In the Hindu Kush-Himalayan (HKH) region (Figure 1.1) in particular, the large populations of China and South Asia rely on both the water and electricity generation provided by the major rivers. Many basins in the HKH region are "water stressed" (Figure 1.2), and this stress is projected to increase due to large forecasted population growth. This has led to concern about potential negative impacts from changes in the availability of water supplies in the coming decades.

Although many glaciers across the globe have retreated over recent decades, the rates of retreat and mass loss can vary widely, indicating that a variety of regional-scale factors such as changes in circulation, cloudiness, precipitation, aerosol concentration, glacier geomorphology, tectonic activity, and debris cover, in addition to warming, can affect glaciers. A recent assessment of glaciers in the region using a combination of remote sensing and in situ data found different patterns of glacial retreat within the HKH region (Yao et al., 2012). Thus, a diverse range of factors affects the timing and amount of glacier-fed streamflow, with significant potential implications for water availability and regional stability. A recent Intelligence Community Assessment found that South Asia is one of three regions likely to be challenged by water scarcity in the coming decades (DNI, 2012).

In the HKH region, conventional wisdom is that glacial meltwater is an important supplement to naturally occurring runoff from precipitation and snowmelt. While correct, the watersheds of the area each exhibit complex hydrology, and the magnitude of the contribution of glacial meltwater to the total water supply in these rivers is less clear. The implications of accelerated rates of glacial wastage for downstream populations have not been precisely characterized.

Despite this fact, or perhaps because of it, there is confusion about how changes in the climate will affect the timing, character, and rates of glacial wastage in different parts of the HKH region. Scientific evidence indicates that glaciers in the eastern and central part of

FIGURE 1.1 The Hindu-Kush Himalayan region extends over 2,000 km across South Asia and includes all or parts of Afghanistan, Bangladesh, Bhutan, China, India, Nepal, and Pakistan. The region is the source of many of Asia's major rivers, including the Indus, Ganges, and Brahmaputra.

this region are retreating at rates comparable to those in other parts of the world, but are relatively stable, and perhaps even advancing, in parts of the western Himalayas. These findings, the findings of recent reviews by the U.S. Agency for International Development (USAID, 2010) and the International Centre for Integrated Mountain Development (ICIMOD, 2011b), and evidence presented later in this report bring into question the results of several earlier studies: one suggested that the glaciers of the HKH would disappear altogether by 2035; another suggested that the origins of accelerated glacial wastage lie with the Medieval Warm Period[1] that occurred over a thousand years ago. Neither of these assertions is supported by scientific evidence, and they have served to create unnecessary confusion. There is also confusion about the ultimate implications of these changes for domestic, industrial,

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[1] The Medieval Warm Period was a period of warmer climate in much of northern Europe, the North Atlantic, southern Greenland, and Iceland. It lasted from roughly A.D. 950 to 1250. It is the "Medieval" Warm Period because it coincided with Europe's Middle Ages (AMS, 2000).

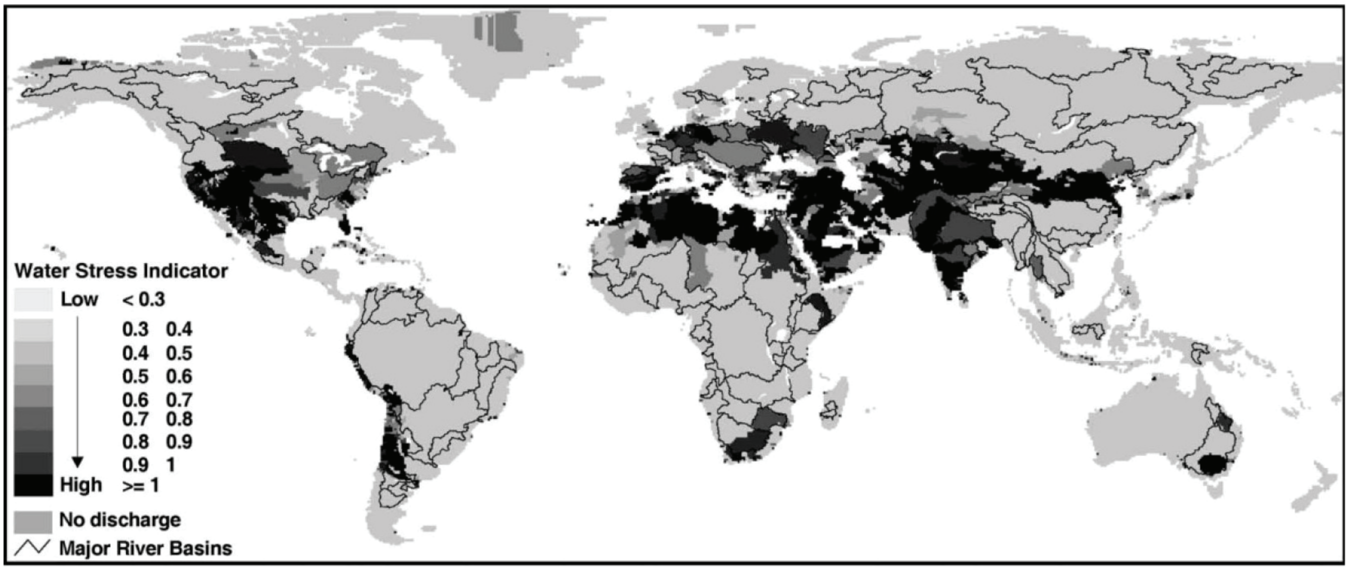

FIGURE 1.2 Global map of water-stressed basins. The water stress indicator is the ratio of total water withdrawals to calculated in-stream flow requirements. Many basins in the HKH region have "high" levels of water stress. SOURCE: Smakhtin (2008).

and agricultural water availability as well as for the various in-stream ecological uses.

In addition, in the context of incomplete science and unresolved uncertainties, there are other important questions about regional water security that need to be addressed. From the beginning the Committee was mindful that it would need to sort out these confusions and resolve any resultant misunderstandings in order to successfully address the statement of task (Box 1.1). Included among the questions examined by the Committee in the course of addressing their charge are the following:

- What are the rates of retreat of the Himalayan glaciers over the last decades and how do they compare with the rates of retreat of glaciers elsewhere in the world?
- Are the rates of glacial retreat in the study region accelerating, decelerating, or remaining static?
- What proportion of the seasonal flows of the Indus and Ganges/Brahmaputra rivers are accounted for by glacier melt?
- What has been the impact of recent climate change on both glacial wastage and streamflow in the region?
- Has the relative contribution of glacier meltwater to dry-season or wet-season flows increased, decreased, or remained static?
- Would the deglaciation of the HKH region imply that the area is headed toward water scarcity within the next few decades?
- Over the next several decades,[2] how will these high-altitude changes in climate and hydrology compare, and interact with, other economic, social, and demographic impacts on regional water supply and demand?
- Does the retreat or accelerated retreat of HKH glaciers increase the likelihood of natural disasters such as outburst floods from moraine dammed lakes or seasonal flooding?

Available science does offer some important information that leads to conclusions that are relevant to these questions.

STUDY CONTEXT AND CHARGE TO THE COMMITTEE

This report was prepared by the Committee on Himalayan Glaciers, Hydrology, Climate Change,

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[2] Wherever possible, the Committee has attempted to limit its projections to the order of three to four decades at most. However, in some cases this was not possible. For example, decadal-scale climate projections are currently an area of active research, and the climate modeling community has more skill in projecting climate over longer timescales.

and Implications for Water Security, appointed by the National Research Council (NRC) in response to a request from the intelligence community, to address the broad charge of identifying what is known scientifically about the glaciers of the Himalayas, their likely future, and the implications of that future on downstream water supplies and populations (see Box 1.1 for full Statement of Task). Part of its purpose was to clarify, where possible, many of the misunderstandings surrounding the broad topic of glacial retreat and its implications in the Himalayas and surrounding region. Recognition of the significance of potential impacts of climate change on glacier-fed streamflow and regional water supplies in the Himalayas led to the commissioning of this study.

BOX 1.1 Committee on Himalayan Glaciers, Hydrology, Climate Change, and Implications for Water Security Statement Of Task

The Committee was charged to explore the potential impacts of climate change on glacier-fed streamflow and regional water supplies in one region, the Himalayas. The glaciers in this region are the headwaters of several of Asia's great river systems, including the Ganges/Brahmaputra, Indus, Mekong, Yangtze, and Yellow Rivers. These rivers are the sources of drinking water and irrigation supplies for billions of people. These rivers also generate hydropower and support important ecological values, such as fisheries. The Committee was asked to summarize the current state of scientific understanding on questions such as

- How sensitive are the Himalayan glaciers to changes in temperature, precipitation, and the surface energy budget?
- What does current glaciological and climatological knowledge imply about potential changes in climate on downstream flows? What are the likely major impacts on water supplies and flood regimes? What additional observational and modeling resources are needed to improve knowledge of hydro-climate trends and forecasts?
- What management systems (including water supply, water demand, land use, and other institutions and infrastructure) are in place to manage climate-induced changes in regional hydrology, and how might they be strengthened? In addressing this question, the Committee will analyze the advantages and disadvantages of various options for improving existing management systems, which could include consideration of new management systems, but will not recommend specific options.
- What are some of the main vulnerabilities to adjusting to changes in water supply in these downstream areas? What are the prospects for increased competition, or improved cooperation, between different downstream water users? What are some of the implications for national security?

To inform its analysis, the study Committee was supported by information gathered at an interdisciplinary workshop, using both invited presentations and discussion to explore the issues that may affect regional streamflow and water supplies in the face of a changing climate. The Committee examined a few selected examples of changes in glacial melt and resultant streamflow for a specified time horizon as a way of developing boundaries for the workshop discussion. The thinking at the workshop took the form of linking potential changes in temperature and precipitation to a range of changes in glacial mass balance and regional hydrology, which in turn could lead to a range of outcomes for downstream streamflow and water security, including water supplies and flooding regimes.

GEOGRAPHIC SCOPE

The focus of this study is the HKH region, which extends over 2,000 km from east to west across the Asian continent spanning several countries (Figure 1.1): Afghanistan, Bangladesh, Bhutan, China, India, Nepal, and Pakistan. The eastern and western areas of the HKH region differ in climate, especially in timing and type of precipitation, and in glacier behavior and dynamics as well. For glaciers, there is no sharp dividing line between east and west; rather, conditions change gradually across the region (e.g., glacier mean elevation; Scherler et al., 2011a). The eastern end is dominated by monsoonal activity in summer while the western end is dominated by the mid-latitude westerlies[3] in winter (Thayyen and Gergan, 2010). The monsoon declines in strength from east to west along the Himalayas, while the westerlies weaken as they move from west to east. This gradient divides at about 78 °E near the Sutlej valley (Bookhagen and Burbank, 2010). To the west (Afghanistan; Kashmir and Jammu, India; western Nepal; Pakistan), there is a general pattern of winter accumulation and summer melt, similar to glaciers in North America and Europe. In contrast, to the east (Bhutan; Sikkim, India; eastern Nepal), glaciers are summer accumulation types, where both maximum

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[3] The mid-latitude westerlies (westerlies) are the dominant west-to-east motion of the atmosphere, centered over the middle latitudes of both hemispheres. At the Earth's surface, they extend from roughly 35° to 65° latitude (AMS, 2000).

accumulation and maximum ablation[4] occur during the summer. River discharge[5] in the eastern end of the HKH arc appears to be driven by monsoonal activity. Large areas of the Indus river systems are dominated by winter snowfall from the westerlies. Monsoon activity is lower and precipitation is dominated by winter snow in the upper Indus, Jhelum, and Chenab basins. Ladakh, which extends from Tibet to India, is a unique cold-arid region (Thayyen and Gergan, 2010).

The political and hydrological boundaries within the study areas are both important and add useful clarity to the study area definition. The political boundaries in the region are shown in Figure 1.3a. The countries found in the study area include all or portions of Afghanistan, Bangladesh, Bhutan, China, India, Nepal, and Pakistan. As the map indicates, some of the political boundaries are disputed, and boundary disputes are likely to remain a potential source of instability for the indefinite future.

The glaciers of the region are found in the headwaters of several of Asia's great river systems, including the Indus, Ganges/Brahmaputra, Mekong, Yangtze, and Yellow Rivers. These rivers are the source of drinking water and irrigation supplies for roughly 1.5 billion people. They also generate significant quantities of hydroelectric power and support important ecological and cultural amenities and services. The surface water of these rivers and associated groundwater constitute a significant strategic resource for all of Asia, which is among the most water stressed regions of the world (Smakhtin, 2008).

The specific study area for this report includes the catchments of the Indus and Ganges/Brahmaputra rivers. The committee defined the primary scope of their report as the countries that include all or part of the Indus, Ganges, or Brahmaputra basins, including

(a)

FIGURE 1.3 The (a) political boundaries, (b) hydrology, and (c) elevation of the Hindu-Kush Himalayan region. Dashed lines are used to indicate disputed political boundaries, which follow the guidance issued by the U.S. State Department, and this Committee takes no position on these boundary disputes.

continued

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[4] Ablation includes any process that removes ice from a glacier.

[5] River or stream discharge is the volumetric rate of flow (AMS, 2000).

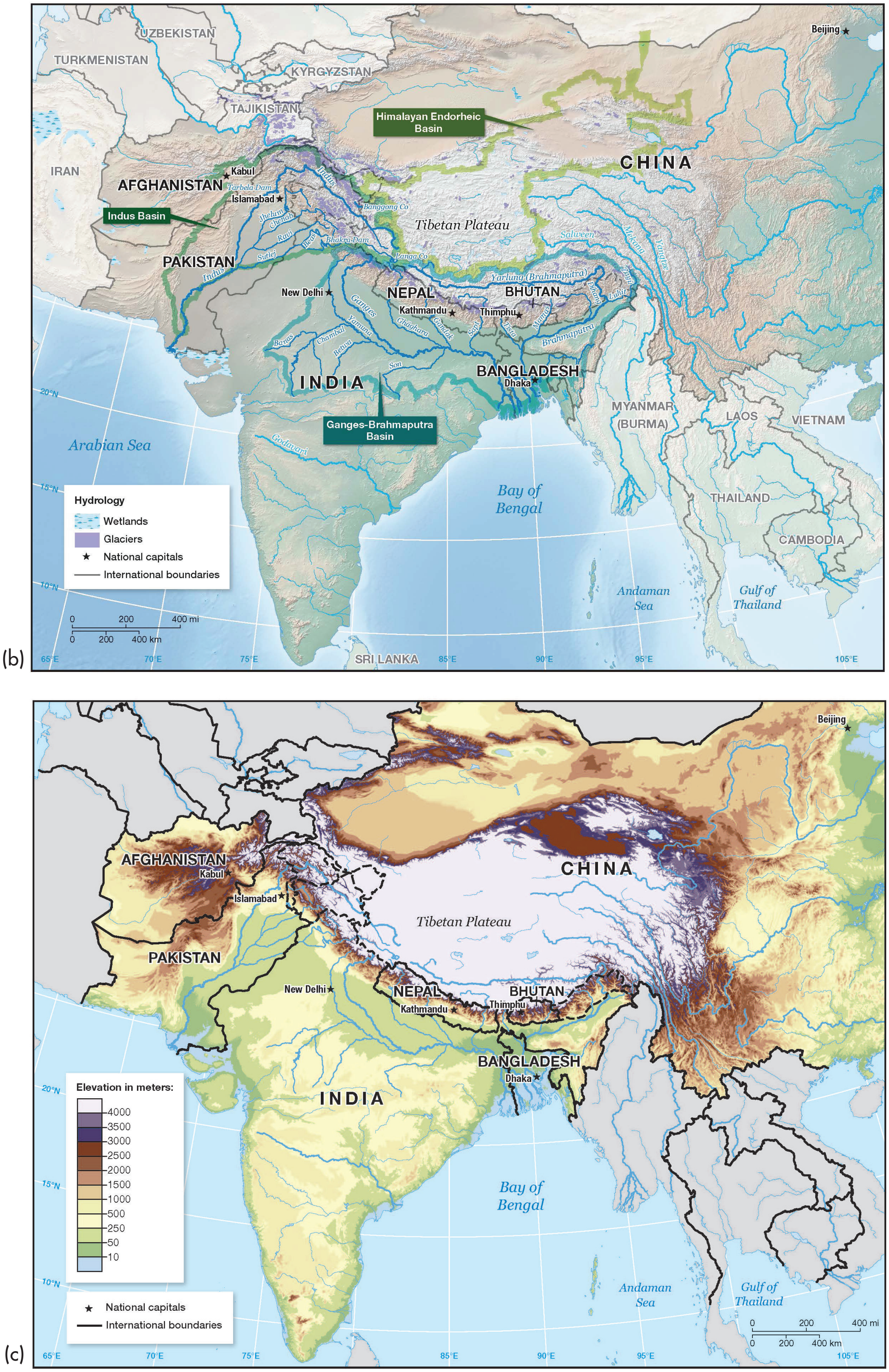

FIGURE 1.3 Continued

the portion of the Tibetan Plateau included in those basins. According to the committee's charge, the areas of major concern are those where the water supply for a significant population could be influenced by changes in the region's glaciers. Figure 1.4 shows the percentage of glaciated area within the river basins of the HKH region. The Indus, Ganges, and Brahmaputra basins combined contain nearly three-quarters of the region's glaciated area. Except for the interior basins (labeled as Himalayan Endorheic basins in Figure 1.3c), the other river basins each contain less than 5 percent of the region's glaciated area. The Committee includes some discussion of the part of the region covered by the Endorheic basins in Chapter 2, Physical Geography, particularly in the section on ice core data (see Figure 2.14). Because the population density of the Tibetan Plateau is very small (see Figure 3.1), it follows that very few people depend on the interior basins for water supply, and any glacier-related changes to the water supply in those basins would not affect a large number of people. Thus the focus of Chapter 3, Human Geography and Water Resources is on the Indus, Ganges, and Brahmaputra basins.

Although the Mekong originates on the Tibetan Plateau and is the source of water for the populations of Cambodia, Laos, Thailand, and Vietnam, glaciers are a small component of water resources in the Mekong (Figure 1.4). The Yangtze and Yellow Rivers, which provide water for large parts of China, also originate on the Plateau and have relatively small glacial coverage (Figure 1.4). Because the Mekong, Yangtze, and Yellow River basins contain a relatively small amount of glacier area, it follows that discharge into these rivers results from snowmelt and rainfall. As discussed in Chapter 2, in most basins, the contribution of rain far outweighs the contributions of snowmelt (e.g., Andermann et al., 2012). These three rivers are located in the eastern part of the HKH region, where annual precipitation is dominated by the summer monsoon (Bolch et al., 2012). On the basis of these considerations, discharge into the Mekong, Yangtze, and Yellow Rivers is more influenced by the monsoons, and in the future, climate change effects on the monsoon will play a greater role than any changes in the glaciers.

It is common to refer to the Tsangpo/Brahmaputra to indicate that the upstream portion of the river on

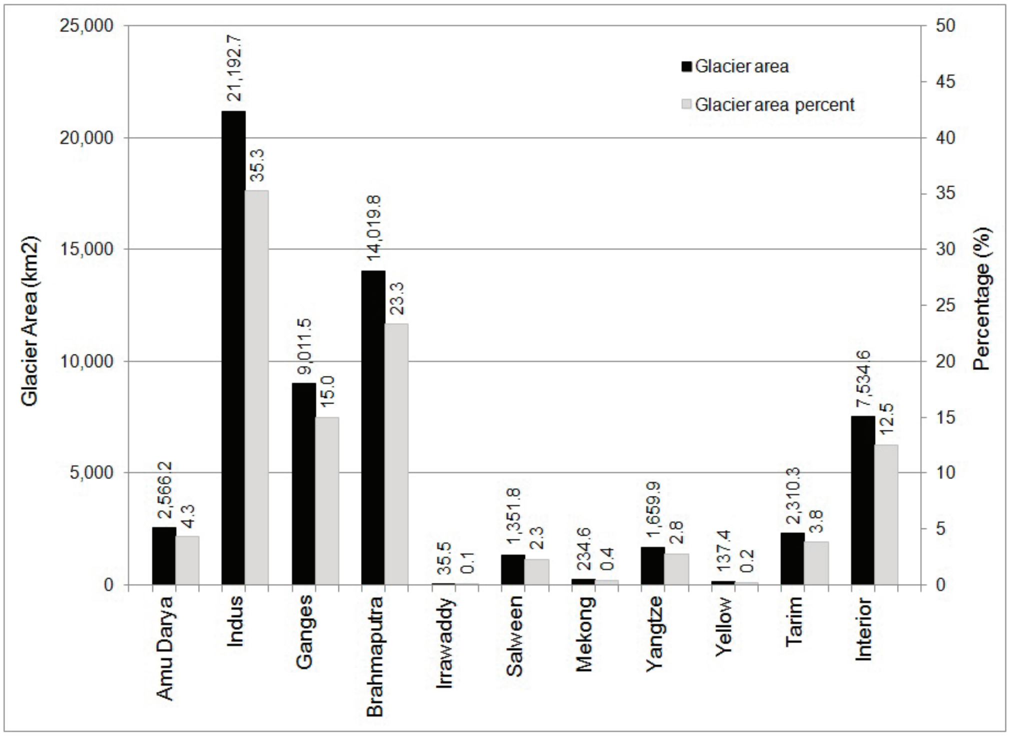

FIGURE 1.4 Glacier area and percentage of total HKH glaciated area in each of the region's river basins. Only the Indus, Ganges, Brahmaputra, and interior basins of the Tibetan Plateau contain more than 5 percent of the region's glacier area. SOURCE: ICIMOD (2011b).

the Tibetan Plateau is called Tsangpo, while the Brahmaputra is the proper name of the river once it enters India. To avoid confusion, the river is referred to as the Brahmaputra throughout this report. In this report, when discussing issues on a watershed basis, the Ganges and Brahmaputra are grouped as a single watershed because they eventually merge before draining into the Bay of Bengal. However, when discussing hydrological issues—for example, river hydrographs[6]—the Ganges and Brahmaputra are treated separately. The tributaries of the Indus and the Ganges/Brahmaputra Rivers are depicted in Figure 1.3b.

The HKH region is geographically vast and complex both climatologically and hydrologically, and this complexity is dynamic and possibly changing. This means that it is very difficult to generalize observations and findings over the entire region because spatial variability is large. The story that emerges in this report is also characterized by the fact that there remain many open science questions that cannot be answered in the absence of additional data and research. Although global temperatures are increasing generally, and these increases have been more rapid in recent decades, spatial variability and lack of local research data mean that the specific manifestations of climate change are unclear in the HKH region. This includes how quickly and regionally glaciers might retreat, and what the subsequent impacts on the hydrological system of the HKH region might be. In recognition of the complexities of these issues, NRC formed the Committee on Himalayan Glaciers, Hydrology, Climate Change, and Implications for Water Security to begin to address some of these important questions.

STUDY APPROACH AND METHODOLOGY

The Committee was formed in summer 2011 and completed its work over the course of the next 12 months. It held four meetings during which it reviewed relevant literature and other information. To inform its analysis, the Committee organized an interdisciplinary workshop, using both invited presentations and discussion to explore the issues that may affect regional streamflow and water supplies in the face of a changing climate. The workshop, which was held in fall 2011 in Washington, D.C., was organized around four broad themes: (1) regional climate and meteorology; (2) regional hydrology and water supply, use, and management; (3) regional demography and security; and (4) risk factors and vulnerabilities. The workshop agenda and participants are included in Appendix A, and workshop presentation summaries are included in Appendix B. Workshop participants identified key concepts about the HKH region. Starting from those concepts, the Committee used its expert judgment, reviews of the literature, and deliberation to develop conclusions about the physical geography, human geography and water resources, and environmental risk and security in the HKH region. These conclusions are listed at the end of each chapter.

ORGANIZATION OF THE REPORT

This report covers three broad areas of knowledge about the Himalayan region: (1) physical geography, (2) human geography and water resources, and (3) environmental risk and security. Chapter 2, Physical Geography, provides an overview of glaciers, followed by a summary of the climate and meteorology of the region within the context of paleoclimate patterns, and descriptions of the regional hydrology and physical hazards. Chapter 3, Human Geography and Water Resources, covers population distribution, poverty and migration, and key natural resource issues of water use, access to water, water scarcity, and water management. Chapter 4, Environmental Risk and Security, presents the Committee's further analyses of the linkages between physical and human systems, with an emphasis on those that may pose potential instabilities for the region. Chapter 5 presents the Committee's synthesis of the range of physical and social changes facing the region, a summary of research questions and data needs, and options for adapting to the changes facing the region.

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[6] A hydrograph is a record and graphical representation of river or stream discharge as a function of time at a specific location (AMS, 2000).

2

Physical Geography

Glaciers play an important role in the global hydrological cycle, through the storage of water for thousands of years (Figure 2.1). Water is stored in a series of reservoirs, including the ocean, lakes, groundwater, atmosphere, snowpack, and glaciers. Water movement is driven by energy: warmer air temperatures speed up the water cycle; colder air temperatures slow the water cycle down. Water movement from the atmosphere to the oceans and continents occurs as precipitation, including snow, sleet, and other forms of solid precipitation. Snow that accumulates for many years may turn into a glacier. This chapter reviews the current understanding of Hindu-Kush Himalayan (HKH) glaciers in the context of the modern climate setting, impacts of aerosols and black carbon[1] on the energy budget affecting the glaciers, what paleoclimate records can tell us about current regional climate conditions, regional hydrology, and physical hazards in the Himalayas.

GLACIAL MASS BALANCE

Glacial ice is characterized by (a) a density between about 830 and 920 kg m^{-3} (83 to 92 percent water content) and (b) air that is trapped in bubbles within the ice and no longer in contact with the atmosphere. When snow falls on a surface, it initially has a density of 50 to 70 kg m^{-3} and within a few days has a density on the order of 100 to 300 kg m^{-3} (10 to 30 percent water content). Over time, through compaction of overlying snow and through metamorphic processes, the density of snowpack gradually increases. Snow that does not melt is carried over to the next season, where it can be buried by subsequent snowfall. Snow that is older than a year but not yet glacial ice is called "firn" or "névé." The density of firn gradually increases over time, and eventually the air trapped in pockets or bubbles is no longer in contact with the atmosphere. The firn has become glacial ice. Local climate determines the rate at which seasonal snow changes to glacial ice (cf. Cuffey and Paterson, 2010).

Glaciers move by gravitational processes, including internal deformation caused by shear stress imposed by overlying ice and snow, and potentially by basal sliding on a layer of liquid or quasi-liquid water. Ice masses can flow down slopes or across flat terrain because of the pressure produced by overlying snow and ice. Once a mass of ice flows as a solid, it is considered to be a glacier. Patches of ice and snow that do not flow are not glaciers.

The fundamentals of glacial behavior can be readily understood by recognizing that glaciers have both a zone of accumulation in which the volume of the glacier grows and a zone of ablation in which volume is lost. During the accumulation season (summer in the eastern HKH and winter in the western HKH), a glacier gains mass. During the melt season (summer in both the eastern and western HKH), some or all of that accumulation is lost. Thus, over the course of a year the size of a glacier may increase, decrease, or remain static. This is determined by whether accumulation or ablation predominates or whether they are equal. The accumulation area is the upper elevation zone where

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[1] Black carbon refers to particulate matter derived from the incomplete combustion of a hydrocarbon.

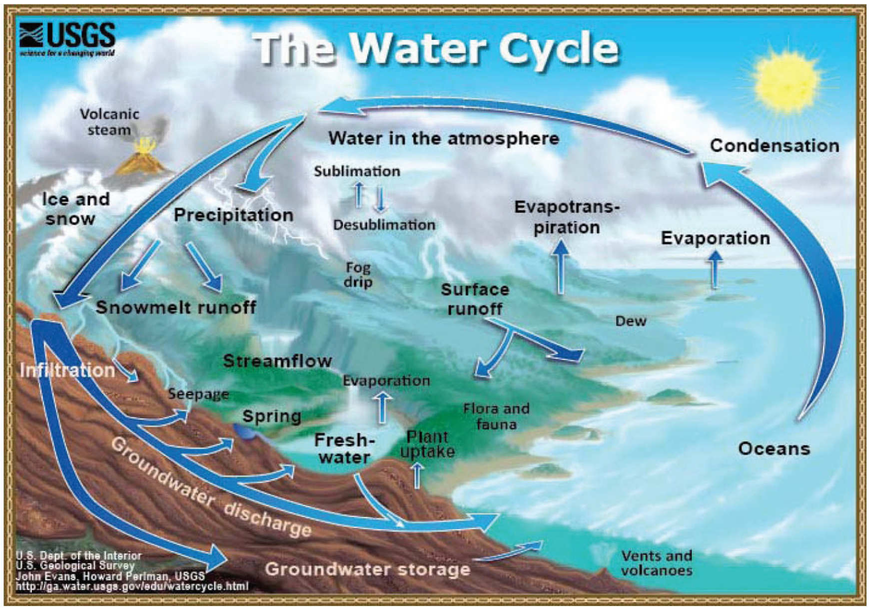

FIGURE 2.1 The global hydrological cycle, or water cycle, is the process by which water moves through a series of reservoirs, including the ocean, lakes, groundwater, atmosphere, snowpack, and glaciers. Water can be in any phase (solid, liquid, gas) in these reservoirs. Water moves from the terrestrial and oceanic reservoirs to the atmosphere through transpiration, evaporation, or sublimation. Water moves from the atmosphere to the terrestrial and oceanic reservoirs through precipitation. Precipitation can occur in liquid form (rain) or solid form (snow, sleet, other types). SOURCE: U.S. Geological Survey.

there is an annual net gain in mass, and the ablation area is the lower elevation zone where there is an annual net loss in mass. The equilibrium-line altitude (ELA) is the elevation where the accumulation and ablation zones meet and where the annual net mass balance is zero (Figure 2.2). The annual mass balance is the net difference between accumulation and ablation (cf. Cuffey and Paterson, 2010).

Accumulation includes all processes by which glaciers increase in snow and ice mass, such as snowfall, condensation, refreezing of rainfall, avalanche transport onto the glacier, and blowing snow transport onto the glacier. Ablation includes all of those processes by which glaciers lose snow and ice mass, such as snowmelt, icemelt, sublimation, blowing snow transport off the glacier, calving and avalanche removal (cf. Cuffey and Paterson, 2010).

When viewed as water supply systems, glaciers are analogous to lakes. Water storage in glaciers is analogous to the total quantity of water stored in a lake. Glacial accumulation is analogous to water input to a lake, which includes processes such as precipitation and water carried into the lake by streams, rivers, and groundwater channels. Glacial ablation is analogous to water removal from a lake, which includes processes such as evaporation, water carried out of the lake by streams, rivers, and groundwater channels, and extraction by humans. When water input sources equal water output sources, the lake is in steady state and the lake level does not change. With glaciers, when accumulation equals ablation, the volume of water stored in the glacier does not change and the ELA does not move. Glacial volumes decrease when ablation persistently exceeds accumulation, the ELA moves up, and the glacier in question ultimately disappears. This is analogous to a lake where persistent overdraft, in which extractions exceed water input, is always self-terminating.

Several important principles follow from this discussion. First, it is the change in the volume of the glacier, not the change in its downhill extent or areal extent that determines whether the net change is positive or negative. However, it is difficult to directly measure the volume of a glacier; thus measurements of glacial volumes are scarce throughout the world. Second, where the entirety of the glacier is below the equilibrium line, there will be no accumulation and with time the glacier will disappear. Third, glacial mass balance information will provide an important

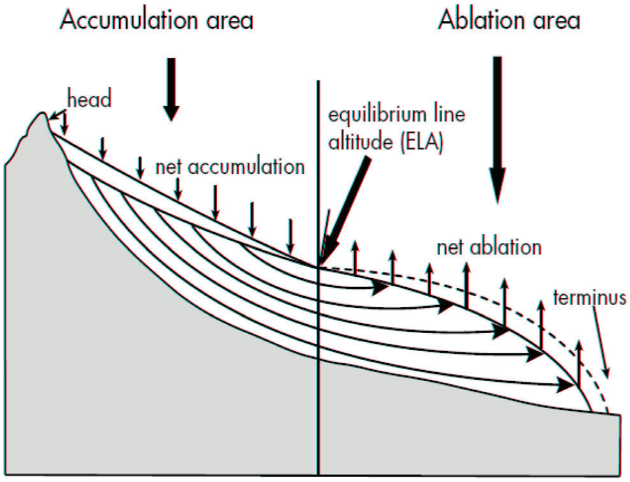

FIGURE 2.2 Schematic of glacial mass balance indicating the accumulation area at higher elevation and the ablation area at lower elevation. Accumulation includes all processes by which solid ice (including snow) is added to a glacier, and ablation includes all processes by which ice and snow are lost from the glacier. The equilibrium-line altitude occurs at the elevation contour where the accumulation and ablation areas meet and the annual net mass balance is zero. SOURCE: Armstrong (2010).

link between variations in glacial volume and climate changes (Meier, 1962). A general understanding of glacial mass balance is essential to understanding what happens to glaciers over time.

Glaciers respond to climate to reach steady state, a state with no change in the mass balance or ELA over time. A glacier advances due to cooling temperatures or snowfall increase, resulting in a positive mass balance. Warming temperatures or a decrease in snowfall results in a negative mass balance and glacial retreat. A glacier that is in disequilibrium with a warming climate will retreat until equilibrium is reestablished or the glacier disappears.

Glaciers in mid-latitude mountain regions of the world, including those in the HKH region, experience melt in their ablation zones at some time in most years. Melting of glacial ice is a normal phenomenon. Most, if not all, mid-latitude glaciers contribute meltwater to streams and rivers. This contribution of glacial meltwater to the discharge of mountain streams and rivers occurs even in years with a positive glacial mass balance. A steady-state situation occurs when climate conditions are such that glacial melt equals accumulation and there is no change in the mass balance over some time period.

Glacier contribution to streamflow can be discussed in terms of the hydrological cycle (Figure 2.1) following the approach of Comeau et al. (2009). For their investigation of glacier hydrology in the Canadian Rockies, they defined "glacial melt" and "glacial wastage" in terms of the water equivalent. They simplified the annual glacial mass balance by treating sublimation as negligible, and assuming no snow inputs or outputs from avalanching, snowdrifting, or blowing snow, and no ice losses from calving. At the high elevations of the HKH, as well as in central and northern Tibet, where it is very cold and dry, sublimation is an important glaciological term in considering the mass balance of the glacier, but not in hydrological considerations. Therefore, the Committee has followed the approach of Comeau et al. (2009) in using the terms "glacial melt" and "glacial wastage" when discussing the relationship between glacial meltwater and streamflow. Because there are differences in meaning implied between glacial melt and glacial wastage for different disciplines, when reporting results from other sources, the Committee has been consistent with the language used in the original reference.

Comeau et al. (2009) defined the annual glacial mass balance as being equivalent to the annual snowfall minus the annual snowmelt from the glacier and minus the annual glacial icemelt. If a glacier is in equilibrium or has a positive mass balance, then the glacial icemelt term is defined as the icemelt volume that is equal to, or less than, the water equivalent of snow that accumulates into the glacier system in a hydrological year. If a glacial mass balance is negative, then glacial wastage is defined as the volume of icemelt that exceeds the water equivalent of the annual volume of snow accumulation into the glacier system, causing an annual net loss of glacier volume. In short, glacial melt does not by itself imply a negative mass balance or wastage. By these definitions, on an annual basis, the presence of a glacier in a basin affects total streamflow volume through wastage contributions only. Glacial melt is a storage term and does not contribute to increased total annual streamflow. Within the hydrological cycle, both glaciers and groundwater are storage reservoirs. Following the convention of Comeau et al. (2009), snowfall on glaciers is analogous to groundwater recharge, glacial melt is analogous to groundwater extraction (or outflow from artesian aquifers), and glacial wastage is analogous to groundwater overdraft. Persistant glacial wastage and persistant overdraft are both self-terminating.

Glacial melt can affect total streamflow on a seasonal basis, and its significance is manifest in its timing, as water is stored as snow accumulation into the glacier system and the water equivalent runoff is delayed until icemelt in the late summer months of the otherwise low streamflow. Therefore, the importance of glacial melt in terms of percentage contribution to streamflow is primarily on a seasonal timescale.

An understanding of ice dynamics is required to understand the response of glaciers to climate change (Armstrong, 2010). If climate and ice dynamics result in a glacier extending farther downslope with time, the advance of the terminus[2] will increase the total glacier area. A time lag on the order of decades or longer occurs between a change in climate and glacier advance or retreat, and year-to-year glacier terminus changes are likely a response to climatic events that occurred several decades or more in the past. The majority of glaciers in the HKH region have response times on the order of decades to a few centuries (Humphrey and Raymond, 1994; Johannesson et al., 1989). The response time is influenced by a glacier's area and volume, precipitation regime, debris cover, and topographic shielding or shadowing (Kargel et al., 2011). All these factors vary widely over the HKH and High Mountain region of Asia.

Measuring Glaciers

The easiest glacial property to measure is the location of the terminus. Simply by walking uphill to the start of a glacier, one can locate the terminus of the glacier. The terminus position for that year can be marked in any number of ways, including a simple pile of rocks. Some glaciers have accurate records of their terminus position that go back a hundred years or more. However, this simple measurement may yield erroneous information about a glacier's retreat and rate of retreat over short timescales of a decade or so. Prolonged retreat of the terminus of a glacier over timescales of several decades does indicate that the glacier is retreating.

The "glaciological" method for determining glacier mass balance relies on a network of stakes and pits on the glacier surface and measuring the change in surface level between two fixed dates (an annual mass balance) or at the end of the ablation and accumulation seasons (a seasonal mass balance) (Racoviteanu et al., 2008). This method is considered the most accurate and provides the most information about spatial variation (Kaser et al., 2003). However, there are currently no long-term glaciological mass balance records for the HKH region, and few measurements of glacial mass balance at all (Kaser et al., 2006).

Mass balance can be estimated using the "geodetic method." This indirect method consists of measuring elevation changes of the glacial surface over time from various digital elevation models constructed over the entire glacier surface (Racoviteanu et al., 2008). Because of large uncertainties, the geodetic method can only be used to estimate glacier changes at decadal or longer timescales (Kaser et al., 2003; Racoviteanu et al., 2008).

The logistical difficulties caused by the rugged topography and remote location of glaciers in the region make remote sensing techniques of particular interest. Remote sensing allows for regular monitoring of glacier area, length, surface elevation, surface flow fields, accumulation/ablation rates, albedo,[3] ELA, accumulation area ratio, and mass balance gradient. A more detailed description of glaciological, hydrological, geodetic, and remote sensing glacier measurement methods is presented in Appendix C.

Glacier Extent and Retreat Rates

The HKH region is often referred to as the "third pole" because it contains the largest ice fields outside the polar regions. Some of the largest glaciers in the world are located here, including the Siachen glacier on the north slopes of the Karakoram Range, which stretches to a length of about 72 km and is the largest nonpolar glacier. Additionally, the mountains and glaciers of the Himalayas are culturally important to the region's population (Box 2.1).

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[2] The glacier terminus, sometimes called the glacier snout, is the lower end of a glacier.

[3] Albedo is the ratio of reflected solar radiation to incident solar radiation for a specific surface and has a value between 0 and 1. For example, fresh snow has an albedo of about 0.8 (AMS, 2000).

BOX 2.1 Cultural Importance of the Himalayas

People have traditionally revered mountains as places of sacred power and spiritual attainment, and the Hindu Kush-Himalayan (HKH) mountains play a central role in the spiritual, as well as practical, lives of millions of people (Bernbaum, 1998). It is from the Himalayas that the Ganges River, considered by Hindus to be the holiest of all rivers in India, rises and cuts its path through the valleys and gorges before it enters the plains. The Ganges River draining the southern area of the Himalaya is considered by Hindus to be both a goddess and a river, Ganga Mata (Mother Ganges; Eck, 1998, 2012), and is seen as sacred along its entire length. Many believe that bathing in the Ganges frees one from past sins and liberates the soul from the cycle of birth and death.

The glaciers have particular cultural importance as the perceived source of water for the Ganges and other rivers in the HKH. This is demonstrated by anecdotal evidence from pilgrims who bathe in rivers and lakes near the outlet of glaciers. For example, the Gangotri glacier is a traditional Hindu pilgrimage site. Devout Hindus consider bathing in the waters near Gangotri town a holy ritual.

The HKH region is also home to Mt. Kailash, in western Tibet (6,600 m in elevation), considered by many religions to be the holiest mountain in the world. This mountain is venerated by Hindus, Buddhists, Jains, Sikhs, and believers of Bonri, the ancient Tibetan religion (Peatty, 2011). For Hindus, Mt. Kailash is the heavenly abode of Lord Shiva and his consort Parvati. Tibetan Buddhists view Mt. Kailash as the pagoda palace of Demchog, the One of Supreme Bliss (Bernbaum, 2006). Mt. Kailash is considered sacred in these religions in part because it is the headwaters of four major rivers aligned in the cardinal directions: the Indus, the Brahmaputra, the Karnali (a major tributary of the Ganges), and the Sutlej (a major tributary of the Indus).

One of Nepal’s most famous places of religious pilgrimage is Gosainkunda Lake (4,400 m in elevation). Every year during the Janai Purnima festival in August, thousands of Hindu and Buddhist pilgrims travel there by foot to bathe in the holy lake. Glacial meltwater is strongly associated with the major lakes and rivers in the HKH region. Rivers, glaciers, and mountains in the HKH are intertwined with the daily activities, spiritual lives, and the cultures of the local populations. Uncertainty surrounding the health of the glaciers and the rivers and lakes resonates deeply throughout these cultures.

The major concentrations of glaciers in the high mountain area of Asia cross more than 12 mountain ranges (Dyurgerov and Meier, 2005). There are currently no complete glacier inventories, but there is general agreement on the area of the glaciers in the region (Armstrong, 2010; Bolch et al., 2012). The total glacier coverage of the HKH and the Tibetan Plateau north to the Tien Shan[4] is thought to exceed 110,000 km^2, with about 50,000 identifiable glaciers (Dyurgerov and Meier, 2005). Table 2.1 summarizes glacial area estimates from different sources. However, comparisons of glacial area among different studies are difficult because spatial extents are often different or not well categorized.

Recent work by Jacob et al. (2012) shows that although previous estimates of mass loss in the region ranged from 47 to 55 Gt yr^{-1}, the rate may be closer to 4 ± 20 Gt yr^{-1}. The gaps and discrepancies in these various reports emphasize the need for a comprehensive glacial inventory of the region. In addition, more information about how glacier area is distributed with elevation would lead to a better understanding of how much glacial area is in vulnerable low-elevation areas (i.e., below the ELA). Glacial hypsometry plots the distribution of glacial area with elevation. Bajracharya et al. (2011) have developed a glacial hypsometry for Nepal (Figure 2.3). The hypsometry shows that glacial ice ranged in elevation from about 3,200 m to 8,500 m. The highest amount of glaciated area was in the 100-m-elevation band centered around 5,400 m. Glacial area decreases with both increasing and decreasing elevation.

Detailed glacier area measurements are not available for the full study area. However, the Committee calculated the proportion of glacier area in different elevation bands for the Indus and Ganges/Brahmaputra. In both basins, the majority of glacier area is in the 5,000- to 6,000-m band (Figure 2.4), with a significant amount in the 4,000- to 5,000-m band. The Indus Basin has a slightly greater proportion of its glacier area below 4,000 m than the Ganges/Brahmaputra Basin, whereas the Ganges/Brahmaputra has a slightly greater proportion of its glacier area above 6,000 m. Although these values should be considered qualitative, they are consistent with the more rigorous hypsometry data from Nepal (Figure 2.3). The differences are small, but they suggest that glacial retreat would be more sensitive to changes in climate in the Indus Basin than in the Ganges/Brahmaputra Basin; however, this qualifies

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[4] A large mountain system located in Central Asia and to the north of this report’s study area.

TABLE 2.1 Glacial Area Estimates from Different Studies[a]

Region	Glacier Area (km^2)	Data Source
HKH	114,800	WGMS (2008)
	116,180	Xu, J., et al. (2009)
	60,000	ICIMOD (2011b)
	99,261	Yao et al. (2012)
Central HKH	33,050	WGMS (2008)
	32,182	ICIMOD: Eriksson et al. (2009)
	71,182	Indian Space Agency: ISRO (2011)
Himalayas	33,050	Dyurgerov and Meier (1997, 2005)
Karakoram	15,400	Dyurgerov and Meier (1997)
	16,000	Dyurgerov and Meier (2005)
	16,600	Yao et al. (2012)
Indus Basin	32,246	ISRO (2011)
	36,431	Raina (2009)
	21,192	ICIMOD (2011b)
Ganges Basin	18,392	ISRO (2011)
	9,012	ICIMOD (2011b)
Brahmaputra Basin	20,542	ISRO (2011)
	14,020	ICIMOD (2011b)
China	59,406	Chinese Academy of Sciences: Liu, et al. (2000)
India	37,959	Geological Survey of India in ICIMOD (2011b)
Nepal	4,212	ISRO (2011)

[a] Comparisons of glacial area among different studies are difficult because spatial extents are often different or not well categorized.

evidence that glaciers are more stable in the western Himalayas. This is because glacial retreat is sensitive to more factors than simply elevation, including precipitation regime, local temperatures, and debris cover.

Rates of glacial retreat in the HKH are not well understood because of a lack of field data (Kargel et al., 2011; Thompson, 2010), making it difficult to understand regional climate change impacts (Scherler et al., 2011b). One of the most studied glaciers in the region, AX010 in Nepal, has consistently been shown to have a negative mass balance. If the climate conditions remain consistent with the period 1992 to 1996, AX010 has been predicted to disappear by the year 2060 (Kadota, 1997). However, this glacier is relatively small, with an area of only 0.38 km^2, and exists at a low altitude, extending to only 5,300 m, and thus only represents small, low-elevation glaciers (Fujita and Nuimura, 2011). However, approximately 50 percent of the area of Nepal glaciers is at altitudes above approximately 5,400 m (Alford et al., 2010; Bajracharya et al., 2011). Therefore, glacier AX010 is not a good indicator of general trends in the HKH region. In a study of glaciers in northern India, Kulkarni et al. (2011) found that glaciers smaller than 1 km^2 lost an average of 28 percent of their area between 1962 and 2001, while glaciers greater than 10 km^2 lost an average of 12 percent of their area in the same time period, further indicating that smaller glaciers cannot be used to determine regional trends.

Extrapolation of these few mass balance studies over the greater High Asian region has been used to estimate a rate of water loss from glacial retreat between 2002 and 2006 of -55 Gt yr^{-1} for this entire region, with -29 Gt yr^{-1} over the eastern Himalayas alone (Dyurgerov, 2010). In contrast, Jacob et al. (2012) used new information from the Gravity Recovery and

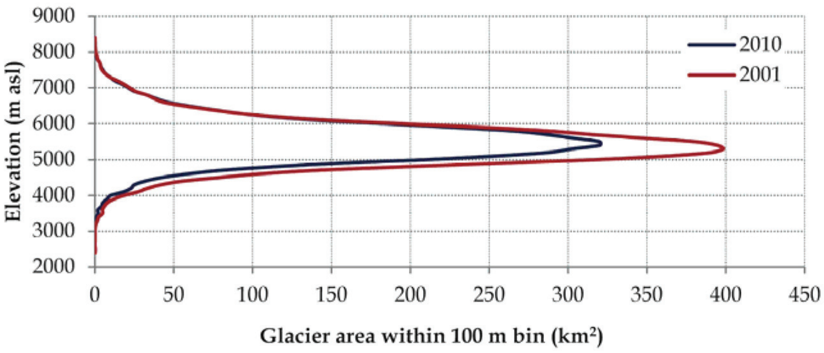

FIGURE 2.3 Glacial area in Nepal is shown as a function of elevation. Glacial ice ranges from about 3,200 m to 8,500 m in elevation. Total glacial area decreased between 2001 (red line) and 2010 (black line) although the highest amount of glacial ice remained at about 5,400 m in elevation. Glacial area decreases as the elevation increases or decreases from 5,400 m. SOURCE: Bajracharya et al. (2011).

Climate Experiment (GRACE)[5] satellite mission to estimate a mass loss of only −4 Gt yr^{-1} for the region of High Asian mountains for the period 2003 to 2010. The much lower estimate of glacier loss from analysis of the GRACE data is at least in part because the GRACE satellite information integrates over the entire region, in contrast to the study by Dyurgerov (2010), which by necessity extrapolated the few glacial mass balance measurements collected at low elevations over the entire region.

Similarly, a recent time series using the geodetic approach based on recently released stereo Corona satellite imagery (years 1962 and 1970), aerial images, and recent high-resolution satellite data (Cartosat-1) to determine mass changes for 10 glaciers south and west of Mt. Everest, Nepal, show a specific mass loss between 1970 and 2007 of 0.32 ± 0.08 m of water equivalent per year. These results are consistent with the global average (Bolch et al., 2011). Terminus measurements of 466 glaciers in the Chenab, Parbati, and Baspa basins in the Indus catchment showed significant deglaciation (Kulkarni et al., 2007). Various studies have estimated the retreat of individual glaciers in the region: the Bhagirath Kharak glacier in Uttarakhand, India, retreated 7 m per year between 1962 and 2005 (Nainwal et al., 2008); the Dokriani glacier in Uttarakhand, India, retreated 550 m between 1962 and 1995 (Dobhal et al., 2004); the Parbati glacier in Himachal Pradesh, India, retreated 578 m between 1990 and 2001 (Kulkarni et al., 2005); the Satopanth glacier in

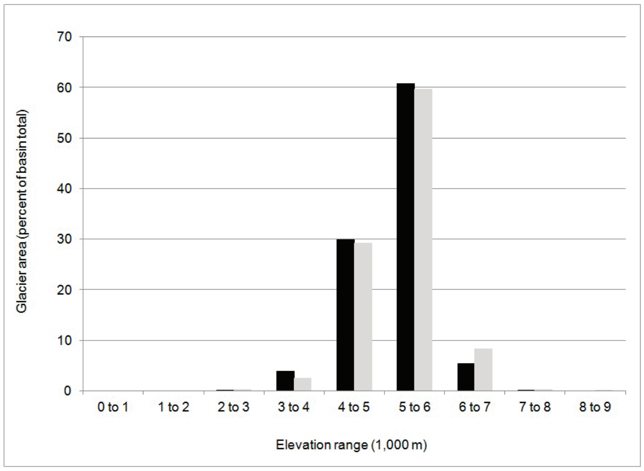

FIGURE 2.4 Glacial area is shown as a function of elevation for the Indus (black bars) and Ganges/Brahmaputra (gray bars) basins. In both basins, the majority of glacier area is in the 5,000- to 6,000-m-elevation band. Comparing the two basins, the Indus Basin has a greater proportion of its glacier area below 4,000 m in elevation than the Ganges/Brahmaputra, and the Ganges/Brahmaputra has a greater proportion than the Indus of its glacier area above 6,000 m in elevation. SOURCE: Based on data from the Natural Earth dataset of the Digital Chart of the World product and the Hydrosheds database.

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[5] The GRACE signal is heavily influenced by groundwater extraction and subcrustal mass and plate movement. The HKH region is a large, complex, and tectonically active area with substantial groundwater depletion. Therefore, use of GRACE satellite data for mass balance measurements in the HKH region leads to substantial uncertainties (e.g., Bolch et al., 2012). Moreover, the use of GRACE satellite data to understand groundwater is complicated by the fact that the coarse resolution of GRACE disallows understanding of groundwater overdraft patterns at the scale of individual or local community consumptive use.

Uttarakhand, India, retreated 23 m per year between 1962 and 2005 (Nainwal et al., 2008). Although there is remaining uncertainty about the retreat rates of specific glaciers (e.g., the Gangotri glacier in northern India; Ahmad and Hasnain, 2004; Bhambri et al., 2011; Kumar, K., et al., 2008; Kumar, R., et al., 2009; Naithani et al., 2001) and more mass balance measurements are needed, glaciers of the eastern HKH region, in general, have a negative mass balance and are retreating, but not at higher rates than other mid-latitude glaciers (Bolch et al., 2012; Racoviteanu, 2011).

In contrast to the eastern HKH, Hewitt (2005) report that in the western HKH, there has been expansion of the larger glaciers in the Karakoram region[6] since about 1990, particularly those at higher altitude. Similarly, Scherler et al. (2011b) report that for the Karakoram region, 58 percent of the studied glacier fronts were stable or slowly advancing with a mean rate of about +8 ± 12 m yr^{-1}. Surging of glaciers has been observed in Karakoram glaciers, but more field observations are needed to confirm whether this indicates a positive mass balance. Data from the late 1980s indicated a possible trend of negative mass balance for the Siachen Glacier (Bhutiyani, 1999), but more recent evidence from remote sensing data shows that glaciers in the central Karakoram had a slightly positive mass balance between 1999 and 2008 (Gardelle et al., 2012). The western end of the HKH appears to show slower rates of retreat, less formation of pro-glacier lakes associated with flood hazard, and frequent observations of advancing glaciers, compared with the eastern region (Armstrong, 2010; Bolch et al., 2012; Hewitt, 2005). For the region as a whole, the loss of glacial ice over the last decade is much less than previously thought (e.g., Dyurgerov, 2010).

Possible Changes in Glacier Extent and Volume

There are few studies of the response of HKH glaciers to changes in climate (Cogley, 2011). Glacial mass balances in the Karakoram area of the HKH appear to be stable, with some of the larger glaciers experiencing positive mass balances. These results suggest that there will be little change in glacier extent over the next several decades in this part of the HKH region. In the eastern HKH, glaciers are retreating, at rates similar to those in the rest of the world. Recent evidence shows that glaciers may be receding at smaller rates than previously estimated (Jacob et al., 2012), although there is still uncertainty in estimates of glacial retreat. The evidence to date suggests little change in rates of glacial retreat and glacial extent in the eastern HKH over the next two to three decades. Even if this is the case, the rate of glacial retreat could increase in the future with appropriate changes in climate forcing.

Currently, retreat rates in the eastern HKH are highest at elevations below 5,000 m. This is particularly serious for glaciers with maximum elevation below 6,000 m. These small, low-elevation glaciers are expected to sustain high rates of retreat. High-elevation communities and activities that depend on glacial meltwater generated by these small glaciers are most likely to experience the impact of these retreating glaciers. The Committee cannot state with certainty whether major changes in either rates of glacial retreat or glacial extent in the HKH region will occur for the next several decades. However, below is a worst-case scenario over a timescale of several decades that could result in very high rates of glacial retreat.

A worst-case scenario of extensive glacial retreat is within the bounds of possibility. One scenario involves albedo feedback processes. Because of the large energy-albedo feedbacks associated with snow and ice, small changes in the amount and timing of snow, and in the overall energy balance can have large effects on a glacier's mass balance. Fresh snow has an albedo range of about 0.75 to 0.95. In contrast, glacial ice has an albedo range of about 0.3 to 0.4. Removing snow from a glacier, holding other factors (air temperature, cloud cover, etc.) constant, results in a 200 to 300 percent increase in the delivery of energy to the surface of the glacier. As the exposed glacier ice heats up and then melts, more nearby snow also melts, resulting in more energy delivery to the glacier, and more glacial wastage. This process results in a runaway positive feedback signal that can accelerate the wastage of glacial ice. This albedo feedback process is currently occurring in Arctic sea ice.

Another scenario involves a regional change in monsoonal activity that reduces snowfall in the Himalayas, coupled with high amounts of black carbon depo-

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[6] The Karakoram region is a large mountain range spanning the border between Pakistan, India, and China.

sition, resulting in very high wastage rates. Imposition of increased air temperatures caused by black carbon heating of the atmosphere would accelerate the rates of glacial wastage. A change in monsoonal activity could result in less snowfall and more exposed glacial ice, which could itself lead to high wastage rates. As discussed later in this chapter, high amounts of black carbon are being entrained in the atmosphere and deposited in the HKH region, decreasing the albedo of glacier ice and snowpack. This decrease, even with no increase in air temperature, could lead to increased surface wastage. In the monsoonal region of the Himalayas, decreased albedo from deposition of black carbon is mitigated by repeated, almost daily, snowfall during the monsoon. Black carbon deposition is also mitigated by snow turnover processes. However, if new snow does not fall because of changes in monsoonal activity, then black carbon transported from the Indo-Gangetic Plain could accumulate on the snow surface, causing an acceleration of wastage rates. Furthermore, in this scenario with less monsoon precipitation and more glacial wastage, the contribution of glacial wastage to summer streamflow would become more important. Such accelerated wastage rates could occur even without a change in air temperature. However, high atmospheric loads of black carbon heat the atmosphere, which would further accelerate melt rates. Another important effect of black carbon could be to change the phase of precipitation (e.g., from snowfall to rainfall). Changes in climate could also result in a shift in the precipitation phase and number of snow days in the region. For example, Shekhar et al. (2010) found significant variations in snowfall trends in the western Himalayas. More precipitation phase data are needed to fully understand whether snowfall events in the region are changing and how such changes will affect glacial mass balance. With the right conditions, accelerated rates of glacial retreat beyond present rates are a possibility. If such a situation does arise, most likely it would be local in origin and not global or even consistent throughout the entire HKH region.

REGIONAL CLIMATE AND METEOROLOGY

The HKH region features one of the world's steepest slopes of an extended mountain range, rising from its base in the alluvial Indo-Gangetic Plain near sea level to the great height of the Tibetan Plateau (~ 8,000 m) in a distance of 100 to 400 km across the width of the arc. Together with the Tibetan Plateau, the Himalayas exert great influence on the powerful Asian monsoon system (Figure 2.5). As such, there is a very high climatic gradient across the region.

The region's climate ranges from tropical at the base of the foothills to permanent ice and snow at the highest elevations. During the late spring and early summer, the Plateau surface heats up quickly and serves as an elevated heat source, which draws warm and moist air from the Indian Ocean toward the Himalayas and Tibetan Plateau region. As the monsoon flow transports moisture from the Arabian Sea to the Indian subcontinent, it spurs heavy monsoon rain over the Indo-Gangetic Plain and the Bay of Bengal. During the winter, the low-level monsoon flow reverses to northeasterly, with prevailing large-scale subsidence and relative dry conditions over India.

Over the Tibetan Plateau, rainfall is scarce all year round with annual totals of 100 to 300 mm. Most of the precipitation falls in the form of snow in winter, with more than 50 percent of the land at elevation above 5,000 m covered by snow. In the summer, the snow

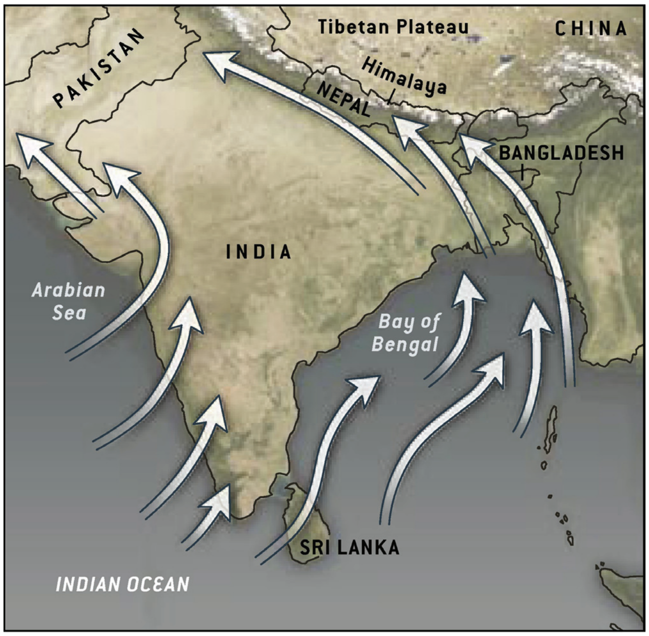

FIGURE 2.5 The moist air currents that drive the South Asian Monsoon are indicated by white arrows. Monsoon flow transports moisture from the Arabian Sea to the Indian subcontinent, resulting in heavy monsoon rain over the Indo-Gangetic Plain and the Bay of Bengal. SOURCE: Hodges (2006).

cover fraction drops to below 30 percent at the same elevation. The melted snow reveals an arid stepped landscape interspersed with scattered glaciers and large brackish lakes.

The climatic gradient is strong not only across, but also along the arc of the Himalayas (Figure 2.6). The Sutlej valley serves as a rough dividing line between the climate regimes of the western and eastern Himalayas (Bookhagen and Burbank, 2010). In the Karakoram in the west, about two-thirds of high-altitude snowfall is due to the mid-latitude westerlies. In the east, more than 80 percent of annual precipitation is from the summer monsoon. (Bolch et al., 2012).

The westernmost portion of the region includes the high mountains and glaciers of the Hindu Kush and the Karakoram, with a large number of rivers flowing into the upper Indus River Basin in Pakistan, eventually draining into the northern Arabian Sea. This region adjoins the arid, rugged regions of Afghanistan in the west, and the Thar Desert of northwestern India to the south. It has a relatively dry climate, with annual precipitation of 400 to 600 mm, primarily from wintertime storms associated with the mid-latitude westerlies. In the cold arid regions of Ladakh, India, the precipitation is somewhat higher in summer, but the mean annual precipitation is as low as 115 mm per year (Thayyen and Gergan, 2010).

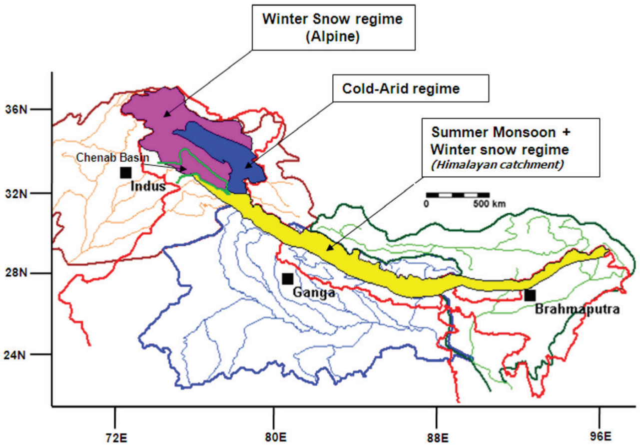

FIGURE 2.6 The climate varies across the HKH region. In the west, indicated by purple, the climate is alpine and dominated by the mid-latitude westerlies. Most precipitation takes the form of winter snow. This area adjoins a cold arid climate regime, indicated by blue. In the east, indicated by yellow, the climate is dominated by the summer monsoon, with most of the precipitation coming during the summer months. The Indus, Ganges, and Brahmaputra watersheds are also shown. SOURCE: Thayyen and Gergan (2010).

Further east along the arc is the Greater Himalayan Range. This region includes snow-capped high mountains and foothills in northwestern India, Nepal, and Bhutan, forming the northern boundary of the fertile and populous Indo-Gangetic Plain, where the Ganges River flows. Rainfall is higher in the east, mostly from summer monsoon rain. The Bay of Bengal, in which the Ganges/Brahmaputra rivers flow out to sea is the wettest part of the Indian monsoon region. Bookhagen and Burbank (2010) reviewed precipitation data for the 10-year period from 1998 to 2007. They showed that mean annual rainfall ranges from ~1 to more than 4 m in the monsoon-precipitation-dominated portions of the region.

Role of Aerosols in Regional Climate

Aerosols are suspended fine particles in the atmosphere that have both natural and manmade sources. Aerosols from natural sources such as desert dusts have been known to coexist with the Indian monsoon in the eastern HKH region for a long time. During April and May, dusts are transported by the mid-latitude westerlies from the deserts in the Middle East and Afghanistan and the Thar Desert in northwestern India to the Indo-Gangetic Plain and Himalayas.

Since the Industrial Revolution, atmospheric loading of aerosols from manmade sources such as factories, power plants, cooking and heating, and slash-and-burn agricultural practices has greatly increased, making the Indo-Gangetic Plain one of the most polluted regions in the world. These aerosols often appear in the form of a brownish haze known as atmospheric brown clouds (Ramanathan et al., 2005). A key component of these brown clouds is black carbon, commonly known as soot. Black carbon sources include internal combustion engines, power plants, heat boilers, waste incinerators, slash-and-burn agricultural activities, and forest fires. Although some aerosol species have a cooling effect, airborne black carbon strongly absorbs solar radiation and heats up the atmosphere. Recent studies have shown that aerosols, in particular, black carbon because of its ability to heat the atmosphere, can affect the regional and global water cycles, including the Himalayan snowpack and glaciers, by altering the radiation balance of the Earth's atmosphere and surface and modulating cloud and rain formation processes

(Lau et al., 2010; Ramanathan et al., 2005; Rosenfeld et al., 2008). Because aerosols have the capability to regulate atmospheric heat sources and sinks, modulate monsoon rainfall, surface evaporation, and river runoff, and possibly affect melting of high mountain snowpack and glaciers, they are an integral component of the monsoon climate system.

The atmospheric loading of aerosols is measured in terms of the aerosol optical thickness (AOT), which is quantitatively determined by the amount of solar radiation attenuation at Earth's surface by the aerosol. During the late spring and early summer season (April to June), the AOT builds up dramatically over the Indo-Gangetic Plain and northwestern India (Figure 2.7, upper panels). The monsoon flow is blocked by the Tibetan Plateau and forced to rise over the Himalayas foothills and northern India. As a result, aerosols transported from remote deserts and from local emissions accumulate against the Himalayan foothills to a great height (>5 km) and spread over the entire Indo-Gangetic Plain and regions to the south (Figure 2.7, lower panel). Additionally, the southwest monsoon flow brings increasingly warm, moist, and unstable oceanic air from the Indian Ocean and the Arabian Sea to the Indo-Gangetic Plain and the Himalayan foothills. The mixture of dust and black carbon in the deep aerosol layer provides efficient heating of the atmosphere. It interacts with the warm moist monsoon air and maximizes the atmospheric water-cycle feedback, and may significantly modulate the summer monsoon rainfall (Lau et al., 2006, 2008).

In contrast, during winter, the prevailing monsoon flow is cold, dry northeasterly with large-scale subsidence. Local emissions of aerosols from the Indo-Gangetic Plain are transported by the northeasterly flow in the form of atmospheric brown cloud plumes emanating from the source region over the Indo-Gangetic Plain to the adjacent ocean (Figure 2.8, upper panels), and are trapped within the stable and low boundary layer (<1 km; Figure 2.8, lower panel). In winter, the atmospheric brown clouds have a higher contribution from local black carbon emissions, but little contribution from dust, because of lack of deserts upwind. The black carbon aerosol heats the boundary-layer air, but cools the land surface, thus further increasing atmospheric stability, suppressing convection and the already-scarce wintertime rainfall. The wintertime high aerosol loading within the boundary layer in the

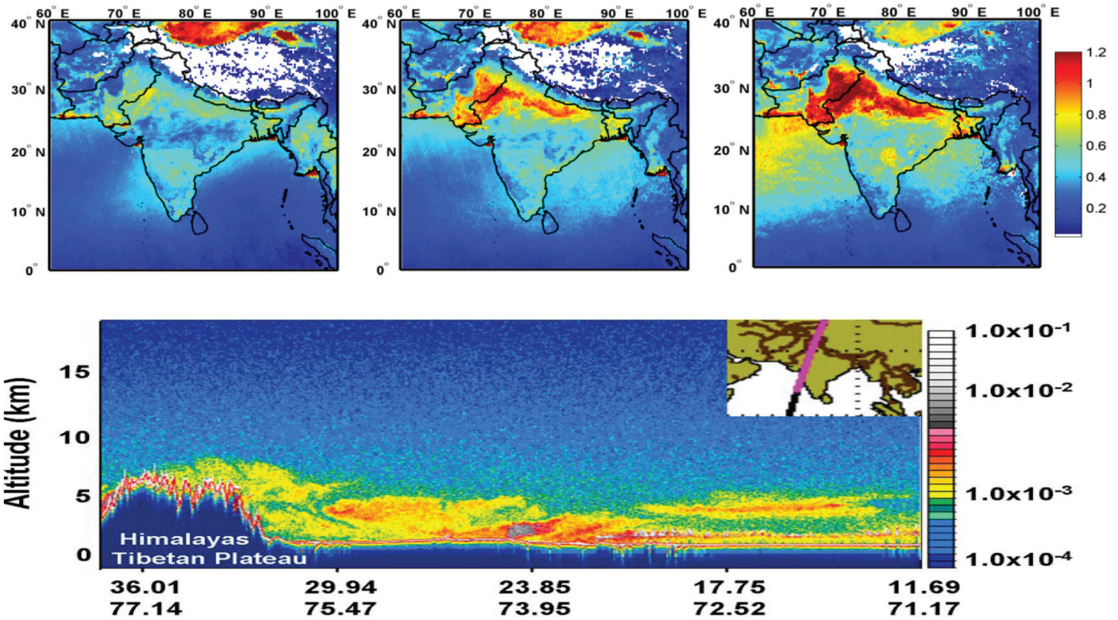

FIGURE 2.7 Climatological monthly distribution of aerosol optical thickness (AOT) during April, May, June from MODIS (upper panels) and vertical distributions across the Tibetan Plateau from CALIPSO (lower panel, horizontal scale shows latitude/longitude coordinates) show the deep and extended layer of aerosols over vast regions of the Indo-Gangetic Plain and Himalayan foothills. Some aerosols can be detected over the top of the Tibetan Plateau. SOURCE: upper panel, Gautam et al. (2010); lower panel, Gautam et al. (2009b).

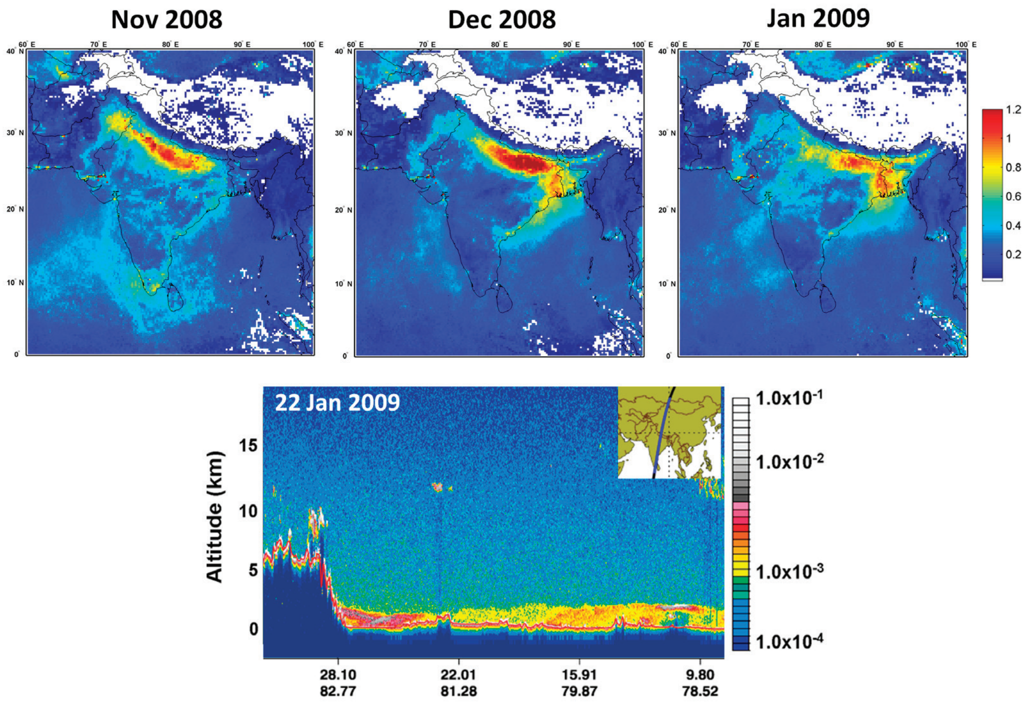

FIGURE 2.8 Monthly distribution of aerosol optical thickness (AOT) during November, December, January from MODIS (upper panels) and vertical distributions across the Himalayan Tibetan Plateau from CALIPSO (lower panel, horizontal scale shows latitude/longitude coordinates) show high concentration of aerosols confined within the shallow boundary layer over the Indo-Gangetic Plain and Himalayan foothills. SOURCE: Ritesh Gautam, personal communication.

Indo-Gangetic Plain is well known for its adverse impacts on local climate, especially on visibility, aviation safety, and human health. However, the aerosols will have minimal large-scale atmospheric water-cycle feedback because the large, stable boundary layer and the free atmosphere above are effectively isolated from the aerosol forcing.

Possible Effects of Aerosols on Glacier and Snowpack

The growth and decay of Himalayan snowpack and glaciers are strongly dependent on changes in the fluctuations of South Asian monsoon climate, and aerosols can affect monsoon temperature and rainfall (Ramanathan and Carmichael, 2008). Ramanathan et al. (2005) suggested that through the reduction of surface solar radiation—the so-called dimming effect—aerosols cool the Earth's surface beneath the aerosol layer. The cooling reduces the land-sea thermal contrast and north-south sea surface temperature gradient, which in turn may lead to weakening of the Asian monsoon.

Other studies have focused on the effect of solar heating by absorbing aerosols (desert dust and black carbon) and induced atmosphere-land feedbacks on the Asian monsoon (Bollasina et al., 2008; Lau and Kim, 2006; Lau et al., 2006, 2008; Meehl et al., 2008; Menon et al., 2002; Wang et al., 2009). Observation studies have shown that desert dust aerosols found over the Indo-Gangetic Plain are more absorbing compared with natural dusts from other parts of the world (Eck et al., 2005; Ramana et al., 2004). These studies suggest that dust particles transported from the adjacent deserts may have been coated with fine soot particles during their passage over the highly industrial regions of the Indo-Gangetic Plain, thus becoming stronger absorbers of solar radiation. It is possible that these highly absorbing aerosols could be instrumental in providing anomalous heating of the atmosphere over northern India and the Tibetan Plateau, through the atmospheric water-cycle feedback—the so-called elevated heat pump (EHP) effect—causing monsoon rainfall to shift northward toward the Himalayan foothills and northern India during the late spring to early summer monsoon season.

The EHP effect is thought to be most effective in May and June because of the great depth and vast horizontal extent of the aerosol layer over the Indo-Gangetic Plain, and its interaction with the warm, moist unstable environment. In contrast, the EHP effect is minimized in the winter because of the cold, dry stable air mass and the confinement of aerosols within the shallow atmospheric boundary layer and narrow regions over the Indo-Gangetic Plain. On the basis of experiments with a global climate model, Lau et al. (2010) showed that the EHP effect caused by dust and soot over the Indo-Gangetic Plain during late spring and early summer could lead to early and accelerated melting of the Himalayan seasonal snowpack via aerosol-induced atmosphere-land surface feedback.

Other studies, however, have questioned and debated the importance of the EHP based on analyses of observations (e.g., Lau and Kim, 2011b; Nigam and Bollasina, 2010). Several global modeling studies have suggested that much of the aerosol forcing of monsoon changes may be caused by nonlocal processes. These include changes in radiative fluxes reaching the ocean surface that help power the monsoon (Wang et al., 2009), consistent with theoretical work on the importance of moist processes rather than land-sea contrasts in creating the monsoon (Boos and Kuang, 2010), remote sea surface temperature forcing (Meehl et al., 2008), and large-scale atmospheric circulation changes (Bollasina et al., 2011). Various studies have also shown evidence that the summer monsoon has weakened over the past 50 years. Analysis of rainfall data for the second half of the 20th century showed a decreasing trend in the length of the monsoon (Dash et al., 2009; Ramesh and Goswami, 2007). Model results also indicate reduced rainfall over India, with small increases over the Tibetan Plateau (Meehl et al., 2008). Although current studies are consistent in finding that aerosols can substantially perturb the timing and intensity of the South Asian monsoon, further work is needed to clarify the magnitude of these effects and to determine the relative importance of the various proposed mechanisms.

An additional important mechanism whereby absorbing aerosols may cause early melting of snowpack and accelerated glacial retreat is the so-called snow-darkening effect. Dust and soot transported from emission sources in the Indo-Gangetic Plain and from remote regions have been found as impurities deposited in Himalayan snowpack and glaciers. These impurities caused a characteristic reduction in the reflectivity of the snow and ice surface in the visible range (Warren and Wiscombe, 1980), lowering the albedo of snow and ice and leading to more solar radiation absorption and possible accelerated rate of snowmelt and glacial retreat.

Recent studies in the HKH region implicate snow darkening by black carbon and dust as a possible cause of glacial retreat. Xu, B. et al. (2009) deduced from observed ice-core samples in Tibetan glaciers that black carbon deposition may have contributed to their rapid retreat. Large, shallow glaciers such as those in the western HKH will be affected more by black carbon deposition than small glaciers with steep surrounding mountains such as those in the eastern HKH, because their snow-turnover rate[7] is higher. This indicates some uncertainty about the effect of black carbon on glacial retreat, but also that there are many factors that influence glacial retreat, and these factors interact in ways that are difficult to predict. Menon et al. (2010) found from model experiments a 0.9 percent reduction in snow/ice cover over the Himalayan region between 1990 and 2000 due to increased aerosol loading over the Indian subcontinent, with a large contribution from black carbon caused by emissions from coal and biofuel. Shindell et al. (2012) found that reductions of black carbon and coemitted pollutants lead to large decreases in Himalayan snow/ice albedo forcing, and that the net mitigation of surface warming by the emissions reductions was strongly enhanced in at least part of that area. However, because of the use of low-resolution models in these studies, it is unlikely that details of aerosol transport across the Himalayan ranges are captured. Further observations are needed to confirm the results of these model studies. For example, Shrestha et al. (2010) found that black carbon was about 10 percent of the total aerosol composition, based on measurements at two low-latitude sites in central Nepal. The effect of different types of snow cover, including black carbon, on albedo have been investigated using remote sensing (Negi and Kokhanovsky, 2011a,b; Negi et al., 2009). Surface observations of the amount of black carbon

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[7] Snow turnover is due to avalanches, gravitational processes, and event-driven snowfall.

deposited on glacier surfaces and how much it affects the albedo are needed.

Kaspari et al. (2011) found increased black carbon concentrations in century-old deep ice core consistent with black carbon from manmade sources being transported to high elevations of the Himalayas (although the reported total black carbon concentrations were surprisingly large, raising some concerns about data quality). Using atmospheric black carbon loading at the Ev-K2 Nepal Climate Observation-Pyramid site, Yasunari et al. (2010) estimated a plausible reduction of surface albedo due to black carbon deposition of 2 to 6 percent, and a corresponding 10 to 30 percent increase in the annual runoff for a typical Tibetan glacier. Using MODIS satellite data and comparing snow albedo before and after major dust storms, Gautam et al. (2011) estimated a 6 to 8 percent reduction in surface albedo. However, observations of dust and black carbon and their effects of surface albedo are still scarce, with large uncertainties due to a lack of instrumental records and limited sampling. Likewise, representation of snow-darkening processes in climate models is still in early development (Flanner et al., 2007, 2009; Yasunari et al., 2011).

Current Trends and Projections of Regional Climate

Reports of surface air temperature and precipitation trends vary greatly across the Himalayas. An increase in maximum and minimum daily temperature of 1.0 to 3.4 °C was found across the Himalayas between 1988 and 2008 (Bhutiyani et al., 2007; Shekhar et al., 2010; Shrestha et al., 1999). In Nepal, the maximum daily surface temperature was found to be increasing at a rate of 0.5 to 1.0 °C per decade from the late 1960s to the mid 2000s. The temperature increase has a tight gradient across the Himalayas with the faster rates of warming at higher elevations, and slower warming rates or even a slight cooling trend found in the lower elevations. This rate of surface warming is more than five times that of global warming by greenhouse gases, suggesting the importance of local heating processes. Note, however, that many of the high-elevation stations are located in deep valleys, and are not actually high elevation. They are not evenly distributed and often are located in villages or urban centers, increasing the potential for urban heat island effects on the data.

In contrast, in the northwestern Himalayas and Karakoram, the trends are less clear. A decreasing trend of both maximum and minimum temperature of 1.6 and 3.0 °C, respectively, has been found (Shekhar et al., 2010). Other studies show a general warming trend, with an increase of 0.06°C per decade during the monsoon season and 0.14°C per decade during the winter (Bhutiyani et al., 2010). Over the same region, an increasing trend in winter precipitation, most likely associated with changes in the mid-latitude westerlies, has also been reported (Fowler and Archer, 2006). However, a recent review of instrumental records in the northwestern Himalayas and Karakoram show no trend in winter precipitation and a decrease in monsoon precipitation between 1866 and 2006 (Bhutiyani et al., 2010). Note that many of these findings are based on in situ historical observations from a very sparse network of stations, especially at higher elevations. Although they provide an extremely important picture of climate trends in the HKH region, they are subject to uncertainties due to inadequate spatial and temporal resolution, possible data inhomogeneity, and local effects.

Satellite remote sensing data have revealed critical spatial and temporal information regarding temperature and precipitation changes in recent decades in the HKH region. Microwave satellite measurements have revealed a widespread warming trend in the troposphere column above the Himalayan-Gangetic region (Figure 2.9).

The warming trend is most pronounced in the premonsoon season (April to May) over the western Himalayas and northern Pakistan region, with a maximum warming rate of approximately 0.8 °C per decade between 1979 and 2007 (Figure 2.9, right panel). This widespread warming also gives rise to an increase in tropospheric land-sea thermal gradient (Figure 2.9, left panel), which favors a stronger monsoon. Prasad et al. (2009) reported large seasonal variations in the tropospheric warming trend, with the statistically significant enhanced warming during the months December to May, and more warming over the western than the eastern Himalayas. Interestingly, the premonsoon tropospheric warming coupled with the cooling at the surface inferred from tree-ring records in Nepal in recent decades is consistent with the direct effect

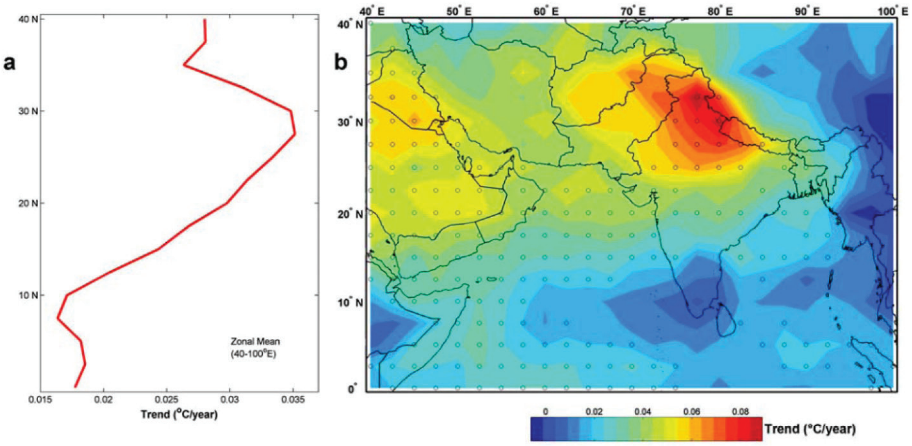

FIGURE 2.9 (a) Zonal mean (40° to 100° E) latitudinal profile of mid-tropospheric temperature trend for the premonsoon season (March-April-May) from 1979 to 2007; (b) spatial distribution of the mid-tropospheric temperature trend over the Indian Monsoon region in May. Open circles denote significance of linear trends at 95 percent. The warming trend in the premonsoon period gives rise to an increase in the tropospheric land-sea thermal gradient. SOURCE: Gautam et al. (2009b).

of absorbing aerosols in warming the atmosphere and cooling the surface (Ramanathan et al., 2005; Satheesh and Ramanathan, 2000).

Figure 2.10 shows that, from satellite measurements, there is high coherence between interannual variations of tropospheric temperature and aerosol index for absorbing aerosols over the Himalayan foothills and the Indo-Gangetic Plain, with both temperatures and aerosols showing a steady rising trend between 1979 and 2007. From field measurements of aerosol optical properties and surface solar flux, the aerosols over the Himalayas-Gangetic Plain are found to be very absorbing with single scattering albedo of 0.89 ± 0.01 (at 550 nm). Scaled by the vertical distri-

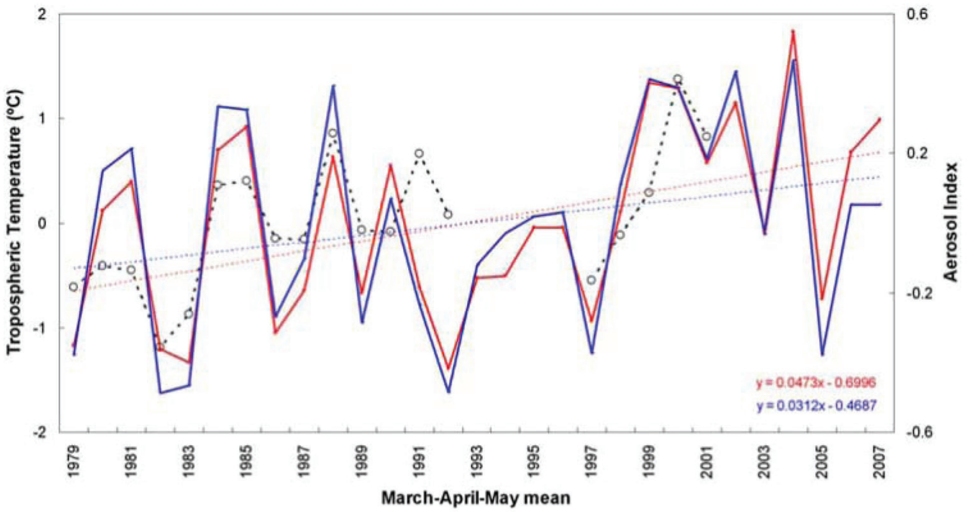

FIGURE 2.10 Red and blue solid lines show interannual variations of temperatures in the middle (4 to 7 km) and lower (surface to 4 km) troposphere, respectively, over northern India (25 ° to 35 °N, 69 ° to 82 °E) for March-April-May (MAM) period between 1979 and 2007. Dashed lines indicate the linear trends within the middle (red) and lower (blue) troposphere, respectively. Aerosol index variations during MAM over northern India since 1979 are shown by the black dashed line. There is high coherence between interannual variations of tropospheric temperature and aerosol index for absorbing aerosols over the Himalayan foothills and the Indo-Gangetic Plain, with both temperature and aerosol showing a steady rising trend between 1979 and 2007. SOURCE: Gautam et al. (2009b)

bution of aerosols from the spaceborne Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP) observations, this value of single scattering albedo yields a model simulated aerosol-induced solar heating profile with maximum heating in the middle troposphere (4 to 5 km) on the order of 2 to 5 °C per day.

In conjunction with the tropospheric temperature increases, Gautam et al. (2009a) also found that the early summer monsoon rainfall over northern India has been on the rise since the 1950s, with over 20 percent increase for the period 1950 to 2004. These results are in agreement with recent observations of increased premonsoon rainfall over northern India (Lau and Kim, 2010), and suggest a future possibility of an emerging rainfall pattern of a wetter monsoon over northern India in late spring and early summer followed by a drier period in central and southern India. Other studies have indicated a weakening of the monsoon, with a trend of fewer rain days over the latter half of the 20th century (Dash et al., 2009; Meehl et al., 2008; Ramesh and Goswami, 2007).

A growing number of recent modeling studies have suggested a causal relationship between Himalayan snow cover changes and the increased loading of absorbing aerosols in the Indo-Gangetic Plain. Menon et al. (2010) reported that the snow cover in the Himalayas estimated from satellites declined by about 5 to 10 percent during the period 1990 to 2001, and that about 30 percent of the decline is due to increased black carbon aerosols in India. Flanner et al. (2009) found that the effects of carbonaceous aerosols are comparable to those due to greenhouse gases in causing the decline in Eurasian springtime snow/ice cover. Lau et al. (2010) showed that the effect of black carbon and dust heating of the atmosphere can lead to an early thawing of the snowpack starting in April, and accelerated melting in May to June in the western Himalayas by 8 to 10 percent. Qian et al. (2011) showed deposition of black carbon in snow cover over the Himalayas and Tibetan Plateau can contribute to a significant change in the anomalous surface radiative fluxes, and rainfall redistribution in the Asian monsoon from preindustrial to present-day climate forcing.

In addition to greenhouse gas warming, regional effects of atmospheric heating and the darkening of the snow and ice surface by dust and black carbon may play an important role in causing the rainfall and temperature trends, as well as accelerated retreat of the Himalayan glaciers and snowpack (Flanner et al., 2009; Gautam et al., 2009a,b, 2010; Lau and Kim, 2006; Lau et al., 2008, 2010; Menon et al., 2010; Qian et al., 2011; Ramanathan et al., 2007; Yasunari et al., 2010). Moreover, black carbon on snowpack and glaciers could have a time-delayed effect. A recent study showed that in the Tien Shan Glacier in Tibet, black carbon concentration at the bottom of unmelted snowpack is much higher than at the surface, because of flushing of black carbon by snowmelt that refreezes at lower layers (Xu et al., 2012). If the ELA rises in response to warmer temperatures, the black carbon-rich snow may be reexposed, increasing solar absorption, and further accelerating the retreat of the snowpack or glacier.

The questions of how aerosols may have affected and will further affect the Asian monsoon and Himalayan glacial retreat in the future remain subjects of ongoing research. One scenario is that unless effective emission control on black carbon is achieved, the continued increased atmospheric loading of black carbon over Asia will exacerbate the solar dimming effect, causing further reduction in land-sea thermal contrast and meridional temperature gradient. Such reductions will in turn reduce evaporation and available moisture in the atmosphere, leading to a spindown of the monsoon large-scale circulation and thus a weakening of the monsoon with reduced rainfall over the Indian subcontinent (Meehl et al., 2008; Ramanathan et al., 2005). Another scenario (Gautam et al., 2009b, 2010; Lau et al., 2009; Wang et al., 2009) is that the initial heating of the atmosphere by increasing dust and black carbon in the premonsoon period may actually increase the meridional tropospheric temperature gradient and induce atmospheric feedback, bringing more moisture and rainfall into the Himalayan region in the late spring and early summer season. This effect will lead to early and accelerated seasonal wasting of the Himalayan snowpack. The increased cloudiness and rainfall in the early monsoon could lead to lower land surface temperature and, subsequently, an early termination or a weakened peak monsoon through atmosphere-land surface and cloud feedback. How much these two scenarios have been in effect in explaining historical trends in monsoon rainfall is still a matter of debate and active ongoing research. The fate of the Himalayan glaciers is strongly dependent on precipitation changes in the region, associated with the vagaries of the Asian summer monsoon and the mid-latitude westerlies winter precipitation regime. Better data from both ground-based and space-based observations as well as improved modeling capability are required to understand and predict the trends of precipitation, temperature, and glacial retreat and their impacts on river runoff and freshwater supply affecting downstream populations.

Evaluation of model projections is largely based on comparison of their historical simulations with observations. As described previously, temperature shows a general warming trend, over the last three decades in particular (Christensen et al., 2007). Evidence shows that temperature is increasing more rapidly with altitude, although there are fewer observation stations at higher elevations, leading to a potential data bias. The eastern and central Himalayan regions (dominated by the monsoon) show a decline in precipitation over the past ~50 years, whereas the western Himalayas show no precipitation trend in the monsoon season.

Winter precipitation in the western Himalayas shows an increasing trend. The relative importance of various forcing agents and of unforced, internal variability in the climate system in driving these trends is not clear. Nonetheless, the ability of models to reproduce these trends remains one of the most important tests of the credibility of model projections.

Climate model projections show warming throughout the region and in all seasons, with greater magnitude over the Tibetan Plateau than over the South Asian continent south of the Himalayas (Figure 2.11). Temperature changes over the next two to three decades show similar spatial patterns but a smaller magnitude. These trends are consistent across models in the sense that the ensemble mean change is greater than the standard deviation across the individual models, and are consistent across scenarios although the magnitude varies somewhat (about 25 percent greater or less than the A1B results depending on the emission scenario). Models are generally fairly successful in reproducing the historical temperature trends, inspiring confidence in their projections.

Precipitation projections, however, vary substantially across models, and models often do not capture historical trends well. The most robust feature is a long-term projected increase in boreal summer precipitation in the eastern Himalayas and Bangladesh, which is seen in most models over the 21st century. This leads to a consistent projection of increased annual mean river runoff in the Ganges and Brahmaputra in the models run in support of the Intergovernmental Panel on Climate Change (IPCC) AR4. A majority of models show a drying trend in winter precipitation in the central Himalayan foothills, but a substantial fraction do not. Over the western Himalayas, models are about as likely to show increases as decreases in precipitation in either season. Many models show trends that vary over time, with, for example, negative rainfall trends in the next decade for the Himalayan foothills but enhanced precipitation in the latter half of the century. Results of the next-generation models run in support of the IPCC AR5 were being analyzed as this report was being written, and may provide more robust indications of likely precipitation changes in this region. Further research may also provide better understanding of the role of black carbon in driving precipitation changes in this region. This appears to be substantial, and thus could contribute to some of the divergence across AR4 models because many did not include black carbon in their projections.

There have been fewer analyses of projected changes in extremes even though there is increasing observational evidence of increased extreme heavy rain in monsoon regions (Gao et al., 2002; Goswami et al., 2006; Rajeevan et al., 2008). It appears that both global and regional models are somewhat more consistent in projecting an increase in the frequency of extreme precipitation events as the climate warms (Christensen et al., 2007). Such a change in variability may have more severe consequences than a change in the mean precipitation. However, confidence in these projections is again tempered by the limited ability of models to accurately represent observed variability, especially in the monsoon systems.

PALEOCLIMATE

Meteorological records from the HKH region are scarce and many of those that do exist extend only back to the mid-1950s to early 1960s. Thus, assessing climate change there, including its true long-term significance and likely future impact, is hampered by a paucity of long-term meteorological and glaciological observations from the higher and more remote elevations of

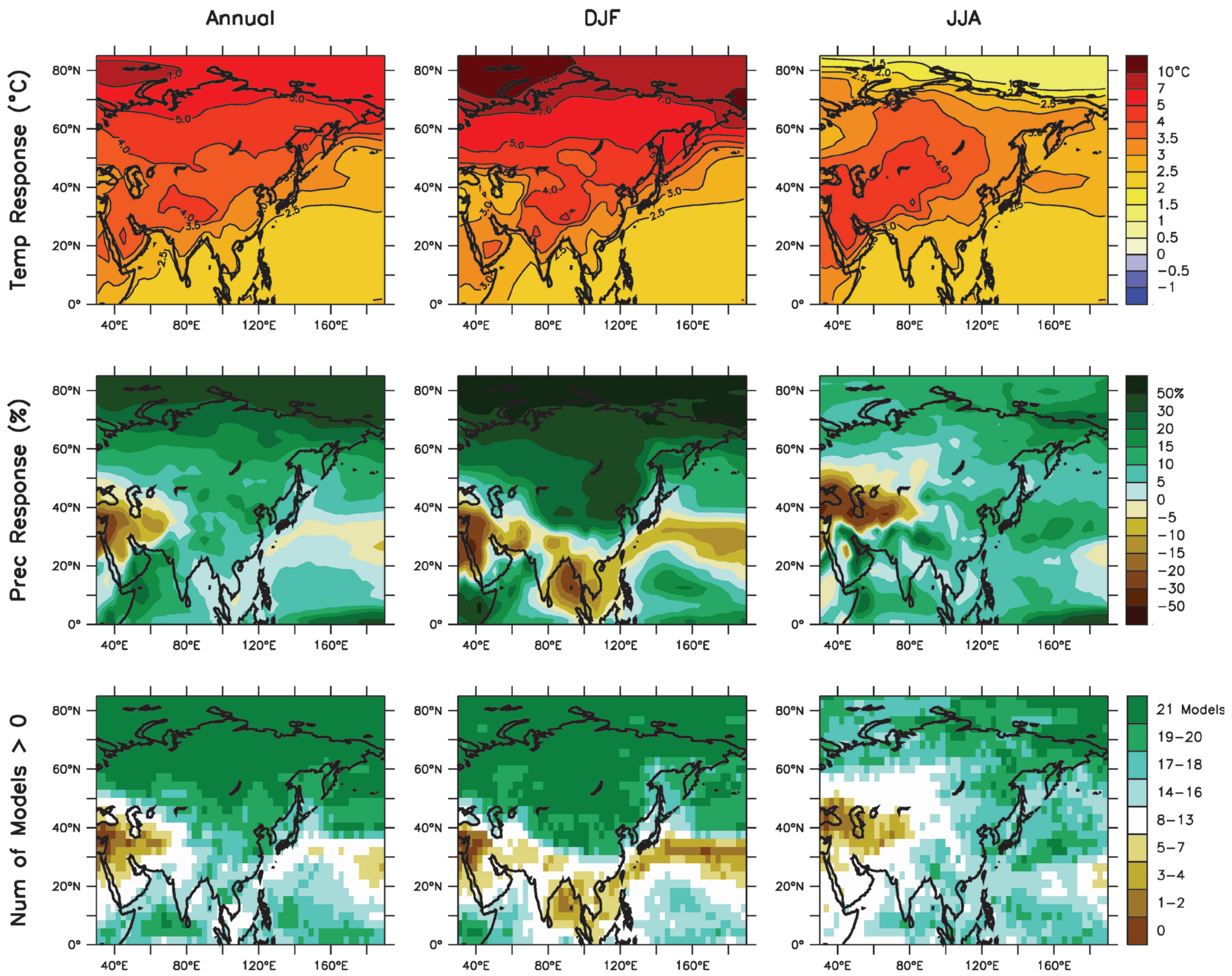

FIGURE 2.11 Mean projected changes in the AR4 models for surface temperature (top) and precipitation (center row) for the annual average (left), December to February (center) and June to August (right). Changes are shown for the mid-range SRES A1B scenario for 2080 to 2099 relative to 1980 to 1999. The lower row shows the number of models out of the 21 analyzed that projected increases in precipitation (increases in temperature were consistent across models). These projections show warming throughout the region and in all seasons, with greater magnitude over the Tibetan Plateau than over the South Asian continent south of the Himalayas. SOURCE: Christensen et al. (2007).

Asia. Regardless, evidence suggests that the eastern Himalayas and the Tibetan Plateau are warming overall (Diaz and Bradley, 1997; Liu and Chen, 2000; Shrestha et al., 1999) and this warming appears to be increasing with elevation, at least up to 4,800 m (Liu and Chen, 2000; Qin et al., 2009). In the western Himalayas, the situation is more complex with all but the Karakoram having warmed since at least the 1980s (Bhutiyani et al., 2007; Fowler and Archer, 2006; Shekhar et al., 2010). The Karakoram remains the principal regional climate anomaly as it likewise is regarding current glacier activity.

Unfortunately, these modern climate studies provide no meaningful insights into how significant the recent observed changes in climate have been compared with the natural variability of the region's climate, because the observation records are too short. This provides the motivation for using centuries- to millennia-long annual tree-ring chronologies as well as ice cores to reconstruct climate over the HKH. Moraine dating can also provide useful information despite not having the same temporal resolution as tree-ring chronologies. Specifically, it can provide evidence of past glacial behavior. Moraine-dating studies have indicated spatial and temporal variation in the advance and retreat of glaciers in the region. Studies suggest that HKH glaciers have not responded uniformly to climate forcing in the past. For example, Benn and Owen (1998) used moraine dating in the Kunlun Mountains along the northern edge of the Tibetan Plateau to determine that during the last glacial cycle, glacial advance was not synchronous. Other studies have shown that there may be a relationship between the spatial and temporal patterns of glacial advance and retreat in the region and the spatial and temporal patterns of the monsoon (Owen et al., 2002, 2005). A recent study of glaciers in northern India confirmed that on the millennial scale, patterns of glacial advance and retreat are related to patterns of monsoon variability (Scherler et al., 2010). More studies of this type would increase understanding of glacier behavior and climate response in the region.

Tree Rings

Tree-ring chronologies can be used to reconstruct climate over the HKH, but to date have not been used to provide a direct history of glacial advance and retreat in the Himalayas using dendrochronological dating methods to reconstruct glacier fluctuations from dead trees overridden by advancing glaciers (e.g., Holzhauser et al., 2005; Luckman, 1993). This is because the HKH glaciers are almost all above tree line, which severely restricts the availability of tree-ring material for dating past glacial advances and associated retreats. With this in mind, three papers have been published on tree growth and related glacier activity in the Himalayas: Singh and Yadav (2000), Bhattacharyya et al. (2006), and Borgaonkar et al. (2009). None have directly dated the timing and extent of past glacier fluctuations in the Himalayas using the dendrochronological dating methods used elsewhere in Europe and North America. Rather, the Himalayan studies have inferred likely changes in past and present glacier activity through changes in tree growth thought to be related to climate (primarily temperature). Thus, we are limited to using tree rings for reconstructing climate over the HKH, using that information to determine how anomalous recent changes in climate are compared with the past, and inferring the degree to which those anomalous changes may be responsible for the observed retreats of the HKH glaciers.

Annual tree-ring chronologies are well suited for reconstructing past climate variability and change in the HKH region because they are annually resolved and exactly dated, making them useful for direct calibration and reconstruction of instrumental climate data back in time. When this is done, some form of statistical validation of the tree-ring estimates of past climate is commonly conducted by comparing climate data withheld from calibration exercises with the tree-ring estimates. This process of verification (Fritts, 1976) has a long history of use in dendroclimatology and is a direct measure of reconstruction accuracy. Cook and Kairiukstis (1990) and Cook and Pederson (2010) provide discussions of statistical validation in dendroclimatology. Estimates of reconstruction precision can also be obtained from error (or uncertainty) estimates associated with the calibration exercise. In regression analysis, this typically involves the use of the root mean square error of the fitted model to determine error estimates around each reconstructed value back in time. Doing so is a relatively recent development in statistical dendroclimatology, one that has not been done in the papers cited here on tree-ring research in the HKH region.

When it is not possible to directly calibrate tree-ring records against climate data, as can be the case in the data-poor regions of the HKH, it is often still possible to infer past changes in climate from them at certain highly stressed locations, like temperature change from tree growth at upper timberline locations. However, such inferences are far weaker for interpreting past changes of climate from tree growth compared with direct calibration and validation using instrumental climate data.

Using tree rings to study past climate in the Himalayas began over 20 years ago (e.g., Ahmed, 1989; Bhattacharyya et al., 1988; Hughes and Davies, 1987; Pant, 1979) and accelerated quite dramatically in the 1990s (e.g., Bhattacharyya et al., 1992; Borgaonkar et al., 1994; Bräuning, 1994; Esper et al., 1995; Yadav and Bhattacharyya, 1992). Thus, the literature on this topic is quite extensive and somewhat variable in its methods of analysis, findings, and interpretations, making a comprehensive literature review for this report impractical. However, the findings on current and past climate change from tree rings in the HKH are nonetheless reasonably consistent for large regions of the HKH and for some seasons. This is most apparent from the many series that extend back into the Little Ice Age (LIA) roughly 300 to 500 years ago. It is far more difficult to make a useful assessment of what climate was like during the Medieval Warm Period in the Himalayas, some 1,000 years ago, because such long tree-ring records are relatively rare. Therefore, no further reference to the Medieval Warm Period will be made in this review. The following summary is divided into two climate change topics over the HKH: temperature and precipitation. For each of these topics, the review of tree-ring evidence for climate change then proceeds from the western to eastern ends of the HKH and up onto the eastern end of the Tibetan Plateau.

Temperature

There is evidence for recent climate warming over large parts of the HKH since the LIA, with the latter decades of the 20th century often being the warmest overall. This is apparent from inferred or calibrated tree-ring reconstructions of past summer temperature in the western Tien Shan in Kirghizia (Esper et al., 2003) and the Karakoram in northern Pakistan (Esper et al., 2002). In the western and central Himalayas of India and Nepal the temperature histories from tree rings are somewhat less seasonally consistent with respect to climate warming since the LIA. In the western Indian Himalayas, Borgaonkar et al. (2009, 2011) described tree-ring evidence for anomalous winter warming that is especially evident since the mid-20th century. Cook et al. (2003) found similar evidence for long-term warming in an all-Nepal cold-season temperature reconstruction. In contrast, Yadav et al. (1997, 1999) and Yadav and Singh (2002) produced spring temperature reconstructions with very subdued warming trends since the LIA and even a small degree of cooling indicated during the latter half of 20th century. Independently, Cook et al. (2003) and Sano et al. (2005) produced similar results in reconstructions of February to June and March to September temperatures, respectively, from Nepal.

The appearance of a cooling trend in predominantly spring temperatures during the late 20th century prompted Yadav et al. (2004) to suggest that the western Indian Himalayas were defying global warming. This was apparently due to daily minimum temperatures in the western Himalayas decreasing about three times faster than daily maximum temperatures, thus resulting in an overall cooling trend in mean daily temperatures for the spring months. In contrast, Borgaonkar et al. (2009, 2011) produced several tree-ring records from the same region that showed accelerated growth due to warmer winter temperatures since the mid-20th century. Coupled with the long-term winter warming trend produced by Cook et al. (2003) for Nepal, this implies that winter temperatures in the western Himalayas have been trending opposite to predominantly spring temperatures in recent decades. It is unclear why this appears to be happening, although the cooling trend in surface temperature could be related to increasing atmospheric loading of aerosols in this region.

Moving eastward to Bhutan, recently developed unpublished results indicate a substantial summer season warming trend there since 1700 based on a large-scale composite of Himalayan spruce (*Picea spinulosa*) tree-ring data that begin in 1400 (Figure 2.12). There is a pronounced below-average growth period from 1590 to 1820 in the data, interpreted here as the LIA in Bhutan, followed by a nearly monotonic growth increase up to recent times that appears to emerge from the background after about 1880. That this tree-ring record can be interpreted as an index of summer temperature change over Bhutan is demonstrated by its correlation with gridded summer temperatures shown in Figure 2.13. This map shows the locations of significant correlations between the Bhutan spruce tree rings and mean monthly temperature data for the period 1901 to 2003. The greatest concentration of significant correlations is exactly over the Himalayas of Bhutan where the tree-ring data are located. The peak correlations over Bhutan (~0.50) are somewhat modest from the perspective of explained variance (~25 percent) between tree rings and summer temperatures, but the gridded temperature data used here is based solely on interpolated data from surrounding Indian meteorological stations. The climate records from Bhutan are extremely short (~10 to 20 years long) and insufficient for this kind of analysis. Therefore, the results presented here are likely to be a minimum estimate of how strongly the tree-ring record in Figure 2.13 is reflecting changes in current and past summer

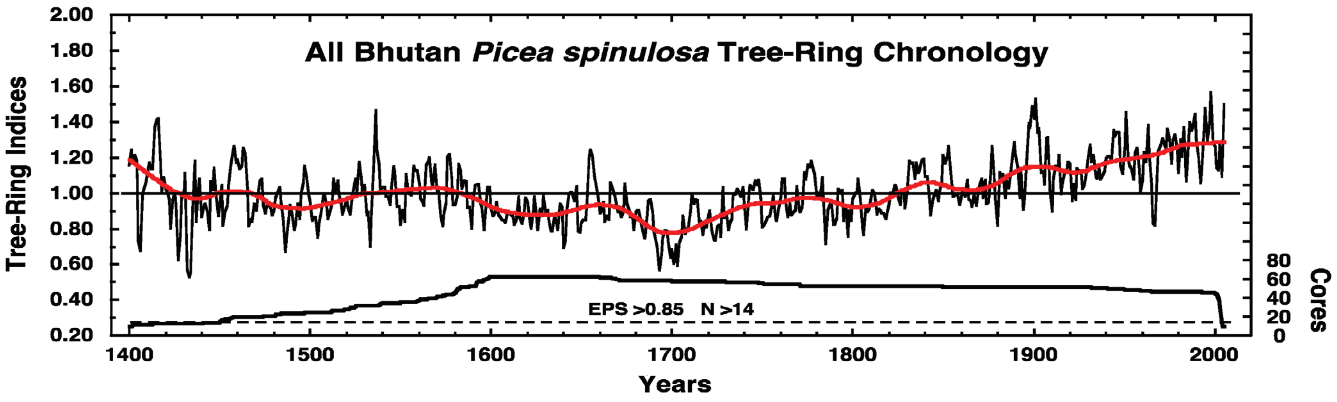

FIGURE 2.12 The "All Bhutan" *Picea spinulosa* tree-ring chronology (1400-2005). The sample size (cores) per year is also shown, along with the chronology range above the dashed line where the expressed population signal (EPS) and sample size (*N*) are sufficient to produce a statistically valid tree-ring chronology (1450-2003 here) for climate modeling and interpretation (Wigley et al., 1984). The data indicate a pronounced below-average growth period from 1590 to 1820, interpreted here as the Little Ice Age in Bhutan, followed by a steady growth increase that indicates a substantial summer season warming trend since 1700. SOURCE: E. R. Cook and P. J. Krusic (unpublished data, 2011).

temperatures over Bhutan. Thus, the glacial retreat now under way in Bhutan (Bajracharya et al., 2007) appears to be associated with unprecedented summer warming over this part of the Himalayas.

Finally, over the Tibetan Plateau on the drier side of the Himalayas, there is less clear and somewhat conflicting evidence for climate warming since the LIA. In southwest Tibet, Yang et al. (2009) produced evidence for a modest summer warming that appeared to increase in strength toward the end of the 20th century. In contrast, a January to June temperature reconstruction from southeast Tibet produced by Yang et al. (2010) showed modest cooling. Comparisons made to other tree-ring reconstructions (e.g., Bräuning and Mantwill, 2004; Fan et al., 2008a; Li et al., 2011; Liang et al., 2008, 2009) from the Tibetan Plateau also yield conflicting evidence for widespread climate warming in the 20th century. This may be due to variations in the seasonal response of the trees to temperature, as previously suggested in the western Indian Himalayas, and also due to variations in site characteristics that could possibly affect moisture availability in this dry region.

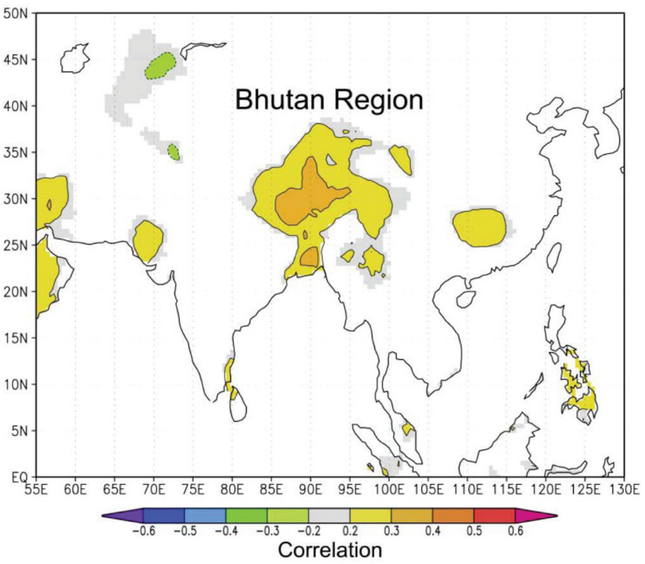

FIGURE 2.13 Mean summer (June-July-August) temperature correlations in the Bhutan region ($p < 0.10$) with the "All Bhutan" *Picea spinulosa* tree-ring chronology shown in Figure 2.12. Correlations are calculated over the 1901-2003 period. The positive correlations indicate that the tree-ring data shown in Figure 2.12 can be interpreted as an index of summer temperature change over Bhutan. SOURCE: Produced with KNMI Climate Explorer using CRU TS 3.1 gridded mean temperature data.

Precipitation—Monsoon and Winter Snowfall

Reconstructions of past precipitation (and related hydrological variability) from tree rings in the HKH are less common than for temperature. However, there have been some notable successes that generally show a trend toward anomalously wetter conditions in the 20th century in the western portion of the HKH compared with earlier times. In the Karakoram of northern Pakistan, Treydte et al. (2006) measured stable oxygen isotope ratios in the annual rings of ancient junipers and showed that the 20th century has been the wettest period of the past millennium there. A bit farther eastward in the western Indian Himalayas, Singh and Yadav (2005), Singh et al. (2006, 2009), and Yadav (2011) all show that the latter half of the 20th century has been the wettest period since at least the LIA. In comparison, precipitation reconstructions for the eastern Tibetan Plateau (e.g., Fan et al., 2008b; Liu et al., 2011) show a more mixed record of interdecadal wetness and dryness, with a tendency for drier conditions in the last half of the 20th century followed by somewhat wetter conditions since that time.

Overall, the tree-ring climate reconstructions indicate that climate has been getting warmer and wetter since the LIA over significant portions of the HKH, but the story is regionally and seasonally complex with not all locations or seasons agreeing in the direction or size of the change. In the drier western part of the HKH, there is reasonably consistent evidence from tree rings for a warming trend in winter temperatures since the LIA, with the 20th century often being the warmest period overall. However, this warming trend does not appear to extend into the spring season. Instead, spring temperatures have generally declined there since the mid-20th century based on tree-ring evidence. The western Himalayas and Karakoram also appear to be getting wetter now compared with the past. This is consistent with the current stable or surging state of glaciers in the Karakoram (Bolch et al., 2012). In the eastern Himalayas of Bhutan, dramatic summer warming has been under way there since the LIA, which does not show any signs of slowing down. This is consistent with the glacial retreat now under way there (Bajracharya et al., 2007). On the Tibetan Plateau, changes in temperature and precipitation indicated by tree rings are mixed, with a tendency for drier conditions in the last half of the 20th century followed by somewhat wetter conditions since that time.

The general tendency for warmer and wetter conditions over large parts of the HKH can affect the glaciers in different ways, depending on whether temperature or precipitation is more important to the mass balance. In the western HKH where moisture delivered by the mid-latitude westerlies is most important, glacial mass balance appears to be reasonably stable because winter snowfall accumulation is presently sufficient to offset any climate warming during the summer ablation season. Whether this stability continues will depend at least in part on the continued delivery of sufficient snowfall to offset any future increases in ablation due to summer warming, a great unknown at this time. However, if the past is any indication, the present period of unusual above-average wetness may be hard to increase enough to offset the effects of future warming. In the summer monsoon-dominated eastern Himalayas, it appears that ablation is already outpacing accumulation based on glacial retreat in areas such as Bhutan, where 20th century summer temperatures appear to be warmer than at any time since 1450. It is hard to imagine how this trend might be reversed in the future because of the way temperatures are expected to continue to rise due to greenhouse warming.

Ice Cores

One of the critical functions that mountain glaciers serve is the preservation of detailed information about past climate and the ability of glaciers to respond to different climate variables. Currently, there are five long ice-core records (greater than 2,000 years) for the HKH region. Three are from the Tibetan Plateau, and only two are from the Himalayas. As discussed in the previous section, the climate of the region varies a great deal from east to west, and to some extent from north to south. Therefore, more ice-core data is needed to form a complete picture of the region's paleoclimate. However, information from the five long ice-core records that do exist, much like tree-ring data, demonstrate the climatic complexity and diversity of the HKH region.

Proxy climate records spanning more than 500,000 years have been recovered from the Guliya ice cap in the far northwestern Kunlun Mountain region of the Tibetan Plateau, dominated by westerly air flow over the Eurasian land mass, while shorter records (< 10,000 years) have been recovered from ice fields in the central Himalayans to the south, where a monsoonal climate regime dominates and the annual accumulation is high. These records show that the Himalayan ice fields are sensitive to fluctuations of the South Asian monsoon, and are affected by rising temperature in the region.

Over the past 25 years the Ice Core Paleoclimate Research Group at the Byrd Polar Research Center has collected ice cores from five sites across the Tibetan Plateau. Figure 2.14 shows the location of these five drill sites. Naimona'nyi (6,050 m a.s.l.) is included

FIGURE 2.14 Location of the five ice-core study sites in the Himalayas and across the Tibetan Plateau.

even though recent melting at the glacier surface has removed the upper 40 to 50 years of the record (Kehrwald et al., 2008). The decadal $\delta^{18}O$ and dust data along with a 3-year moving average are illustrated in Figure 2.15. The data illustrate the effect of the recent warming across the Plateau on the mean $\delta^{18}O$ values since 1950. There is a strong enrichment of ^{18}O that is enhanced with altitude. The average values of $\delta^{18}O$ from 1000 to 1950 are −10.85‰ for Dunde (5,325 m a.s.l.), −15.01‰ for Purguogangri (6,070 m a.s.l.), −14.28‰ for Guliya (6,200 m a.s.l.) and −20.48‰ for Dasuopu (7,200 m a.s.l.). From 1950 to the top of these records (except for Naimona'nyi where the most recent part of the record is missing) the $\delta^{18}O$ averages have increased by 0.71‰, 1.35‰, 1.08‰, and 2.63‰ for Dunde, Puruogangri, Guliya, and Dasuopu, respectively. These trends are consistent with instrumental temperature records since the 1950s across the plateau (Liu and Chen, 2000) as well as with the model predictions of the vertical amplification of temperature across the region.

The mineral dust record for the same periods in these five cores shows a great deal of site-to-site variability because dust is often more of a local to regional signal. The only record that shows an increase in concentrations in the 20th century is the 7,200-m a.s.l. Dasuopu record. There is a very large difference in dust concentrations from region to region. The Dunde and Guliya ice cores located on the most northeastern and northwestern areas of the Tibetan Plateau contain 20 times higher dust concentration than that of the most southern ice-core study site, Dasuopu, at the top

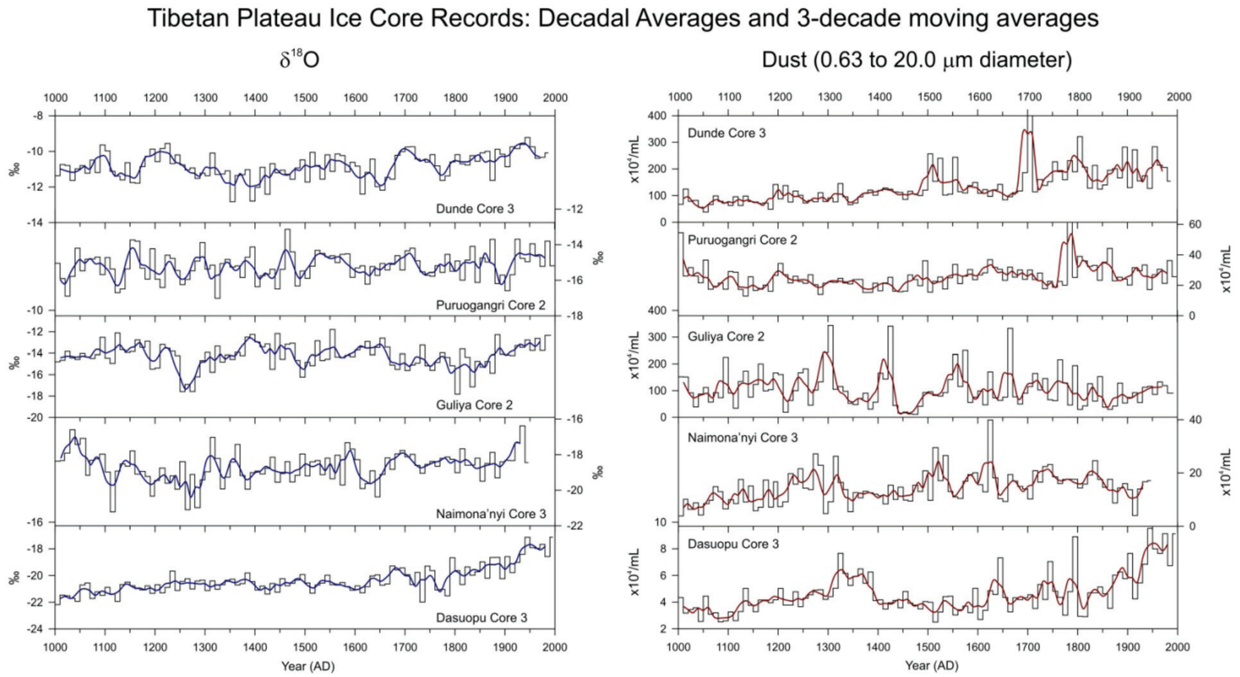

FIGURE 2.15 One thousand year records of δ^{18}O and mineral dust concentrations, shown as decadal averages, from five Tibetan Plateau ice-core study sites along with a three-decade moving average.

of the Himalayas. The larger concentration of dust in cores in the north is due in part to the proximity to Takla Makan and Gobi deserts and the fact that they are located in regions of the plateau that are dominated by the westerlies. Puruogangri, Naimona'nyi and Dasuopu located in the central Tibetan Plateau and the Himalayas to the south are under greater influence of the monsoons and contain far lower concentrations of mineral dust. The lowest mineral dust concentrations are found in the 7,200-m a.s.l Dasuopu ice-core study site. The ice-core data files along with the metadata files for Dunde, Guliya, Dasuopu, and Puruogangri ice cores are archived at the National Climatic Data Center (NCDC).[8] Naimona'nyi ice core data files and metadata will be archived pending publication.

A high-resolution ice-core record from Dasuopu at 7,200 m in the central Himalayas (located just north of the China-Nepal border) shows that this location responds to fluctuations in the intensity of the South Asian monsoon. Measurements of dust and chloride concentrations yield information about changes in monsoonal intensity. Older sections of the ice cores reveal periods of drought in the region, with the drought of greatest intensity occurring from 1790 to 1796. Recent increases in anthropogenic activity in India and Nepal are shown by a doubling of chloride concentrations and a fourfold increase in dust in the upper sections of these cores. The Dasuopu ice core also suggests a 20th-century warming trend that appears to be amplified at higher elevations (Thompson et al., 2000).

The ice fields located in more arid regions of the Tibetan Plateau (i.e., Guliya, Puruogangri, Dunde) have rather similar annual net mass balances, averaging 220 mm water equivalent (liquid water obtained from melting snow or ice) per year for Guliya in the far northwestern Tibetan Plateau, 350 mm water equivalent per year for Puruogangri in central Tibetan Plateau, and 390 mm water equivalent for Dunde in northeastern Tibetan Plateau. Ice-core records from these three ice fields have rather similar histories with net balance higher in the 17th and 18th centuries, consistently lower values in the 19th century, and a general increase in the 20th century. In contrast, the net balance history on Dasuopu in southern Tibetan Plateau in the Himalayas shows a different pattern, with current net balances averaging 1,000 mm of water equivalent per year. The net balance history shows consistently high

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[8] *http://www.ncdc.noaa.gov/paleo/icecore*.

values over the 19th century. Although the 600-year net balance history for the Himalayas (e.g., Dasuopu) is quite different from that in the Tibetan Plateau to the north, their oxygen isotope histories, or proxy temperature records, are remarkably similar at lower frequencies. During the 17th century, temperatures were warmer over Guliya and Puruogangri than over Dunde and Dasuopu, but there has been persistent, gradual warming from the 18th through the early 20th century and accelerated warming over the second half of the 20th century. The recent isotopic enrichment is consistent among the Tibetan Plateau sites and independent of the net balance (Duan et al., 2006; Thompson et al., 2006).

A sulfate record, which indicates deposition of sulfate aerosol, for 1000 to 1997 from the Dasuopu ice core shows that this site is sensitive to anthropogenic activity originating in southern Asia. Before 1870, sulfate concentrations in the atmosphere were relatively low and constant, but after 1870, concentrations increased and the rate of increase has accelerated since 1930. This trend in sulfate deposition is accompanied by growing SO_2 emissions in South Asia. This is in contrast to sulfate concentrations derived from Greenland ice cores, which have declined since the 1970s. This is a result of regional differences between Europe and Asia in emission and transport of sulfate, as well as different levels of environmental regulation (Duan et al., 2007). As discussed earlier in this chapter, a number of recent studies have concentrated on the impact of black carbon and aerosols on atmospheric heating and glacier melting (Lau et al., 2010; Menon et al., 2010; Ramanathan and Carmichael, 2008).

Regional composites for the Tibetan Plateau have been constructed using decadal averages of oxygen isotopes over the last 2,000 years to reveal larger temporal-scale changes. The 2,000-year perspective from these Tibetan Plateau ice cores shows large and unusual warming at high elevations. The oxygen isotope record clearly shows that large-scale dynamics have changed over the past century, regardless of whether the record is used as a proxy for temperature, precipitation, or atmospheric circulation (Thompson and Davis, 2005; Thompson et al., 2006; Vuille et al., 2005; Yao et al., 1996). Similar to tree-ring chronologies, ice-core records collected across the Tibetan Plateau demonstrate that it is a climatically diverse and complex region. Ice-core datasets from exposed mountain summits away from the effects of urbanization and topographic sheltering provide relatively unbiased records of the planet's climate.

REGIONAL HYDROLOGY

Mountains are the water towers of the world, characterized by high precipitation and little evaporation because of lower air temperatures and longer snow coverage, resulting in large contributions of snowmelt and icemelt to the runoff of lowland areas (Viviroli et al., 2007). This is especially true for the HKH region, where the snow and ice stored in high-altitude glaciers in the Greater Himalayas are a source of water for almost every major river system in the region. However, a complete understanding of the regional hydrology—including the actual contribution of snow and glacial meltwater to surface waters and groundwater of the region—is lacking because of the same incomplete science and unresolved uncertainties discussed earlier in the report.

The lack of understanding of the regional hydrology is intimately tied to water security concerns in the region. Some reports and peer-reviewed publications suggest that glacial meltwater provides a large share of the water feeding discharge into major rivers such as the Ganges. This apparent contribution of glacial meltwater to these large rivers, combined with the misconception that the region's glaciers are experiencing the highest rates of glacial retreat in the world, have combined to create a sense of water scarcity in the region (e.g., Kehrwald et al., 2008).

Uncertainty About the Contribution of Glacial Melt to the Hydrology of the Region

Barnett et al. (2005) report that "there is little doubt that melting glaciers provide a key source of water for the region in the summer months: as much as 70 percent of the summer flow in the Ganges and 50 to 60 percent of the flow in other major rivers." This statement is based on estimates of glacial melt contributions to river flow derived from models that relied on many assumptions because of the lack of field data (Singh and Bengtsson, 2004; Singh and Jain, 2002; Singh et al., 1997). Rees and Collins (2006) used a theoretical modeling approach to conclude that for large distances downstream, the contribution of discharge from glacier icemelt often dominates flow, particularly when other sources of runoff are limited.

Attempts to improve the understanding of the contribution of glacial wastage to the regional hydrology confound these interpretations by identifying scientific gaps, important nuances in geography, and contrasting results when using different scientific methods. For example, modeling[9] showed that in Nepal the glacial meltwater contribution to tributaries to the Ganges near the base of the Himalayan sub-basin streamflow varies from approximately 20 percent in the Budhi Gandaki Basin to approximately 2 percent in the Likhu Khola Basin. The average across nine basins in Nepal was 10 percent (Alford et al., 2010), a far lower percent than that discussed above. Using remote sensing approaches,[10] Racoviteanu (2011) corroborated these lower values by showing that for the Langtang basin in Nepal, glacial meltwater contributes about 10 percent of discharge at an elevation of 900 m. This work also showed that the contribution of glacial meltwater to discharge increases with increasing elevation, reaching about 50 to 70 percent at an elevation of 3,800 m (Racoviteanu, 2011). Using ice-core records and measuring radioactivity, Kehrwald et al. (2008) suggested that reports of the relationship between glacial retreat and downstream water resources have not accounted for mass loss through thinning of high-elevation, low-latitude glaciers. For example, this is apparently occurring in the Naimona'nyi glacier in Tibet. Thinning of high-elevation glaciers could result in a decrease in water availability in regions where the water supply is dominated by high-elevation glacial melt. Armstrong (2010) reported that previous assessments of the relationship between glacial meltwater and surface water supply have been highly qualitative or local in scale. Direct evidence is lacking to support the higher-end values reported for the contribution of glacial icemelt to total river flow volume (i.e., 50, 60, 70 percent). However, it is generally accepted that the percent contribution increases from east to west across the region (Immerzeel et al., 2010).

Finally, contributing to the confusion about the relative importance of glacial melt to the discharge of rivers is the often-overlooked differentiation between relative contributions of snowmelt versus glacial melt. For example, any water source from high elevation is sometimes assumed to be glacial melt, when in fact snowmelt may be a major contributor. Snowmelt is a renewable resource that is replenished every year, in contrast to the fossil water[11] contributed by glacial wastage (Barnett et al., 2005). In addition, some reported values include runoff from rain and other forms of precipitation that would occur with or without the presence of glacial ice. In most basins, the contribution of rain far outweighs the combined contributions of snowmelt and glacial wastage to discharge. For example, Andermann et al. (2012) found that snowmelt and glacial melt contributed roughly 10 percent to the discharge of the three main Nepal rivers. Therefore, in these catchments, rainfall could contribute as much as 90 percent to the total discharge.

A Complex Hydroclimate System

Glaciers are only one part of the complex HKH hydroclimate system,[12] where the relative importance of the contribution of glacial meltwater to runoff depends on the magnitude of other components of the hydrological cycle. The different climate regimes of the region are characterized by differences in the spatial and temporal distribution of precipitation (type and amount) and runoff. As mentioned previously, summer monsoon rains dominate the annual precipitation cycle of the eastern Himalayas while the west is dominated by winter snowfall with low amounts of summer precipitation. A similar variation in the relative contributions of rain, snowmelt, and melt of glacier ice to the discharge of different rivers throughout the HKH is expected.

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[9] The model was based on limited mass balance measurements from glaciers in the region, remote sensing measurements of glacier area, and a variety of assumptions.

[10] Datasets were derived using remote sensing resources discussed further in Appendix A, such as the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor, declassified Corona imagery, and Landsat ETM+.

[11] Fossil water is water that has been stored in a glacier or an aquifer for a long (years or more) period of time.

[12] The hydroclimatic system includes the processes by which the climate system causes global and local variations in the hydrological cycle.

Methods comparing measurements or models of glacial meltwater production with measurements of downstream discharge volume are problematic. Glacial meltwater can be interpreted as raw volume input into the system, but downstream of the glaciers discharge has been modified by a number of factors, including precipitation, evaporation, irrigation, damming, and groundwater exchange. With increasing distance from the glaciers, these modifications increase in relative importance, while the relative contribution of glacial meltwater decreases. In a direct comparison between glacial meltwater and runoff downriver, the volume contribution from glaciers can be overestimated with increasing distance from the glaciers (Kaser et al., 2010).

Furthermore, limited data on the water cycle of the region, due to a variety of reasons ranging from difficult terrain to political instability, is a chronic problem. Scientists compensate by using many assumptions in models or remote sensing imagery. The overall result, however, is more overall uncertainty in the body of scientific literature than in other parts of the world that are not limited by these challenges. Despite this uncertainty, many studies have contributed to reducing this uncertainty associated with the complexity of the HKH hydroclimate system.

There is strong seasonality in annual precipitation. Annual hydrographs for the Ganges and Indus rivers clearly show strong seasonality in the amount of discharge, leading to seasonal differences in water availability. The Ganges River exhibits a significant discharge during the summer months, resulting in a water surplus that can maintain in streamflows and in some areas recharge groundwater storage. However, water consumption exceeds natural runoff in the winter months of February and March when there is some reliance on groundwater and/or storage (Hoekstra and Mekonnen, 2011). The Indus River has a lower peak discharge and lower annual discharge than the Ganges River. The Indus River discharge also varies seasonally and interannually. (The relationship between natural runoff and water use in the major river basins in the study region is discussed in more detail in Chapter 3.)

Using a modeling approach, Immerzeel et al. (2010) concluded that glacial melt and snowmelt are "extremely important in the Indus Basin and important for the Brahmaputra basin, but plays only a modest role for the Ganges, Yangtze, and Yellow Rivers." Preliminary results show that in the Indus, snow and glacial melt contribute one and a half times as much discharge as that generated naturally downstream below 2,000 m. In the Brahmaputra, snow and ice discharge is about a quarter of that generated downstream. The model found snow and glacial melt to be less important in the Ganges, with discharge being about one-tenth of that generated downstream. For the Indus, this indicates that the source of much of the streamflow at low elevations is snowmelt and/or icemelt from elevations greater than 2,000 m. The values for the Ganges are remarkably similar to those of Alford et al. (2010) and suggest that glacial melt is not a major contributor for river systems to the east but is much more important for river systems to the west.

Recently, Wulf et al. (2011) quantified the water resources and discharge components for the Sutlej River from 2004 to 2009, which is a major tributary of the Indus River flowing through northern India and Pakistan. As discussed earlier in this chapter, the Sutlej Basin is located at the interface between the monsoon-dominated precipitation regime to the east and the winter-snow-dominated regime to the west. Results indicate that the discharge of the Sutlej River at Bhakra located at low elevation and situated at the base of the mountains is sourced predominately by snowmelt (48 percent) followed by effective rainfall (rainfall-evapotranspiration,[13] 39 percent) and glacial melt (13 percent). Average runoff per square meter is less than 0.2 m yr^{-1} in the high-elevated, low-relief Transhimalayan part of the Sutlej Valley, peaks at about 1.5 m yr^{-1} in the snowmelt-dominated High Himalaya, and is about 0.9 m yr^{-1} at the rainfall dominated-mountain front. Snowmelt is thus a much more important component of discharge than glacial melt for the Sutlej Basin, where monsoon rains are less important than farther to the east in Nepal and Bhutan.

The hydrograph of the upper Indus Basin is highly seasonal, with about 85 percent of annual discharge occurring between May and September. Figure 2.16 shows the time series of monthly and yearly variability in May to September discharge at the historic Partab

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[13] Evapotranspiration is the combined processes through which water is transferred to the atmosphere from open water and ice surfaces, bare soil, and vegetation (AMS, 2000).

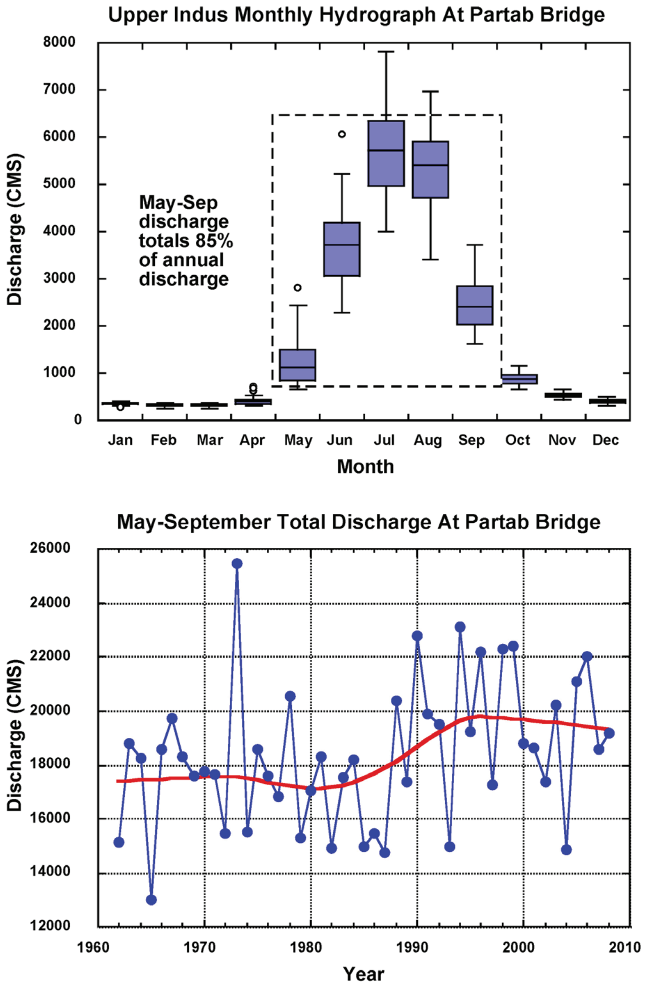

FIGURE 2.16 The monthly hydrograph of upper Indus River discharge at Partab Bridge, Pakistan, for the period 1962 to 2008 (top) and the cumulative discharge series for the May to September months (bottom) that collectively account for about 85 percent of the annual discharge on average. In both the top and bottom, the discharge on the *y*-axis is in units of cubic meters per second (m^3 s^{-1}), or CMS. The red curve is a 50 percent LOWESS robust smoothing of the yearly discharge data. The annual discharge has the appearance of two flow regimes: about 3,500 m^3 s^{-1} from 1962 to 1987 and about 3,900 m^3 s^{-1} from 1988 to 2008, an approximate 11 percent increase. This is reasonably consistent with periods of observed glacial recession from 1985 to 1995 and expansion from 1997 to 2002 in the Karakoram.Plateau ice-core study sites along with a three-decade moving average.

Bridge, Pakistan, for the period 1962 to 2008. Median discharge is 3,658 m^3 s^{-1}, but has the appearance of two flow regimes: 3,519 m^3 s^{-1} from 1962 to 1987 and 3,902 m^3 s^{-1} from 1988 to 2008, an approximate 11 percent increase. These two periods are reasonably consistent with periods of observed glacial retreat in 1985 to 1995 and expansion in 1997 to 2002 in the Karakoram (Hewitt, 2005). The upper Indus Basin record at Partab Bridge is too short to determine whether these are indicative of long-term trends or shorter random changes at the decadal scale, hence the value of producing a much longer May to September river flow reconstruction from tree rings (Ahmed and Cook, 2011). However, the results do indicate that recent measurements of increased snowfall in the area and positive glacial mass balances are correlated with recent increases in discharge. Furthermore, the sub-basins and tributaries of the Upper Indus Basin are not always in phase with respect to their relative contributions to the overall discharge. Fowler and Archer (2006) report conflicting signals of temperature and discharge in tributary inflows that ultimately discharge into the Tarbela Reservoir, farther downstream on the Indus Basin. In summary, if the observed +11 percent change is a short-term phenomenon, it falls within the interannual variability of flows and is of little import for water supply; if it indicates a long-term step increase in discharge, +11 percent over 5 months represents approximately 4 million acre-feet, which would be significant for downstream mountain communities and also for downstream reservoir operation, storage, and deliveries. But again, the period of record is too short to speculate about the trend, driving forces, or water resources significant of this record at present.

The Role of Groundwater

Groundwater is an important part of the hydrological system in any part of the world. It is the primary source of freshwater in many areas around the world and responds more slowly to meteorological conditions when compared with the surface components of the water cycle. The full role of groundwater in the HKH region is not clearly understood. For example, the amount of groundwater storage in the HKH region is largely unknown because storage is notoriously difficult to measure, especially in mountainous terrain. Furthermore, the relationship between glacial melt and snowmelt and groundwater recharge is not fully understood. Understanding the average spatial and temporal characteristics of groundwater fluxes, recharge, and discharge is a research frontier facing the hydrological science community (NRC, 2012a) and the HKH region is no exception; the mechanisms and pathways of groundwater recharge and discharge remain unclear.

There is no evidence that glacial melt or wastage contributes to groundwater recharge outside local regions in any significant way. Research from other mountainous regions has shown that groundwater recharge outside local impacts is negligible and there are no circumstances that hint that this would not be so in the HKH. The effect of glacial melt on groundwater recharge on the plains is likely small because the contribution of glacial meltwater to flows downstream is generally small, and therefore any groundwater recharge from major rivers downstream would be little affected by changes in flows of glacial meltwater. This is important because there is substantial evidence that groundwater withdrawals are increasing and it appears unlikely that increases in glacial wastage would have any significant impact on the supplies of groundwater available to meet the increased demands.

Groundwater extraction across northern India and the surrounding area in response to the growing demand for water[14] is exceeding groundwater recharge, causing a lowering of the water table (Qureshi, 2003; Shah, 2009; Sikka and Gichuki, 2006). The GRACE[15] satellite mission revealed a steady mass loss that has been proposed to be due to this excessive groundwater extraction (Rodell et al., 2009; Tiwari et al., 2009). Tiwari et al. (2009) estimate the region lost groundwater at a rate of 54 ± 9 km^3 yr^{-1} between 2002 and 2008, which is likely the largest rate of groundwater loss for comparably sized regions. A more recent analysis by Moiwo (2011) of the loss of groundwater storage in this area using GRACE data shows a similar depletion. If this trend is sustained, there could be water shortages in the region when the aquifers become economically exhausted (Tiwari et al., 2009). More specifically, it is possible that groundwater withdrawals during the low-flow period of these river basins may cause these rivers to become seasonally dry. Finally, advances from satellite gravimetry in the GRACE mission have helped to quantify groundwater depletion in the plains of northwest India, but the spatiotemporal resolution of the current satellite system is too coarse to fully distinguish between all mass changing processes (groundwater, icemelt, sediment, and tectonic forces (Bookhagen, 2012).

Although there is still a great deal of uncertainty, non-glacial mountain runoff (recharge) from the Himalayas toward low-elevation areas, in other words, the mountain water tower effect, could be a significant source of recharge to northern India. Preliminary results from a simple but effective hydrological model combined with daily rainfall and discharge measurements found that groundwater flow through bedrock is approximately six times the annual contribution from glacial icemelt and snowmelt to central Himalayan rivers (Andermann et al., 2012). However, this hydrological model used by Andermann and colleagues accounts only for snowmelt waters and not for the melting of glacial ice, which is likely to be an important discharge contribution during the late summer. Furthermore, with a model based on mean monthly values, it is difficult to establish the infiltration behavior of relatively short, but strong, monsoon storms (Bookhagen, 2012).

Groundwater storage in the middle and upper Indus River plains of Pakistan is also significant, and it has been increasingly pumped to fulfill agricultural and urban water demands. This is consistent with the decrease in discharge (discussed above) below the Partab Bridge over the last 10 years. However, groundwater in this region is recharged by the distribution of upper Indus basin runoff through Pakistan's extensive canal irrigation system across the Indus plains, mitigating groundwater depletion. But in some areas the canal system contributes to waterlogging, a high water table resulting in the saturation of soil to the degree of hindering or preventing agriculture (Briscoe and Qamar, 2006). Salinization of waterlogged lands soon follows.

These groundwater balance processes are difficult to estimate, however, because they involve water-level fluctuations over the year, as well as high levels of spatial variation in depths to groundwater and salinity levels (Van Steenbergen and Gohar, 2005). Waterlogging and salinity issues increase with the successive reuses of water downstream in the canals of the lower Indus Basin (Bhutta and Smedema, 2005). Again, the signal of the contribution of glacial meltwater in the downstream hydrological cycle can be lost in the noise of other processes, such as irrigation and the resulting hydrological impacts.

In contrast to northern India and Pakistan, groundwater resources in the Kabul Basin of Afghanistan appear to be adequate for current needs and for at least the next several decades. A quantitative study of

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[14] Groundwater accounts for 45 to 50 percent of irrigation and 50 to 80 percent of domestic water use (Rodell et al., 2009).

[15] See *http://www.csr.utexas.edu/grace/*.

groundwater resources in the Kabul Basin (a very arid region), Afghanistan by the U.S. Geological Survey and Afghanistan authorities (Mack et al., 2010),[16] has shed light on the role of groundwater in this country. This study integrated a variety of hydrological datasets—for example, streamflow data, water quality data, and satellite imagery—into a groundwater flow model to assess current and future water availability in the region.

The study gleaned that groundwater from the upper aquifers has been the primary source of water for agriculture and municipalities (Mack et al., 2010). The availability of groundwater in the Kabul Basin primarily depends on (a) surface-water infiltration from rivers and streams, (b) water leakage from irrigated areas, (c) subsurface groundwater inflows from mountain fronts and, (d) groundwater storage in thick sediments. However, most recharge is derived from leakage of streamflow. Snowmelt in the mountains surrounding Kabul Basin, particularly the Paghman Mountains, contributes an unknown but important amount to the water resources of the basin (Mack et al., 2010).

Groundwater resources in the upper aquifer during years of normal precipitation and in the northern Kabul Basin are considerable. Existing community water-supply wells that are shallow, or screened near the water table, likely would be affected by increased groundwater withdrawals, however, and could be rendered inoperable or dry during summer months with groundwater-level declines as small as about 1 m. Simulations of the effects of increasing water use on groundwater levels indicate that a large percentage of existing shallow water-supply wells in urban areas may contain little or no water by 2057 (Mack et al., 2010).

Possible Changes in Regional Hydrology

The analysis of future climate change impacts on the hydrology of the HKH region is complex because of climate variability, sparse data, and uncertainties in climate projections and the response of glaciers to current and future changes in climate, as discussed earlier in this chapter.

Immerzeel et al. (2012) evaluated the hydrological response to future changes in climate for the Langtang Basin in Nepal using a high-resolution combined cryospheric-hydrological model that explicitly simulates glacier evolution and all major hydrological processes. The analysis showed that both temperature and precipitation are projected to increase over the next century. These increases will lead to greater evapotranspiration and greater snowmelt and icemelt. This, combined with more snow falling as rain, results in a steady decline of the glacier area in the model. Furthermore, the analysis shows that increased precipitation and icemelt will lead to increased streamflow. The seasonal peak in meltwater coincides with the monsoon peak; therefore no shifts in the hydrograph are expected.

If these results are representative of the region, the Committee expects little change in the hydrograph of large rivers in the HKH region in response to changes in climate and potential glacial retreat over the next several decades. If anything, there may be an increase in discharge. Potential changes in climate that result in drier and/or warmer conditions will result in negative glacial mass balances, providing an additional water source for these large rivers over the next several decades. Decreases in available water from changes in climate (less precipitation, more evapotranspiration, etc.) will be compensated by the release of water from storage in glaciers. However, higher elevation areas can receive more than 50 percent of their annual water flow from glacial meltwater. Populations that live in high-elevation areas—or use them for activities such as seasonal grazing—may face water shortages in the near future (years to decades) if their basins have glaciers where the upper end of the glacier is at or near the elevation of the local ELA.

There is the possibility of reduced availability of groundwater below the front of the HKH, for example, the Gangetic plain in northern India. Andermann et al. (2012) have recently shown that groundwater storage in the fractured bedrock significantly influences the Himalayan river discharge cycle for the Ganges River Basin. They show that water from rainfall and snowmelt is stored temporarily in a groundwater reservoir with a characteristic response time of about 45 days. Further, they suggest that water traveling through groundwater reservoirs in the eastern HKH represents about two-thirds of annual discharge. Groundwater is the primary source of water during low-flow times

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[16] The study was conducted by the U.S. Geological Survey (USGS), under an agreement funded by the U.S. Agency for International Development (USAID). It was conducted with cooperation from the Afghanistan Geological Survey (AGS) and the Afghanistan Ministry of Energy and Water (MEW).

such as winter months, where consumptive use of water in the Ganges Basin is already greater than flow. The short response time and large amount of water flowing through the groundwater systems, in combination with the GRACE measurements that suggest a rapid reduction in the amount of groundwater in northern India, are consistent with a system that is experiencing overdrafting of groundwater. Current recharge rates do not appear to be able to replenish present rates of groundwater removal. Continued or accelerated rates of groundwater removal can easily lead to water shortages on the scale of years.

The largest changes to the hydrological system over the next decade or two will most likely be because of changes in the timing, location, and intensity of monsoonal activity. Interannual variability of the monsoon strongly affects spatial patterns. At some locations in the central Himalayas, one monsoon depression alone can account for 10 to 20 percent of all monsoon rainfall. A small shift in storm path from one year to another can cause large differences in water availability. An example is the flooding in Pakistan in July and August 2010 that resulted from an unusual combination of severe weather events (Lau and Kim, 2011a). The 2010 Pakistan flood caused historic social and economic losses for the country. The flooding was primarily due to heavy rain that fell during late July and early August 2010, from a shift of monsoon activities from the Bay of Bengal to northern Pakistan. Glacial wastage from the Himalayas likely did not play a role in this case.

While flow in the Indus and the Ganges/Brahmaputra basins will be highly affected by changes in precipitation, climate change will also have other impacts on the hydrological cycle. For instance, evapotranspiration rates may increase over large parts of the irrigated area of both basins. To compensate, farmers may apply more irrigation water, further drawing down surface water and groundwater. This trend may be most important during the dry months of the year, and may be most significant on the Indus River, which already has dry periods when available flow does not meet demand for irrigation water.

PHYSICAL EXTREME EVENTS

As discussed in Chapter 1, lack of observational data in the HKH region has led to misunderstandings about the effects of climate change on glacial retreat rates. One such misunderstanding is that retreating glaciers will lead to widespread flooding. While this is not likely, the region does face other physical hazards, including flash flooding due to extreme precipitation, flooding due to monsoon rainfall, lake outbursts, landslides, and avalanches. Monsoon flooding and lake outbursts are covered in detail here.

Monsoon Flooding

Monsoon flooding can cause loss of life and property, and potentially economic and social calamities. During the historic flooding in Bangladesh in 1998, two-thirds of the country was submerged; about 1,000 people perished from flooding or succumbed to waterborne diseases such as typhoid and cholera. Nearly 16,000 km of roads and more than 700,000 hectares of cropland were damaged or destroyed, and over one million people were displaced (BBC News, 1998; del Ninno et al., 2001).

Monsoon flooding can have important political impacts. Because of the enormous cost involved in rebuilding businesses, agriculture, and infrastructure, a major monsoon flood can have profound and long-term impacts on the policy and politics of the local and national governments in the Himalayan region. The way governments respond, and how they interact with international relief groups in managing the relief efforts, may also contribute to public perception of inefficiency, favoritism, political discord, and unrest, as in the case of the 2010 Pakistan flood. Another example is the 2008 flooding of the Kosi River, which flows from the Himalayan foothills of Nepal to a confluence with the Ganges in the Bihar region of northern India. The flood event led to a dispute between Nepal and India regarding mismanagement of the Kosi River (Malhotra, 2010).

The main cause of monsoon floods is heavy rain. Monsoon floods occur most frequently in the foothill regions along the arc of the Himalayas, and low-lying areas in the head of the Bay of Bengal during the summer monsoon season from June through September. The heavy monsoon rains range from Bangladesh, Bhutan, Nepal, and northeastern India, to north and northwestern India and Pakistan. With few exceptions, every year somewhere in the region, some degree of monsoon flooding will occur, due to the uneven distribution of monsoon rain.

A number of additional factors have the potential to contribute to the severity of monsoon floods by compounding the impact of heavy rains (NRC, 2012a). For example, if the heavy rains are coupled with unusually high volumes of runoff from melting snowpack in the Himalayas (especially rain-on-snow events), the result might be devastating. Land use changes and deforestation could also affect the severity of monsoon floods through an increase in surface-water flow leading to more severe flooding. Changes in the distribution of monsoon rainfall in response to climate and other factors may bring heavy rain to relatively dry regions (e.g., the 2010 Pakistan flood), where the local population may be less prepared or equipped to carry out prevention, evacuation, and mitigation measures. Although these scenarios are speculative, it is clear that how hydrological extremes (in this case, monsoon flooding) are intertwined with anthropogenic effects is poorly understood (NRC, 2012a).

The monsoon varies with many factors, including air-sea interactions and land processes. Increased aerosol concentrations may also influence the monsoon through local heating. The severity of monsoon flooding also depends on the local topography and infrastructure. Although the magnitude of the heavy monsoon rain during the Pakistan flood of 2010 was small compared with that of the 1988 Bangladesh flood, the impacts of the flooding were equally devastating. One-fifth of the country was underwater; nearly 2,000 people perished; 20 million people were affected. The direct damage caused by the floods was estimated to be US$6.5 billion, with an additional US$3.6 billion in indirect losses (Asian Development Bank and World Bank, 2010).

Outburst Floods

A glacial lake outburst flood (GLOF) is a type of flood that occurs when water dammed by a glacier or a moraine is rapidly released by failure of the dam (e.g., Bajracharya et al., 2007; Hewitt, 1982; Xin et al., 2008). There are two distinctly different forms of glacial lake outbursts: those that result from the collapse or overtopping of ice dams formed by the glacier itself, and those that occur when water drains rapidly from lakes formed either on the lower surface of glaciers (supraglacial) or between the end moraine and the terminus of a retreating glacier (moraine-dammed; Figure 2.17). The phenomenon of ice-dammed lakes is more prevalent in the Karakoram Mountains in northern Pakistan and the Pamirs. In the eastern Himalayas (e.g., Bhutan, Nepal) GLOFs are generally caused by water draining rapidly from supraglacial lakes or the collapse of moraines. Failure of the confining dam can have a variety of causes, including earthquakes, catastrophic failure of slopes into the lake (avalanches, rock slides, ice fall from a glacier into the lake), a buildup of water pressure, or even simple erosion of the confining dam over time.

An example of a potential threat from ice-dammed lakes is the Medvezhi Glacier in the Pamir Mountains. In 1963 and 1973, the surge of the glacier was large enough that the ice dam exceeded 100 m in height, creating a lake of over 20 million m^3 of water and debris. A series of large floods resulted from the outburst of that lake, but there were no victims because of monitoring and early warning systems. Infrastructural damage, however, was significant (UNEP, 2007).

New glacial lake formation and the enlargement of existing lakes have resulted from thinning and retreat of glaciers in the HKH region. Many glacial lakes in Nepal are growing at a considerable rate, increasing the risk to local populations. Twenty-four GLOF events have occurred in Nepal in the recent past, causing considerable loss of life and property. For example, the 1981 Sun Koshi GLOF damaged the only road link to China and disrupted transportation for several months, and the 1985 Dig Tsho GLOF destroyed the nearly completed Namche Small Hydroelectric Project, in addition to causing other damage farther downstream (Bajracharya et al., 2007).

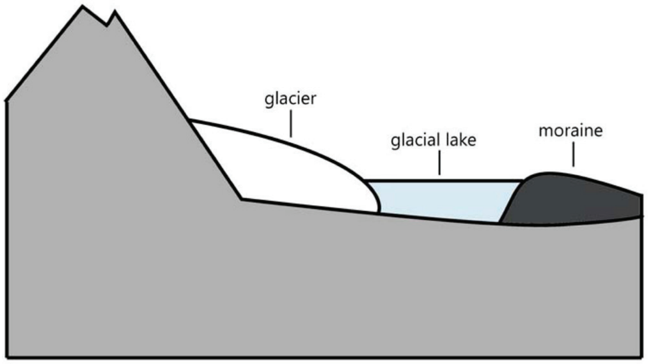

FIGURE 2.17 Schematic diagram of a moraine-dammed glacial lake formed by glacial meltwater. Failure of the confining moraine dam leads to an outburst flood.

There is no doubt that people and property for considerable distances downstream from the unstable lakes are facing a serious threat; the problem, however, is how to determine the degree of probability of such an event. Analysis of the rapidly growing worldwide literature, including field and theoretical knowledge, on the outburst of glacial lakes, led a recent ICIMOD commission on GLOFs in Nepal to conclude that it is not feasible to make a reliable prediction of a specific occurrence on the basis of existing knowledge (ICIMOD, 2011a). Because direct predictions cannot be made, a careful selection of prioritized lakes needs to be monitored on a regular basis.

GLOFs are not the only outburst lake hazards in the HKH region. Another is the landslide lake outburst flood (LLOF), which is a catastrophic release of impounded water from behind a natural dam formed by a landslide. In the steep mountainous Himalayas, landslides are a common event, whether they are triggered by normal weathering and erosion processes, extreme rainfall events, or earthquakes. The release potential of water by LLOFs can exceed that for GLOFs (Hewitt, 1982). This is because landslide dams can be very large. Dunning et al. (2006) describe a landslide dam that formed in Bhutan in 2003 and subsequently impounded 4×10^6 to 7×10^6 m^3 of water before its failure in 2004. Landslide lakes can also occur at much lower elevations than glacial meltwater lakes, where they can impound runoff from larger upstream catchment areas compared with the areas contributing to glacial meltwater lakes. Hewitt (1982) provides a detailed history of outburst floods in the Karakoram, including some massive LLOFs, and Gupta and Sah (2008) present an example of a LLOF in the Satluj catchment in Himachal Pradesh, India, well below the termini of any glaciers above it.

Like GLOFs, LLOFs pose a serious hazard to people, property, and infrastructure downstream from the landslide dams. However, compared with the large number of glacial meltwater lakes forming today because of climate warming and glacial retreat, landslide lakes are less commonly formed in the high Himalayas (e.g., Hewitt, 1982). Therefore, the risk posed by future LLOFs is likely to be significantly less than that posed by GLOFs in the HKH region. In the lower trans-Himalayan regions where landslide lakes replace meltwater lakes as hazards (e.g., Gupta and Sah, 2008), LLOFs will be a greater future risk. That being said, the development of landslide lakes is almost certainly less predictable than meltwater lakes because landslides are more random and where they will occur is harder to predict than glacial retreats. Thus, LLOFs are even less predictable than GLOFs.

CONCLUSIONS

Key features of the physical geography of the HKH region were identified at the workshop by the breakout groups on Climate and Meteorology and on Hydrology, Water Supply, Use, and Management. Starting from those concepts, the Committee used its expert judgment, reviews of the literature, and deliberation to develop the following conclusions:

- The climate of the Himalayas is not uniform and is strongly influenced by the South Asian monsoon and the mid-latitude westerlies. Projecting impacts of climate change in the Himalayas is challenging because of complex interactions between global, regional, and local forcing and responses.
- Evidence suggests that the eastern Himalayas and the Tibetan Plateau are warming, and this trend is more pronounced at higher elevations. However, a lack of sufficient paleoclimate data makes assessing the long-term significance of this warming trend a challenge.
- There are sparse historical climate data in the region, but scientists are fairly confident about projections of future temperature increases. There is more uncertainty in projections of amounts and timing of precipitation.
- Aerosols from the combustion of fossil fuels, wood, and other sources are increasing in the Indo-Gangetic Plain and the foothills of the Himalayas. Absorbing aerosols such as desert dust and black carbon may contribute to the rapid warming of the atmosphere, and model results indicate that this may in turn contribute to accelerated melting of snowpack and retreat of glaciers. Black carbon deposited directly on non-debris-covered glaciers and snowpack could increase the rate of retreat by reduction of surface albedo.
- Over the next few decades, atmospheric concentrations of greenhouse gases are projected to continue to increase globally, while black carbon aerosols are

likely to continue to increase in the Indo-Gangetic Plain and Himalayas. Unless these trends are stabilized or reversed, the impacts of greenhouse gases and black carbon on the rate of Himalayan glacial retreat will increase. That is, both the rate and volume of the glacial retreat will be relatively greater than it would be otherwise.

- The rate of retreat and growth of individual glaciers is highly dependent on glacier characteristics and location. The most vulnerable glaciers are small glaciers at low elevation and with little debris cover. These characteristics also make glaciers more susceptible to black carbon deposition, and model results indicate black carbon deposition may make them more vulnerable to retreat.
- In the eastern and central Himalayas there is evidence of glacial retreat with rates accelerating over the past century. Retreat rates are comparable to other areas of the world. Glaciers in the western Himalayas appear to be more stable overall, with evidence that some may even be advancing.
- In the short term, climate change is likely to increase glacial wastage. In the longer term the impact of continued retreat of glaciers is not clear. The rate of glacial retreat depends not only on temperature, but also on precipitation changes associated with the summer monsoon in the central and eastern HKH and the winter westerlies in the western HKH. Black carbon aerosols, via atmospheric heating and deposition on snowpack and glaciers, may increase the rate of glacial wastage.
- Surface-water flow is highly seasonal and varies across the region, as does the relative importance of glacial meltwater. In most instances, the annual contribution of snowmelt and rainfall to streamflow exceeds that of glacier wastage. Recent literature indicates that the importance of the glacial contribution to runoff has previously been overestimated.
- The contribution of glacial wastage can be more important when the glacial wastage acts as a buffer against hydrological impacts brought about by a changing climate. For example, in the late summer when all snow has melted and the monsoon-rainfall contribution is declining or in the eastern HKH during times of drought.
- Although retreating glaciers will subsidize surface flow and mitigate immediate losses to discharge by retreating glaciers, the loss of glacier "insurance" becomes more problematic for flows in the upper reaches of the eastern HKH over the long term.
- In the western HKH where more of the surface-water flow is from higher elevations, the contribution of glacial wastage could be particularly important in affecting the timing and volume of surface-water discharge.
- Overall, retreating glaciers over the next several decades are unlikely to cause significant change in flows at lower elevations, which depend primarily on monsoon rain. However, for high-elevation areas, current glacial retreat rates, if they continue, appear to be sufficient to alter the seasonal and temporal streamflow in some basins. Removing water stored as glacial ice does not imply any a priori effect on average annual discharge in the long term, assuming annual precipitation remains the same. In the short term with constant annual precipitation, glacial wastage will augment the quantity of streamflow.
- Limited streamflow data in upper basin regions, along with government constraints on scientific access to international streamflow data, increase the uncertainties surrounding hydrological trends, variability, and extreme events in the region. Limited streamflow data also limit the understanding of the relative contributions of rain, snowmelt, and glacial meltwater, as well as groundwater recharge mechanisms in the region.
- Uncertainties in the role of groundwater in the overall hydrology of the region are even greater than those of surface water. Current understanding of groundwater in the region is confounded by a variety of limitations including knowledge gaps about the interaction between surface water and groundwater; difficult terrain; the fractured and variable nature of the underlying geological substrate; and the inability to easily distinguish the contributions of snowmelt, glacial meltwater, monsoonal precipitation, and human actions such as groundwater overdraft to flows. Evidence suggests that sizable and extensive overdraft in the central Ganges Basin is likely to have an earlier and larger impact on water supplies than foreseeable changes in glacial wastage.
- For upstream populations, GLOFs and LLOFs are the dominant physical hazard risk. For downstream populations in the central and eastern Himalayas, floods from changes in monsoon rainfall and cyclones are more likely to be important, along with changes in the timing of extreme events.

3

Human Geography and Water Resources

Water use and scarcity are functions of water supply and demand. This chapter focuses on the demand for water, with an emphasis on the social factors affecting water use and availability: population growth, distribution, and migration; types and distribution of water use including irrigation; clean water and sanitation access; infrastructure; and institutions. Finally it includes a discussion of methods for measuring and managing water scarcity.

POPULATION DISTRIBUTION AND MIGRATION

The study region includes some of the most densely populated areas on Earth as well as some of the least densely populated regions, with a stark increase in population density as one moves from the mountains to the ocean. As of 2010, India alone was home to about 1.2 billion people, while Bangladesh and Pakistan each contained about 149 million and 174 million people, respectively. Nepal had a smaller population of about 30 million, while Bhutan was home to about 726,000 people (United Nations, 2011a).

The water dependencies and vulnerabilities of populations living in lower-lying areas will be quite different from the dependencies and vulnerabilities of populations in higher-lying ones. However, demographic compositional data are collected through national censuses and surveys and are reported by administrative units, such as provinces and states, which typically do not conform neatly to geographic features of interest, such as river basins or zones of elevation. By using a spatial population model of gridded population counts, though, it is possible to at least estimate the current population of each country living in the watersheds of interest in this study. This can be further segmented into coarse elevation zones (low, below 1,000 m; high, above 4,000 m; and moderate, between 1,000 and 4,000 m). In this report, the Committee uses both Global Rural Urban Mapping Project (GRUMP) (CIESIN, 2004) and Landscan (2010) population data to estimate populations at risk, relying on the former when estimating urban populations[1] and the latter when estimating population distribution per se.

Nepal and Bhutan are wholly contained within the Ganges and Brahmaputra river basins, and most of Pakistan is found within the Indus Basin. Bangladesh lies within the Ganges, Brahmaputra, and Meghna basins; and India has territory within all of these basins, though much of India's land area also falls outside the main study watersheds (Figure 3.1). Note, as discussed in Chapter 1, that the population density of the Himalayan Endorheic basins is very small, and therefore the Committee focused the discussions in this chapter on the Indus and Ganges/Brahmaputra basins. Estimates of the shares of national populations living in these basins are presented in Table 3.1.

In 2010, approximately 195 million people lived in the Indus Basin, with 16 percent of them (31.9 million) living at elevations above 1,000 m (Table 3.2). In contrast, nearly all (97 percent) of the more than

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[1] GRUMP data rely primarily on nighttime lights to delineate urban areas and therefore provide a cross-nationally consistent basis by which to measure urban areas (Balk, 2009).

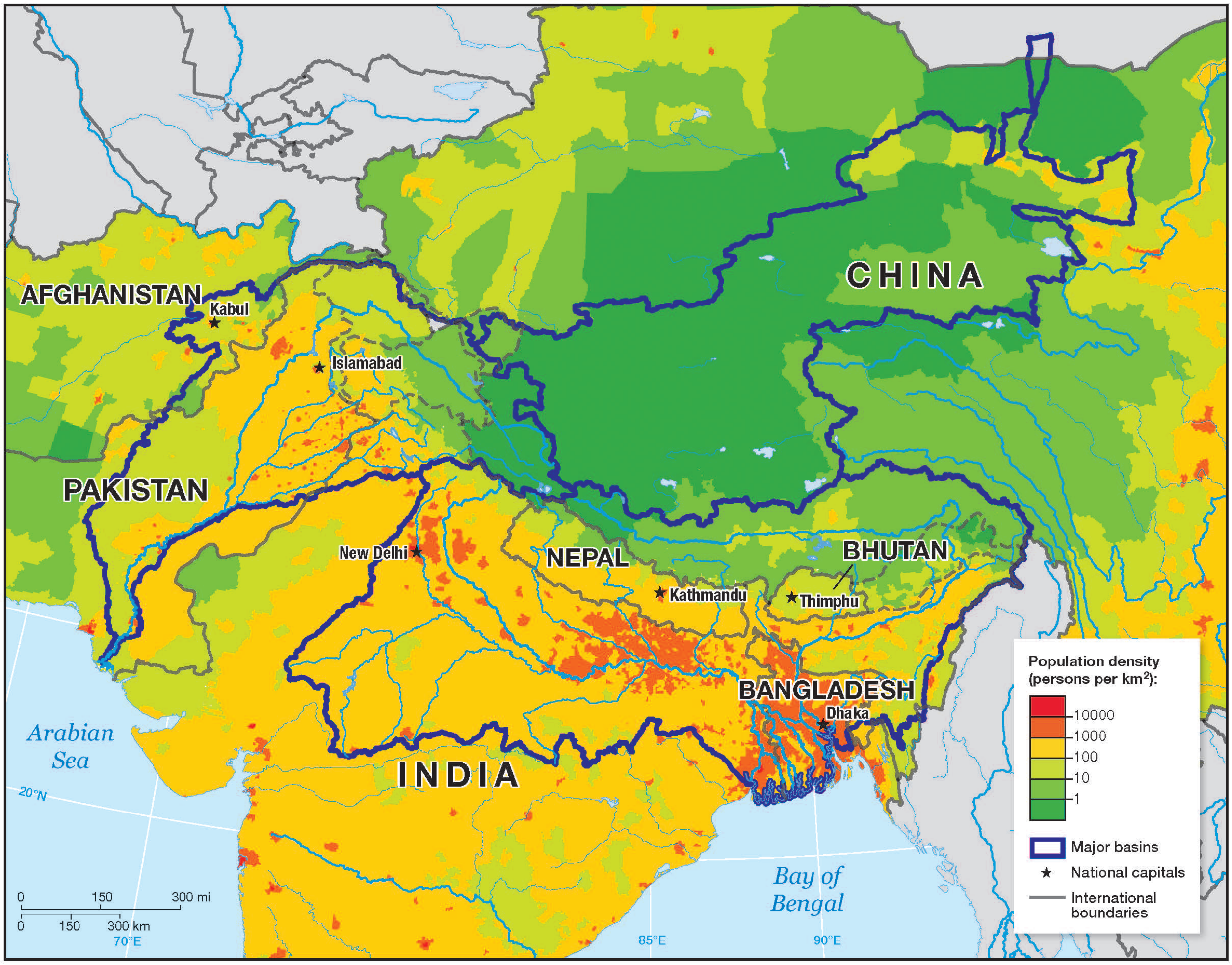

FIGURE 3.1 Population distributions in the HKH region. Population data were taken from the Global Rural/Urban Population Mapping Project. Dashed lines indicate disputed political boundaries, following the guidance issued by the U.S. State Department, and this Committee takes no position on these boundary disputes.

TABLE 3.1 Shares of National Populations Living in Hindu-Kush Himalayan Region Water Basins

Country	Basin	Population in Basin[a]	National Population[b]	National Population Living in Basins (%)
Afghanistan	Indus	10,636,154	31,412,000	33.9
Bangladesh	Gang/Brahm	103,326,928	148,692,000	69.5
Bhutan	Gang/Brahm	699,847	726,000	96.4
China	Gang/Brahm	1,712,145		
	Indus	35,585	1,348,932,000	0.13
India	Gang/Brahm	466,738,395		
	Indus	36,074,708	1,224,614,000	38.1
Nepal	Gang/Brahm	28,951,851	29,959,000	96.6
Pakistan	Indus	148,104,460	173,593,000	85.3

[a] Landscan (2010).

[b] United Nations (2011a).

600 million people in the Ganges/Brahmaputra Basin live at elevations below 1,000 m.[2] Most of those living below 1,000-m elevation are in India (79 percent) and Bangladesh (18 percent; Table 3.3). Even in Nepal, where 29 million people live in this basin, almost two-thirds live below 1,000-m elevation. Even in mountainous Bhutan, more than one-quarter of its population in the Ganges/Brahmaputra basin lives at an elevation below 1000 m.

On a global scale, the countries of this region encompass some of the world's poorest and least developed areas, alongside areas that are also experiencing rapid economic growth. The region is characterized by relatively low shares of the population living in cities.

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[2] In Bangladesh, furthermore, nearly 60 percent of the population lives within 10 m of sea level and contiguous to the seacoast.

TABLE 3.2 Population in the Ganges/Brahmaputra and Indus Basins, by Elevation and Country

Country/Basin		**<1,000 m**	**1,000 to 4,000 m**	**>4,000 m**
Afghanistan	Population in Indus Basin	1,701,185	8,901,679	33,290
	Share of basin population living in elevation zone	16.0%	83.7%	0.3%
Bhutan	Population in Ganges/Brahmaputra Basin	193,974	496,887	8,986
	Share of basin population living in elevation zone	27.7%	71.0%	1.3%
Bangladesh	Population in Ganges/Brahmaputra Basin	103,326,928	—	—
	Share of basin population living in elevation zone	100.0%	—	—
China	Population in Ganges/Brahmaputra Basin	1,433	866,630	844,082
	Population in Indus Basin	—	1,084	34,501
	Share of basin population living in elevation zone	0.08%	49.6%	50.3%
India	Population in Ganges/Brahmaputra Basin	459,157,952	7,502,996	77,447
	Population in Indus Basin	26,539,558	9,431,329	103,821
	Share of basin population living in elevation zone	96.6%	3.4%	0.04%
Nepal	Population in Ganges/Brahmaputra Basin	19,239,788	9,604,421	107,634
	Share of basin population living in elevation zone	66.5%	33.2%	0.4%
Pakistan	Population in Indus Basin	134,747,024	13,159,600	197,836
	Share of basin population living in elevation zone	91.0%	8.9%	0.1%
Total population in Ganges/Brahmaputra Basin		581,920,075	18,470,934	1,038,149
Total population in Indus Basin		162,987,767	31,493,692	369,448
TOTAL		744,907,842	49,964,626	1,407,597

SOURCE: Data from Landscan (2010).

In 2000, Pakistan had the greatest percentage—one-third—of its population living in cities. Despite relatively low levels of urbanization, this region is home to some of the world's largest cities: Dhaka (Bangladesh), Delhi (India), Kolkata (India), Mumbai (India), Karachi (Pakistan), Lahore (Pakistan).[3] Cities are growing rapidly, with rates of urban growth that exceed those historically found in the West. In all countries in this region, the average annual rate of change of the urban population exceeds 2 percent, in Nepal and Bhutan, the rates exceed 4 percent per year (United Nations, 2011b). Nevertheless, the pace of urbanization in this region is not historically unusual (NRC, 2003a). Urbanization may also affect water demand. Wealthier and more urban populations, for example, have different dietary possibilities and preferences than their rural

TABLE 3.3 Urban Population Projections as Percent of Total Population, by Country 2010-2050.

	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Bangladesh	28.07	30.80	33.89	37.35	41.045	44.84	48.69	52.57	56.415
Bhutan	34.71	38.54	42.40	46.23	49.97	53.62%	57.22	60.75	64.17
India	30.01	31.72	33.89	36.56	39.75	43.30	46.93	50.58	54.23
Nepal	18.62	21.58	24.78	28.18	31.74	35.47	39.38	43.42	47.56
Pakistan	35.90	37.67	39.88	42.53	45.62	49.07	52.54	55.98	59.37

SOURCE: Based on data from United Nations (2011b).

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[3] One thing that makes Asia stand out, particularly the subregions dependent on the water resources of the Indus and Ganges/Brahmaputra deltas, is the number of extremely large cities, or the phenomenon of urban "giganticism" (Preston, 1979).

counterparts, and changes in diet (e.g., toward consuming more meat) can have implications for agricultural water demand.

Rural dwellers tend to be poorer than their urban counterparts, but there is also substantial urban poverty and slum-dwelling in this region. Water supply and wastewater services in cities and towns are often underdeveloped, and many cities in the region are located in areas of high flood potential, exacerbated by poor urban drainage during monsoons (Moser and Satterthwaite, 2008). Urban poverty itself often exacerbates the development of systems for delivery of water and sanitation, as well as access to those resources when such systems are in place (Johnstone, 1997).

Nevertheless, cities serve as major magnets for migrants. Most migration takes place within country, between cities themselves, and between rural areas and cities. International migration is a small share of total migration, although some borders are effectively more fluid than others (e.g., between Bangladesh and India).[4]

Although temporary migration has long been a strategy used by families and households to accommodate climate variability (especially flooding), there is little evidence that climate change or other environmental factors (with the possible exception of long-term drought) result in major migration flows (McLeman and Smit, 2006; Tacoli, 2009). To the contrary, many countries in the region are known for their high adaptive capacity. Yet, theoretically it is possible that long-term changes to cropland and losses of livelihood could make it more difficult to earn a living from farming. Such "livelihood fragility" could affect migration over a much longer time span, albeit through a pathway that is less direct than a single climate-related event or change in the environment (Raleigh, 2011).

Migrants tend to be younger and better educated than those who do not move, and it is these nonmovers who may be regarded as most vulnerable. A recent study found that migration has implications not just for the mover but for those left behind: "Poorer households are likely to be 'trapped' in circumstances where they are at once more vulnerable to environmental change and less able to move away from it" (GO-Science, 2011). That said, those who migrate are by no means better off than the native population in their places of destination. New migrants often do not have access to land, housing, safe water and sanitation, or public services (e.g., schooling or health care).

Projected Demographic Trends

Key population-related questions of interest for this study include whether certain watersheds and elevation zones will experience higher rates of population growth than others, and how the demographic composition of those specific areas will change. Existing demographic methods, however, do not allow one to make such fine-grained projections. That being said, one thing that we do know about the distribution of future population is that countries in this region will become increasingly urbanized (Table 3.3) and that cities (which are predominantly at lower altitudes) will continue to absorb migrants in search of economic and other opportunities. Migration has the potential to serve as an adaptive strategy to environmental change—even as the cities that receive the migrants cope with their own set of economic challenges and environmental stresses and vulnerabilities (Hardoy et al., 2001). However, many complex factors beyond environmental change contribute to migration.

Country-level population projections are limited by the fact that they do not have any population-environment interactions or feedback loops built in. This will matter more as projections are made further into the future. Nevertheless, it can be said with substantial confidence that the populations of the countries in this region will grow considerably over the next few decades. India alone is projected to add nearly half a billion people to its population between 2010 and 2050 (Table 3.4). Larger populations will result in increased demand for water and may exacerbate problems of resource scarcity and vulnerability. Over the longer term, though, rates of population growth are projected to become smaller over time (see Table 3.5). The slowing of population growth will be driven by declines in fertility rates, which are in turn caused by, among other things, rising standards of living, decreases in childhood mortality rates, and better access to family planning.

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[4] The bulk of international migrants from Bangladesh, Bhutan, India, Nepal, and Pakistan stay within the region (DRC, 2007).

TABLE 3.4 Population Projections by Country (thousands) 2010-2050

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Bangladesh	148,692	158,317	167,256	175,195	181,863	187,103	190,934	193,344	194,353
Bhutan	726	784	829	867	899	924	943	956	962
India	1,224,614	1,308,221	1,386,909	1,458,958	1,523,482	1,579,802	1,627,029	1,664,519	1,692,008
Nepal	29,959	32,581	35,164	37,653	39,943	41,977	43,749	45,257	46,495
Pakistan	173,593	189,648	205,364	220,609	234,432	246,789	257,778	267,240	274,875

SOURCE: Based on data from United Nations (2011b).

PATTERNS OF WATER USE

Types of Water Use

There are many ways to measure water use, and care must be taken when comparing different metrics. The most common type of water use measurement, and the subject of this report, is the quantity of water withdrawn or consumed for human purposes from surface water or groundwater. This type is sometimes called "blue water" use (Falkenmark and Rockstrom, 2006; Hoekstra et al., 2011). Water withdrawal is defined as the amount of water withdrawn from surface water or groundwater for some human use. Some of this water may be returned to surface water or groundwater after use. Water consumption is typically defined as the amount of water withdrawn from surface water or groundwater that is not returned to the system, usually because it is lost to evapotranspiration, incorporated into a final product, or contaminated too badly to be reused.

"Green water" use is defined as the amount of rainwater used by natural vegetation, land cover, and agricultural production primarily through rain-fed crops (Hoekstra et al., 2011). Both green water and blue water (irrigation water) are used for agricultural production in the HKH region. If agricultural development replaces natural land cover with crops with a higher level of evapotranspiration than natural vegetation, it follows that a conversion from natural land cover to crops will decrease the amount of runoff that makes its way into surface water or groundwater.

For water to be useful, it must be available when and where it is needed. Issues of water timing are often critical for both blue and green water use. For instance, many climates have a rainy period when available water exceeds human demand and a dry period when human demand exceeds available water. Because of the mismatch between the natural hydrological cycle and human needs for water, infrastructure is often built to help societies manage water; for example, many times reservoirs are constructed to store water during wet periods for use during dry periods. Similarly, groundwater is often used in the HKH region when surface supplies are insufficient because of seasonality of water flows or short-term droughts.

Water must also be of sufficient quality to be of use, and different water uses require different qualities. Some industrial and urban water uses require high-quality waters; agriculture often uses lower quality waters. When water is highly polluted because of high salinity or concentrations of human or industrial wastes, water quality can become the limiting factor for water availability—in some parts of the HKH region, pollution may reduce overall water availability. Sometimes "gray water" use is also measured. In the water

TABLE 3.5 Population Growth Rates, by Country, 2010-2050

	2010-2015	2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050
Bangladesh	6.47%	5.65%	4.75%	3.81%	2.88%	2.05%	1.26%	0.52%
Bhutan	7.99%	5.74%	4.58%	3.69%	2.78%	2.06%	1.38%	0.63%
India	6.83%	6.01%	5.19%	4.42%	3.70%	2.99%	2.30%	1.65%
Nepal	8.75%	7.93%	7.08%	6.08%	5.09%	4.22%	3.45%	2.74%
Pakistan	9.25%	8.29%	7.42%	6.27%	5.27%	4.45%	3.67%	2.86%

SOURCE: Based on data from United Nations (2011b).

footprint system of water use accounting, gray water is defined as the amount of water needed to safely dilute a contaminant or problematic compound to a concentration at which the water will be usable for some purpose, which is increasingly important at a river basin scale (Hoekstra et al., 2011; note that this is a different concept from municipal gray water, or sullage).

Any alterations to the water quantity or quality also have the potential to negatively affect freshwater biodiversity or the natural ecosystem services they provide. Often, a certain minimum environmental flow is calculated for a watershed and its watercourses, which if left in surface water and groundwater will be sufficient to maintain freshwater biodiversity and crucial ecosystem processes (Poff et al., 2010). Necessary environmental flows vary significantly between basins depending on the hydrology and ecology.

Key Trends in Water Use

In general, the Committee found water use is greater relative to natural runoff in the Indus Basin than in the Ganges/Brahmaputra Basin, consistent with the findings of other studies (e.g., UNEP, 2008). At a national level, water use relative to availability is lowest in Bhutan and Nepal, intermediate in Bangladesh and India, and greatest in Pakistan.

National-Level Water Use Statistics

Comprehensive and consistent data on water availability and water use are not available for the HKH region, or most other regions of the world (Gleick, 2011). One of the primary sources of data for gross water availability and withdrawals is the Aquastat database maintained by the Food and Agriculture Organization of the United Nations (FAO, 2011). Aquastat data come from a variety of sources, estimates, and surveys, including national-level estimates submitted by national governments. Because of the lack of water availability and water use data, the Aquastat database contains the most widely used estimates of these quantities and is used here to assess broad patterns and trends, but should not be considered scientifically rigorous. As discussed earlier in this chapter, Bangladesh, Bhutan, India, Nepal, and Pakistan have substantial portions of their area contained within the watersheds that make up the study area. National-level water availability and use data are also available for China, but they are not considered here except in the context of the portions of the HKH watersheds shared by China.

One rough measure of water supply is the per-capita availability of water (the total average renewable water supply of a region divided by the population of that region). Another is the ratio of water withdrawals (as an indicator of demand for water) to renewable water availability (as an indicator of water supply). Of the five countries, Bhutan has the largest supply of water, both relative to water withdrawals and on a per-capita basis. Total internal renewable water supply is 78 billion m^3 yr^{-1}, and because Bhutan is located high in the Himalayas, there is no significant flow into the country from elsewhere. Total per-capita available water remains high but has fallen slightly over time with population, from 174,000 m^3 $person^{-1}$ yr^{-1} in 1992 to 109,000 m^3 $person^{-1}$ yr^{-1} in 2009 as its population has grown. Total water withdrawals were 0.34 billion m^3 yr^{-1} in 2009, or around 470 m^3 $person^{-1}$ yr^{-1}.

As a downstream nation, Bangladesh has greater reliance on external water supplies relative to water withdrawals (Figure 3.2). Total internal renewable water supply is about 100 billion m^3 yr^{-1}, supplemented by another 1.1 trillion m^3 yr^{-1} of water that flows in from outside the country. Total per-capita available water has fallen from approximately 10,000 m^3 $person^{-1}$ yr^{-1} in 1992 to 7,700 m^3 $person^{-1}$ yr^{-1} in 2008. Total water withdrawals were 36 billion m^3 yr^{-1} in 2008, or around 220 m^3 $person^{-1}$ yr^{-1}.

India's water withdrawals are closer to water availability than most other countries in the region (Figure 3.2). Total internal renewable water supply is 1,400 billion m^3 yr^{-1}, supplemented by another 640 billion m^3 yr^{-1} of water that flows in from outside the country. Total per-capita available water has fallen from 2,100 $m^3 person^{-1}$ yr^{-1} in 1992 to 1,600 $m^3 person^{-1}$ yr^{-1} in 2008. Total water withdrawals are increasing from 500 billion m^3 yr^{-1} in 1990 to 760 billion m^3 yr^{-1} in 2010, or from around 560 m^3 $person^{-1} yr^{-1}$ in 1990 to 640 m^3 $person^{-1}$ yr^{-1} in 2010. India contains several large watersheds and these national average figures hide significant regional variations. In some basins, total water demands are approaching, or may have reached, the limits of renewable water availability. In other basins, water use already depends on nonrenewable extraction of groundwater resources, which is unsustainable in the long run.

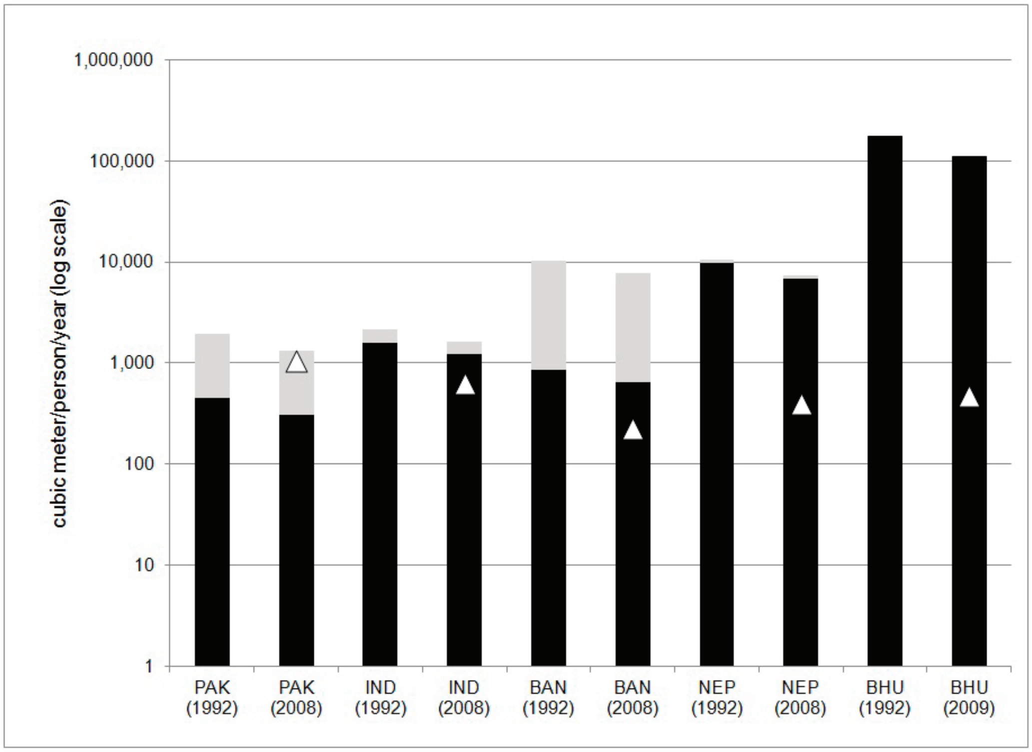

FIGURE 3.2 Available per-capita water and per-capita water withdrawal for countries in the study region. Countries are arranged from greater relative water stress (left) to less relative water stress (right). Note the logarithmic scale on the *y*-axis. Available per-capita water is shown as a stacked bar-chart for two points in time, showing the portion of available water that originates within a country (internal, black) or that originates in headwaters located in another country (external, gray). The per-capita withdrawal information is shown as a white triangle for the most current time point. PAK= Pakistan, IND= India, BAN= Bangladesh, NEP= Nepal, and BHU= Bhutan. For Nepal, per-capita withdrawal information was available only for the year 2002. For India, per-capita withdrawal information was linear interpolated between the years 2002 and 2010, to estimate the value in 2008. SOURCE: Based on data from FAO (2011).

Nepal has a substantial supply of water in both absolute terms and relative to water withdrawals, on a per-capita basis (Figure 3.2). Total internal renewable water supply is about 200 billion $m^3\ yr^{-1}$, supplemented by another 12 billion $m^3\ yr^{-1}$ of water that flows in from outside the country. Total per-capita available water has fallen from approximately 10,500 $m^3 person^{-1}\ yr^{-1}$ in 1992 to 7,300 $m^3\ person^{-1}\ yr^{-1}$ in 2008 because of population growth. Total water withdrawals were 10 billion $m^3\ yr^{-1}$ in 2000, or around 390 $m^3\ person^{-1}\ yr^{-1}$ in 2002.

Pakistan's internal water supplies are very limited relative to water withdrawals, on a per-capita basis (Figure 3.2). Total internal renewable water supply is only 55 billion $m^3\ yr^{-1}$, supplemented by another 180 billion $m^3\ yr^{-1}$ of water that flows in from outside the country. Population growth has reduced total per-capita available water, which has fallen from 1,900 $m^3\ person^{-1}\ yr^{-1}$ in 1992 to 1,300 $m^3\ person^{-1}\ yr^{-1}$ in 2008. Total water withdrawals have increased from 160 billion $m^3\ yr^{-1}$ in 1990 to 180 billion $m^3\ yr^{-1}$ in 2008, but on a per-capita basis have fallen from around 1,300 $m^3\ person^{-1}\ yr^{-1}$ in 1990 to 1,000 $m^3\ person^{-1}\ yr^{-1}$ in 2008. Pakistan would not be able to meet its water withdrawal demand without external water resources, primarily from rivers that flow from India into the Indus, as allocated by the Indus Waters Treaty.

National water availability and use data for China are uninformative for this study, because they are dominated by regions of the country outside the HKH study area. Nevertheless, China is the upstream nation on major watersheds of the HKH region; the Tibetan Plateau encompasses the origins of the Ganges (whose headwaters are mostly in India), the Brahmaputra (which joins the Ganges in Bangladesh), and the Indus Rivers. Thus, China can influence the long-term regional management of these rivers. In addition, the Chinese government has announced plans for "leapfrog development" in the Tibetan Plateau, including improving the economic status of farmers and herders and providing services such as education, health, and social security—with the express purposes of achieving stability and national unity (Xinhua News, 2010). Mining, which requires water (see Xiang [2010] for a study of mining effects on river water quality in Tibet), and hydroelectric dams are part of planned development in the Tibetan region (Watts, 2010). In addition, Chinese plans to divert some regional water resources from the south to its northern regions will also play a role in future regional water politics (Turner, 2011). Further analysis of how climate factors, including glacial retreat, may influence Chinese needs for water and Chinese water policies is needed.

Water for Irrigation

In most countries, the largest sector of water use is the agricultural sector, which withdraws, and consumes through evapotranspiration, large quantities of water for irrigation. The general trend throughout the study area is for increased irrigation water withdrawals to put increasing strain on hydrological supplies of available water. See Box 3.1 for a historical overview of early and modern irrigation systems.

Irrigated area in the study region is shown in Figure 3.3. According to the Global Map of Irrigated Area (Siebert et al., 2007), which is nominally for around the year 2000, irrigation is widespread in the Indus Basin, with a total of 15 million ha equipped for irrigation, the vast majority of which is in Pakistan. However, the national- and basin-level data are rough estimates. According to FAO Aquastat data, Pakistan had about 16 million ha equipped for irrigation in 1990, which had risen to 20 million ha by 2008. Total Pakistan agricultural water withdrawal went from 150 billion $m^3\ yr^{-1}$ in 1991 to 170 billion $m^3\ yr^{-1}$ in 2008, or from 9,600 $m^3\ ha^{-1}\ yr^{-1}$ in 1991 to 8,600 $m^3\ ha^{-1}\ yr^{-1}$ in 2008.

Another useful large-scale dataset (Hoekstra and Mekonnen, 2011) provides estimates of water con-

BOX 3.1 Early and Modern Irrigation Systems

The history of irrigated agriculture in the region goes back to Harappan civilization during the Bronze Age in the greater Indus Basin and adjacent areas. Early irrigators relied on shallow wells, flood inundation canals, and simple diversions from adjacent streams to water farmlands in arid and semiarid regions. With time and the advent of canals, surface waters could be delivered to arable lands that were less proximate to surface-water courses. Canal irrigation expanded most dramatically in South Asia during the 19th and 20th centuries. Canals also allowed irrigators some control over the timing and quantity of water applied to cropland. Groundwater initially became a source of irrigation supply with the development of simple water lifting devices powered by humans and animals. The use of groundwater for irrigation allowed lands to be irrigated in dry seasons during drought periods when surface supplies were diminished or absent altogether.

The Persians were early groundwater innovators who developed the *Qanat* or *Karez* system of tapping and conveying groundwater. This system required the drilling of multiple wells into alluvial water-bearing formations in foothill environments and then constructing a tunnel that conveyed water underground to elaborate surface-water distribution systems on the plains. This clever system, which is still used in some locations in the Middle East and South Asia (Mustafa, 2011), permitted the extraction of groundwater by gravity and avoided the need to lift the water from the wells. This system required a high level of community cohesion to operate effectively.

Much later electrical and diesel pumps were developed that allowed water to be lifted from wells in substantial quantities. Early pumps were limited in the depth from which they could lift water but the later development of modern submersible pumps allowed the pumping of groundwater from great depths. Simultaneously, small inexpensive pumps were developed that allowed growers to lift water to irrigate small farm acreage (Shah, 2009).

Again, historically water was applied through simple flood irrigation technologies where fields were flooded at times of high water. Flood irrigation was replaced in many parts of the world by furrow and basin irrigation that allowed the grower more control over the timing and quantities of water application. Over the last 75 years of the 20th century, closed conduit irrigation systems were increasingly developed and employed. These systems, which include various types of sprinklers and, later, drip and sprinkler irrigation systems, allow water to be applied with great precision. These systems are particularly well adapted to irrigate loose agricultural soils where control of infiltration rates is very important in determining irrigation efficiency, and have substantial additional potential. By contrast, surface application systems such as furrows and basins are best suited for farming operations on tight soils where infiltration rates are low and tend to be more constant, particularly where precision land leveling and watercourse improvements were adopted. Modern irrigation technology has resulted in more extensive and more efficient irrigation, particularly when linked with institutional and management reforms. Yet, in many instances, such as South Asia, it has increased the pressure on both surface water and groundwater sources and even threatened the long-term sustainability of the basic water resource (e.g., because of soil and water salinity; CAST, 1988; cf. extensive publications on irrigation in South Asia by the International Water Management Institute).

sumption by basin for irrigation of different crops. Around 120 billion $m^3 yr^{-1}$ of irrigation water were estimated to be consumed through evapotranspiration in the Indus. Total consumptive water use for irrigation is approximately 100 billion $m^3 yr^{-1}$ for the Ganges, much greater than the 1.4 billion $m^3 yr^{-1}$ for the Brahmaputra. More than a third of irrigation water consumed is used for wheat, with rice taking just under a third of the remaining water. Compared with the other basins in the study area, a relatively large amount of irrigated water consumption in the Indus Basin is for cotton production, along with rice, sugarcane, and wheat. In the Brahmaputra Basin, by comparison, around 75 percent of irrigated water was used to grow rice.

Irrigation is very common in the Ganges and less common in the Brahmaputra Basin. The overall Ganges/Brahmaputra Basin supported 29 million ha of area equipped for irrigation around the year 2000, primarily in India but also in Bangladesh. Nepal has much more limited irrigated area because of its climate and topography. According to Aquastat data, India had a total of 62 million ha equipped for irrigation in 2001, which had risen to 66 million ha by 2008. Total Indian agricultural water withdrawal increased from 560 billion $m^3 yr^{-1}$ in 2000 to 690 billion $m^3 yr^{-1}$ in 2008, or from 9,000 $m^3 ha^{-1} yr^{-1}$ in 2000 to 10,400 $m^3 ha^{-1} yr^{-1}$ in 2008. Bangladesh had 5 million ha equipped for irrigation in 2008. Total Bangladeshi agricultural water withdrawal was 32 billion $m^3 yr^{-1}$ in 2008, or around 6,300 $m^3 ha^{-1} yr^{-1}$. Assuming the average Indian application rate of 9,000 $m^3 ha^{-1} yr^{-1}$ in 2000 is accurate for the irrigated area in the Ganges/Brahmaputra Basin, total withdrawals in 2000 were 260 billion $m^3 yr^{-1}$.

There is very little irrigation in the upstream nations of the Himalayan plateau region (Figure 3.3). The only exception seems to be near Koko Nor (Qinghai) Lake in the Tibetan Plateau and the far northern portions of the study area, which includes parts of northwest Gansu Province of China. Because this small amount of irrigated area is dwarfed by irrigated areas elsewhere in China, the Aquastat statistics on overall irrigation in China are not informative.

Groundwater and surface water are frequently substitutes for each other. There are many historical examples in which emerging shortages in surface-water supplies have been offset by increased reliance on groundwater and vice versa. It would not be unreasonable, therefore, to consider further groundwater development and use as a potential response to surface-water shortfalls that might ultimately occur because of changes in the rates and magnitudes of glacial melt.

Today, groundwater use is the focus of what Shah (2009) characterizes as a “colossal anarchy.” The need to feed a growing population and agricultural markets has resulted in intense pressure to farm arable land as extensively and intensively as possible. In India, this has caused a transition away from the established large-scale irrigated agriculture that relied on water deliveries through canals and irrigation systems that were managed in a more centralized bureaucratic way. The combination of land scarcity, the availability of small, inexpensive pumps that can be used to extract groundwater, and subsidized electricity has led to a situation in which approximately 22 million farmers in India, for example, are pumping groundwater in an individualistically competitive fashion to intensively irrigate relatively small plots of land. The resultant levels of groundwater overdraft are significant. Thus, for example, Rodell et al. (2009) estimated that between 2002 and 2008, groundwater extraction in three Indian states (Rajasthan, Punjab, and Haryana) exceeded recharge by 18 billion $m^3 yr^{-1}$ (Rodell et al., 2009). This estimate is consistent with the empirical data referred to in the previous chapter that documents the magnitude of groundwater overdraft. It is clear that current levels of groundwater overdraft cannot be sustained and efforts to “tame the anarchy” have not been especially successful to date (Shah, 2009).

Groundwater is managed in accord with the dictates of irrigated agriculture. As in other parts of the world, the price of water includes no scarcity value for the water itself and consists solely of the costs of extraction. Even extractive costs are at levels less than their true value (or cost) because the cost of the energy has been subsidized in various ways by governments. This results in an array of water prices that significantly understate the real value of the water, sending, in turn, false signals to consumers about its relative scarcity. That is, the prevailing prices signal irrigators that water is more plentiful than it is in fact. The consequence is that cropping patterns are not always appropriate and the quantities of water applied are more than they would be if the water was appropriately priced.

FIGURE 3.3 Fraction of the land equipped for irrigation in the HKH region. Irrigation is widespread in both the Indus and Ganges/Brahmaputra basins. A relatively large amount of irrigated water consumption in the Indus Basin is for cotton production. In the Brahmaputra Basin, by comparison, irrigation water use is dominated by rice production, while in the Ganges Basin, irrigated water is used primarily for wheat production.

At least two factors militate against bringing extractions into some reasonable balance with recharge. First, the sheer numbers of extractors mean that the transaction costs associated with any of the conventional forms of groundwater regulation such as pump taxes (prices) and supervised pumping quotas would be enormous and would outweigh any likely benefits of such regulation. Second, groundwater extractors could collectively represent a significant political force that would resist any attempts by government to require or induce reductions in the quantities of groundwater extracted or energy subsidized. An additional and potentially problematic feature of this situation is that successful efforts at groundwater regulation, whether by pricing, pump quotas and other means such as the control of complementary inputs, would condemn large numbers of people who currently survive by irrigating small plots with groundwater to poverty (Shah, 2009). Thus, India's groundwater economy is very likely to become a source of additional demands for surface water as elements of the groundwater resource become economically exhausted. Indeed, the consequences of such economic exhaustion are thought to be so severe that a contested plan has been proposed to link the Himalayan rivers with the peninsular rivers of India, which would allow the import of some 200 km^3 annually to southern and western India to offset the effects of overdraft (Shah, 2009; Supreme Court of India, 2012; cf. Iyer, 2012).

Water Use in Other Sectors

In most countries, the sector that makes the most withdrawals after agriculture is the municipal and industrial sector. In some regions, withdrawals for electric power production and cooling are predominant, though urban withdrawals are increasingly significant. Figure 3.4 shows the location of the major cities within the study area. Most major cities in Pakistan are within the Indus Basin or draw their water from the Indus (e.g., Karachi). Kabul, Afghanistan, is also in the upper headwaters of the basin. Aquastat data estimate 2.5 billion m^{3} yr^{-1} of withdrawals for municipal purposes in Pakistan in 1991, rising to 9.7 billion m^{3} yr^{-1} in 2009, or from around 20 m^{3} person^{-1} yr^{-1} in 1992 to 54 m^{3} person^{-1} yr^{-1} in 2008. However, the per-capita statistics from Aquastat divide municipal water use by the total population of the country, not just that of urban dwellers.

Another dataset, the Global Rural/Urban Mapping Project (GRUMP) database (CIESIN, 2004), maps cities for the region. The version of this dataset developed for McDonald et al. (2011a) was used, which considered only urban agglomerations of more than 50,000 people. This dataset estimates 41.5 million urban dwellers in Pakistan in 2000. Dividing the Aquastat value for municipal withdrawal in 2000 of 6.4 billion m^{3} yr^{-1} by just this urban population, that is a use rate of 154.2 m^{3} urbanite^{-1} yr^{-1}. The GRUMP database shows 34.3 million urban dwellers in the Indus Basin, which with the above use rate would imply 5.3 billion m^{3} yr^{-1} of municipal withdrawals in the Indus Basin in 2000. This approach, however, ignores cities that are outside the Indus Basin but draw water from it through canals (cf. McDonald et al., 2011b).

The majority of the 87.9 million urban dwellers in cities > 50,000 in the Ganges Basin in 2000 were in India (69.6 million), with some in Nepal (2.6 million) or Bangladesh (15.6 million). Total urban population in India in 2000 was 234.9 million in cities > 50,000, and Aquastat lists total municipal withdrawals in 2000

FIGURE 3.4 Major urban areas in the HKH region. Urban water withdrawals are increasingly significant, and the locations of urban areas provide a rough estimate of the locations of most municipal and industrial water withdrawals.

as 42 billion m^3 yr^{-1}, which implies a use rate of 179 m^3 $urbanite^{-1}$ yr^{-1}. This would imply that total municipal withdrawals from the Ganges/Brahmaputra Basin in India in 2000 were 12.4 billion m^3 yr^{-1}. Total urban population in Bangladesh in 2000 was 23.2 million in cities > 50,000, and Aquastat lists total municipal withdrawals in 2008 as 3.6 billion m^3 yr^{-1}, which implies a use rate of 155 m^3 $urbanite^{-1}$ yr^{-1}. This would imply that total municipal withdrawals from the Ganges/Brahmaputra Basin in Bangladesh in 2000 were 2.4 billion m^3 yr^{-1}. Finally, the entire urban population of Nepal is within the Ganges/Brahmaputra Basin, and so Aquastat's estimate of total municipal withdrawals in 2000 as 0.20 billion m^3 yr^{-1} can be assumed to be all from the Ganges/Brahmaputra Basin. Bhutan's total municipal withdrawals in 2008 was 0.017 billion m^3 yr^{-1} are all from the Brahmaputra Basin.

The other major sector making water withdrawals is industry, whose spatial distribution generally follows that of urban areas. Industrial withdrawals from the Ganges/Brahmaputra in India are unknown, and country-level industrial water statistics for India as a whole can be misleading, because a significant proportion of India's industrial capacity is in other river basins. Nevertheless, India is likely the largest industrial water user in the Ganges/Brahmaputra Basin. Nepal's industrial withdrawals of 0.40 billion m^3 yr^{-1} in 2000 are all taken from the Ganges Basin, while Bhutan's industrial withdrawals of 0.003 billion m^3 yr^{-1} in 2008 are all taken from the Brahmaputra Basin. Similarly, a large portion of Bangladesh's 0.77 billion m^3 yr^{-1} in 2008 are taken from the Ganges or the Brahmaputra basins. Relatively little industrial activity happens in China in the Brahmaputra basin. The majority of Pakistan's 1.4 billion m^3 yr^{-1} of industrial withdrawals in 2008 was likely from the Indus Basin.

Water is also used to produce hydroelectricity in the region (see Figure 3.5). Although this water use is typically considered as nonconsumptive, large dams lose water to evaporation, and new dam construction will increase this consumptive use. The Committee does not provide estimates of these demands here, but notes that changes in the hydrological cycle in the Himalayas will have implications for power production and increases in temperatures will increase consumptive losses from reservoir surfaces. The Brahmaputra is the least dammed of all the major rivers in the study area, with the significant exception of the Yamzho Yumco dam in China. In contrast, both the Ganges and the Indus have a number of large dams and proposals for many more. In addition, China has plans for extensive expansion of dams on the Mekong, Salween, Irrawaddy, and other regional rivers, and Pakistan (along with donors) has long-standing plans to further dam the Indus. All of these plans have been extensively criticized for their potential disruptions.

The operation of a dam or system of dams almost always entails complex issues and trade-offs that must be anticipated. This is true because river inflows, the input to reservoir storage, are subject to hydrological variability and are thus rarely constant from year to year. It is also true because dams are rarely built to satisfy a single purpose and the allocation of reservoir outflows needs to be balanced over time and between purposes depending upon available storage. Consider a dam that holds storage for both flood control and to provide irrigation water for nearby farmlands. Common practice is to release water and draw down the storage pool in advance of the rainy and/or snowmelt season to provide storage for flood flows, thereby lessening the chances of downstream flooding. However, if the reservoir drawdown occurs in circumstances where irrigation water is unneeded and the anticipated floods fail to occur, water that could have been stored for the next irrigation season is lost. This problem requires management regimes that recognize the inherent conflicts between the purposes for which the reservoir is managed. The problems become considerably more complicated when there is more than one dam to be operated conjointly and/or there are multiple purposes to be served (Yeh and Becker, 1982). There are few river basins where there is sufficient water everywhere, all the time, to serve fully all of the various purposes and activities that require water. Typically, the resulting problems are managed by specifying a set of operating criteria under which releases from reservoirs are governed by inflows in the current and recent years, the time or season of the year, the demands for water to serve different purposes, and any legal or administrative constraints. Operating criteria will usually require revision from time to time in response to changing hydrology as well as new laws and regulations that require new management regimes (Benson, 2008). Constraints of water scarcity will likely become more intense in the future and will also

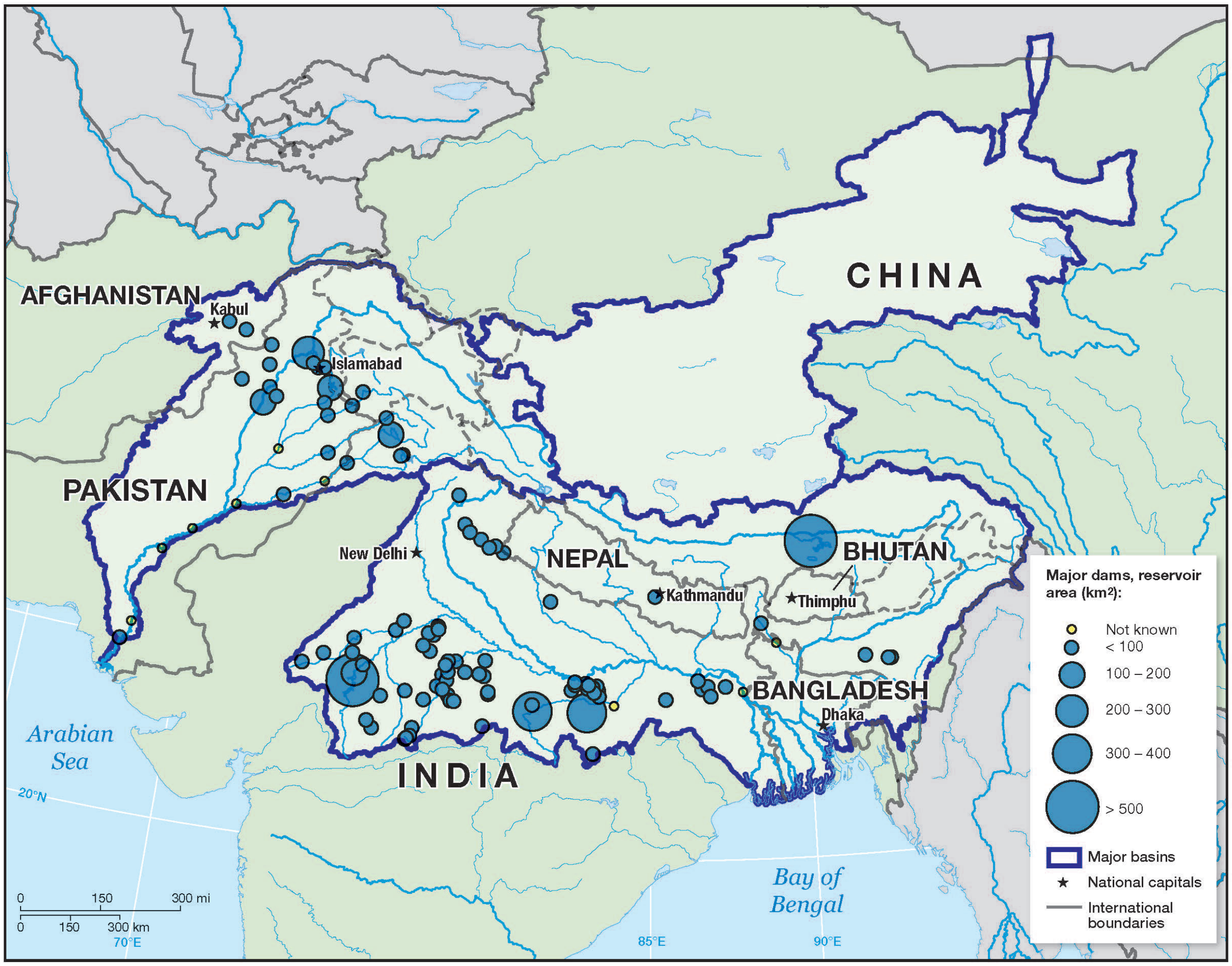

FIGURE 3.5 Dams listed in the GRAND database are shown in blue. Note that this database is not complete, and newer or smaller dams may be missing from this figure. The Brahmaputra is the least dammed of the major rivers in the study region. In contrast, both the Ganges and the Indus are highly dammed.

be manifested in times and places where they have not appeared before (Milly et al., 2008).

Projected Water-Use Trends

Water use may change in the HKH region, with implications for water scarcity. Generally, water use seems to be increasing over time in both the Indus and Ganges/Brahmaputra Basins, a trend that will likely continue over the next several decades. This alone would increase physical water scarcity without changes in human water-use practices. For instance, in India one estimate is that by 2050 Indian demands will exceed all available sources of supply, regardless of climate change (World Bank, 2006). Human water-use practices will also change. Construction of dams and other infrastructure will change water-use patterns. Rising standards of living are also likely to increase water use.

This section begins by presenting information on how water use may change for irrigation, municipal use, and industrial use. This information whenever possible is presented relevant to specific basins (i.e., Indus, Ganges/Brahmaputra), but national-level statistics for the five countries (i.e., Bangladesh, Bhutan, India, Nepal, and Pakistan) in the study area are also used. Generally, much of the focus is on water use by India, Pakistan, and Bangladesh, because Bhutan and Nepal have relatively small water withdrawals. Next is a discussion of how changes in water use will affect metrics of water scarcity in the region. The effects of climate change on water availability will be discussed in a narrative fashion; the Committee did not develop quantitative scenarios of how hydrological flows will change in each of the basins in response to climate change. The potential changes in water supply discussed earlier in this chapter could also affect water use.

Water for Irrigation

Trends in irrigation water use vary throughout the region. In some countries, irrigated crop area has been increasing, which increases water use. At the same time, in some countries average irrigation rates ($m^3\ ha^{-1}\ yr^{-1}$) have been decreasing because of more efficient applications of irrigation water or changes in the kinds of crops produced. Future trends in irrigation water use are difficult to predict and depend on (among other things) changes in farming practices, government policies toward irrigation, and the magnitude and direction of the effect of climate change on evapotranspirative demand of crops.

In the Indus Basin, approximately 15 million ha of cropland was equipped for irrigation in 2000 (Siebert et al., 2007), mostly in Pakistan. Aquastat (FAO, 2011) statistics show that between 1990 and 2008, area equipped for irrigation in Pakistan increased by 1.3 percent annually, up to 20 million ha, the vast majority of which is in the Indus Basin. If this trend continues, by 2030, Pakistan would have 25 million ha and by 2050 there would be 30 million ha. At the same time, between 1990 and 2008, the irrigation rate fell by 0.5 percent annually, to 8,600 $m^3\ ha^{-1}\ yr^{-1}$. Assuming this trend continues, by 2030, Pakistan's irrigation rate would fall to 7,500 $m^3\ ha^{-1}\ yr^{-1}$ and by 2050 would reach 6,500 $m^3\ ha^{-1}\ yr^{-1}$. The net result of such a scenario for Pakistan would be an increase in agricultural withdrawals from 170 billion $m^3\ yr^{-1}$ in 2008 to 190 billion $m^3\ yr^{-1}$ in 2030 and 195 billion $m^3\ yr^{-1}$ in 2050. Assuming that in the future a similar fraction of water withdrawals is consumed, water consumption under such a scenario would increase from around 120 billion $m^3\ yr^{-1}$ in 2000 to 128 billion $m^3\ yr^{-1}$ in 2030 and 132 billion $m^3\ yr^{-1}$ in 2050.

Whether such a scenario would be feasible depends on whether there is enough water available to meet this increased need, whether there is adequate arable land to allow continued expansion of irrigated area, and whether Pakistan can make the necessary investments in improving irrigation efficiency. Scenarios of future agricultural water use developed by Archer et al. (2010) are similar, and the authors stressed the necessity of increased water storage to allow for a continued increase in agricultural withdrawals. Moreover, agricultural withdrawal and consumption could be significantly reduced if Pakistan increased the productivity of agricultural water use, which would permit them to expand production without substantial increases in demand for water, through on-farm and basin efficiency improvements, changes in irrigation technology and management, changes in crop types, or other practices.

The overall Ganges/Brahmaputra Basin had 29 million ha of area equipped for irrigation in 2000 (Siebert et al., 2007), primarily in India and to a lesser extent Bangladesh. Nepal and Bhutan have much more limited irrigated area because of their climate and topography, a trend likely to persist into the future. India's irrigated area increased by 0.9 percent annually between 2001 and 2008, with some of the increase in the Ganges Basin and some of it elsewhere in the country. Over the same time period, India's irrigation rate has increased by around 2 percent annually, from 1995 to 2008, Bangladesh's irrigated area, which is in both the Ganges and Brahmaputra basins, increased by 2.3 percent annually. Time-series data for Bangladesh on irrigation rate are unavailable, although in 2008 it appeared to be lower than Indian rates, at around 6,300 $m^3\ ha^{-1}\ yr^{-1}$. Other pertinent data reveal that about 75 percent of total land cultivated in Bangladesh is irrigated by groundwater (Zahid and Ahmed, 2006) and that groundwater has been decreasing (Shamsudduha et al., 2009). Thus, irrigation in Bangladesh has been increasing, with noticeable effects on groundwater depletion.

Because the vast majority of irrigated area in the Ganges/Brahmaputra is in India, changes in irrigation practices in India will drive changes in the Ganges/Brahmaputra area. If the irrigated area in the overall Ganges/Brahmaputra continues expanding at the same rate as irrigated area is currently expanding in India, by 2030 there would be 39 million ha of area equipped for irrigation and by 2050 some 48 million ha. It is not clear whether there is enough room in the crowded Ganges basin for such a continued expansion, nor is it clear that there is sufficient water. If India's irrigation rate remains at 2008 levels of around 10,400 $m^3\ ha^{-1}\ yr^{-1}$, such a scenario would increase agricultural water withdrawals in the Ganges/Brahmaputra from 260 billion $m^3\ yr^{-1}$ in 2000 to 400 billion $m^3\ yr^{-1}$ in 2030 and nearly 500 billion $m^3\ yr^{-1}$ in 2050. It seems unlikely that there is enough water in the Ganges to support this level of withdrawal, particularly in the dry months (see discussion below).

This scenario for the Ganges/Brahmaputra is similar to one developed by the 2030 Water Resources Group (2009), which predicted that, if current trends continue, by 2030 Indian agricultural withdrawals would have nearly doubled from current levels. This report also notes that changes in the agricultural sector's water use also represents the most cost-effective way to reduce India's water withdrawals, especially implementation of measures that increase yields from India's cropland without increasing water applied as irrigation. Similarly, Cai et al. (2010) found that if less productive areas in India were to achieve the same water productivity as more productive areas, agricultural withdrawals could be reduced by 31 percent without reducing agricultural production.

Municipal Water Use

Trends in the municipal sector are consistent across countries, with an increasing urban population resulting in an increase in municipal withdrawals. Trends in the use rate ($m^3\ urbanite^{-1}\ yr^{-1}$) are generally not available as time series, although economic development is likely to increase this use rate over time.

In 2000, the GRUMP database (CIESIN, 2004) shows 34 million urban dwellers in the Indus Basin (cities > 50,000 people). The vast majority of these urbanites are in Pakistan, where the average urban use rate was around 150 $m^3\ urbanite^{-1}\ yr^{-1}$, a relatively high rate, which with the above use rate would imply over 5 billion $m^3\ yr^{-1}$ of municipal withdrawals in the Indus Basin in 2000. For Pakistan as a whole, urban population is projected to increase by 3.1 percent per year between 2000 and 2030, or by 2.8 percent per year between 2000 and 2050 (United Nations, 2011b). If this rate of urban population growth holds for the Indus Basin as a whole, population might grow to nearly 85 million urban dwellers (cities > 50,000 people) by 2030 and 140 million urban dwellers (cities > 50,000 people) by 2050. Assuming the urban use rate of water stays the same, expected population growth implies an increase in municipal water use to 13 billion $m^3\ yr^{-1}$ of municipal withdrawals in the Indus Basin in 2030 and 22 billion $m^3\ yr^{-1}$ of municipal withdrawals in the Indus Basin in 2050.

In 2000, there were 88 million urban dwellers in cities > 50,000 in the Ganges/Brahmaputra Basin, primarily in India (70 million) and to a lesser extent Bangladesh (16 million) (CIESIN, 2004). India had an urban use rate of 179 $m^3\ urbanite^{-1}\ yr^{-1}$, and Bangladesh had an urban use rate of 155 $m^3\ urbanite^{-1}\ yr^{-1}$. For India, urban population is projected to increase by 2.4 percent per year between 2000 and 2030, or by 1.7 percent per year between 2000 and 2050. Bangladesh is forecast to have similarly rapid urban population growth, increasing by 3.1 percent per year between 2000 and 2030, or by 2.1 percent per year between 2000 and 2050. Assuming these urban population growth rates, and that urban use rate stays the same, India's municipal withdrawals from the Ganges/Brahmaputra Basin would grow from 12 billion $m^3\ yr^{-1}$ in 2000 to 26 billion $m^3\ yr^{-1}$ in 2030 and 29 billion $m^3\ yr^{-1}$ in 2050. Similarly, Bangladesh's municipal withdrawals from this basin would grow from just over 2 billion $m^3\ yr^{-1}$ in 2000 to 6 billion $m^3\ yr^{-1}$ in 2030 and 7 billion $m^3\ yr^{-1}$ in 2050. Municipal withdrawals for Nepal and Bhutan will likely increase as well, driven by increases in urban population in these countries, although their municipal withdrawals will continue to be a very small proportion of the municipal withdrawals in the Ganges/Brahmaputra Basin.

This scenario of growth in municipal water demand in the Ganges/Brahmaputra Basin appears consistent with the scenarios developed for India by the 2030 Water Resources Group (2009). That report predicted municipal demand would double from 2000 to 2030, a slightly slower rate of growth than in the Committee's scenario of growth developed specifically for the Ganges.

Industrial Water Use

Industrial water use appears likely to increase over time, driven by increases in population and economic development. In the Aquastat database, there is little consistent trend in industrial water use per capita, with some countries increasing and some countries decreasing. However, even if water use per capita stays constant at 2008 levels, it appears likely industrial water use will continue to rise because of fast rate of population growth in many of these countries.

The majority of Pakistan's 1.4 billion $m^3 yr^{-1}$ of industrial withdrawals in 2008 was likely from the Indus Basin, and if industrial water use per capita stays the same might rise to 2.3 billion $m^3 yr^{-1}$ in 2030 and 3 billion $m^3 yr^{-1}$ in 2050. India's industrial withdrawals in the Indus are unknown, but are likely smaller than Pakistan's, because few major Indian cities are located in the Indus Basin.

Trends in India's industrial withdrawals from the Ganges/Brahmaputra are unknown, but are likely increasing over time. One study by the 2030 Water Resources Group (2009) suggests that industrial withdrawals for all of India will quadruple, reaching 196 billion $m^3 yr^{-1}$ in 2030. A large portion of Bangladesh's 0.8 billion $m^3 yr^{-1}$ of industrial withdrawal in 2008 was taken from the Ganges/Brahmaputra Basin and, if industrial water use per capita stays the same, might rise to 1.1 billion $m^3 yr^{-1}$ in 2030 and 1.2 billion $m^3 yr^{-1}$ in 2050. Similarly, Nepal's industrial withdrawals of 0.4 billion $m^3 yr^{-1}$ in 2000 are all taken from the Ganges Basin, and if industrial water use per capita stays the same might rise to 0.6 billion $m^3 yr^{-1}$ in 2030 and 0.7 billion $m^3 yr^{-1}$ in 2050. Bhutan uses a relatively trivial amount of water for industrial purposes, a trend that is likely to continue.

Trends in Water Scarcity

As discussed in Chapter 3, we primarily present simple metrics of physical water scarcity. This approach is driven by the limited data available for more sophisticated measures that take into account, for example, economic water scarcity or water quality issues. However, we stress that these other issues may be important and deserve future study. Levels of water stress in the future will also be affected by adjustments to human behavior or technological interventions to make existing water use more efficient, both of which are difficult to predict.

Even without climate change affecting water availability in the study area, many countries would have a significant challenge providing enough water to meet their needs under traditional projections. In this section, the Committee explores how some metrics of water scarcity will change with increases in population and water use as well as with climate change. Because quantitative scenarios of how the hydrological cycle will be affected by climate change were beyond the scope of this report, most of the discussion of climate change is narrative, describing the likely direction of change.

As noted earlier, the simplest way to define physical water scarcity is to take the amount of water in a region and divide by the population. One common set of thresholds defines regions with more than 1,700 $m^3 person^{-1} yr^{-1}$ as "water sufficient," while those below this threshold have some degree of water stress (<1,700 $m^3 person^{-1} yr^{-1}$), chronic scarcity (<1,000 $m^3 person^{-1} yr^{-1}$), or absolute scarcity (<500 $m^3 person^{-1} yr^{-1}$) (Falkenmark, 1989; Falkenmark and Lindh, 1974; Falkenmark and Widstrand, 1992; Falkenmark et al., 1989). Using this metric, with population growth (ignoring potential changes in water availability) Pakistan will move from water stress in 2000 (1,400 $m^3 person^{-1} yr^{-1}$) to chronic scarcity in 2030 (900 $m^3 person^{-1} yr^{-1}$) and 2050 (700 $m^3 person^{-1} yr^{-1}$), even without factoring in climatic changes to regional hydrology. Any reductions in flow in the Indus caused by climate change would further intensify this scarcity. The next driest country by this metric is India, which stays classified as water stressed but moves from 1,600 $m^3 person^{-1} yr^{-1}$ in 2009 to 1,300 $m^3 person^{-1} yr^{-1}$ in 2030 and 1,200 $m^3 person^{-1} yr^{-1}$ in 2050. By this simple measure, and ignoring potential changes in water availability, Bangladesh, Bhutan, and Nepal remain classed as water sufficient through 2050.

Another way to define physical scarcity is the ratio of water use to water availability. By this metric, and ignoring potential changes to water availability, the Indus Basin seems the most likely of any of the study area basins to face problems of water scarcity (Figure 3.6). Significant increases in irrigation water use in this basin, particularly during the dry months of November to March, may result in essentially all flow in these months being used for irrigation. Increased irrigation water use in the Ganges, particularly in the dry period of November to May, may likewise result in essentially all flow in these months being used for irrigation (Figure 3.7). One potential response by policy makers would be to attempt to increase storage during the monsoon season so that water would be available for irrigation during the dry season. Even with increases in irrigation water use by Bangladesh, the Brahmaputra

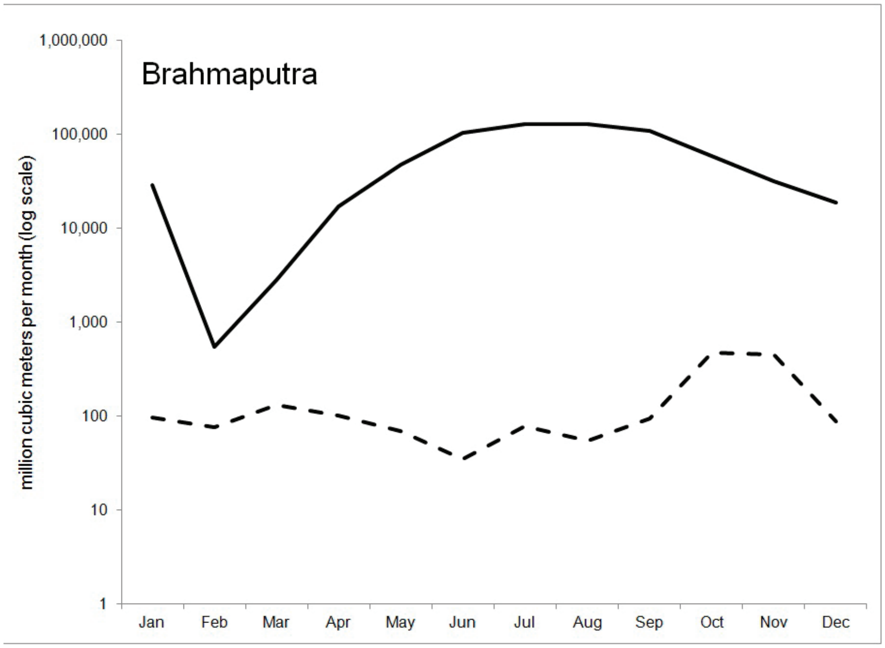

FIGURE 3.6 Natural runoff (solid line) and blue water consumed (dashed line) per month for the Brahmaputra. Note that the *y*-axis is a log scale. The Brahmaputra has very little water scarcity, except in February and March, although water consumption still does not exceed natural runoff during those months. The large spike in natural runoff in the period June to September corresponds to the monsoon period. SOURCE: Based on data from Hoekstra and Mekonnen (2011).

Basin seems less likely to be water stressed according to this metric, except for a brief dry period in February and March (Figure 3.6).

The picture that emerges is nevertheless one in which water scarcity, be it generalized or seasonal, will intensify in the coming decades. Climate change will also influence the extent and severity of intensifying

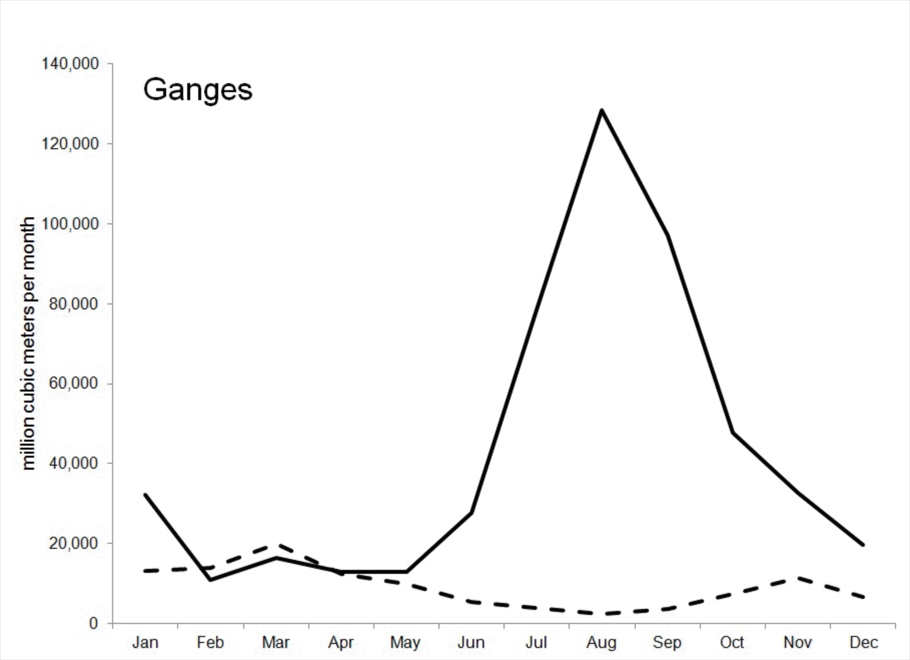

FIGURE 3.7 Natural run-off (solid line) and blue water (dashed line) consumed per month for the Ganges. The Ganges has very little water scarcity, except in February and March, when water consumption exceeds natural runoff. The large spike in natural runoff in August corresponds to the monsoon period. SOURCE: Based on data from Hoekstra and Mekonnen (2011).

scarcity. It follows, then, that one means of addressing potential changes in hydrological circumstances that are uncertain is to ensure that current water management practices are as effective and equitable as possible. This means making all efforts to increase and maintain the productivity of water that is currently available. Such productivity increases need to be sought for both consumptive and in-stream uses. Thus, for example, employment of more rational water pricing practices and the development of flexible schemes of water allocation that will allow droughts and unanticipated shortfalls to be managed in both a timely and effective way could strengthen the capacity of the region to manage its water resources more effectively in the face of climate change and other hydrological uncertainties.

CLEAN WATER AND SANITATION ACCESS

A basic measure of water development and conditions is access to improved drinking water and sanitation systems, as measured by the United Nations on a regular basis. This measure forms the standard by which the water-related Millennium Development Goals were set. Political and social stability is affected by the societal capacity to cope with and adapt to large- and small-scale changes in water availability that may result from glacial retreat and other impacts of climate change on the hydrological system. This societal capacity, often called vulnerability or resilience, depends on conditions that promote human well-being generally. The water-related aspects commonly measured include water availability or scarcity (discussed in the next section) and clean water and sanitation, which are important for human health and general well-being.

Countries in Africa have the most serious problems in terms of the fraction of population without access to these basic water services, but Asia has the largest absolute number of people without access (hundreds of millions), with a wide divergence among countries and within countries. Table 3.6 shows the fraction of the populations in countries of the region with access to "improved drinking" water systems and "improved sanitation" systems, as of 2008 (WHO/UNICEF, 2010). As these data show, urban dwellers are typically more reliably served than rural dwellers, and access to water is typically higher than access to sanitation. However, national-level estimates of improved water and sanitation, even when stratified by urban and rural residence, tend to mask considerable spatial variation in access. Data from the nationally representative Demographic and Health Surveys (DHS),[5] for example, suggest that there is greater variation in access to clean water and sanitation in rural districts than urban districts. It is possible, in principle, to use these data to create district-level mappings of access to clean water and sanitation. This could provide finer-grained insight into the geographic distribution of water-related need and vulnerability, including by river basin and proximity to the Himalayas.

TABLE 3.6 Share of Population with Access to Improved Drinking Water and Sanitation, by Country

	Improved Drinking Water			**Improved Sanitation**		
	Urban	**Rural**	**Total**	**Urban**	**Rural**	**Total**
Afghanistan	78	39	48	60	30	37
Bangladesh	85	78	80	56	52	53
Bhutan	99	88	92	87	54	65
China	98	82	89	58	52	55
India	96	84	88	54	21	31
Nepal	93	87	88	51	27	31
Pakistan	95	87	90	72	29	45

SOURCE: Data from WHO/UNICEF (2010).

MEASURING WATER SCARCITY

With the preceding analysis in mind, it is not surprising that there are many different ways to measure water scarcity. Water scarcity can occur when problems of water quantity, water quality, or timing mean there is not enough water to meet people's wants. Scarcity in the physical sense is often defined in terms of arbitrary but useful criteria such as those discussed in the next paragraph. Economic scarcity is customarily defined in terms of the cost of making water available and a willingness to pay. One significant manifestation of economic scarcity is the economic exhaustion of groundwater, which contrasts with physical exhaustion, as explained in Box 3.2. In this section, we focus on simple measures of physical water scarcity, primarily because they are easy to estimate from available data.

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[5] Data available at *http://www.measuredhs.com/data/available-datasets.cfm*.

BOX 3.2 Economic Exhaustion Of Groundwater

Groundwater is an important element of hydrological systems throughout the world. It is known to be a significant, if not completely understood, part of the hydrology of the Himalayas, the Ganges Plain to the south, and the southern Peninsula of India (Bookhagen, 2012; Shah, 2009). Over time, extractions of water from an aquifer must be roughly equal to recharge if the aquifer is to remain economically viable. Overdraft is the situation in which extractions exceed recharge. Overdraft itself is not problematic as long as periods of intermittent overdraft are punctuated with periods in which recharge exceeds extractions and the aquifer recovers. Over such periods of time the aquifer is in equilibrium. Circumstances characterized by persistent overdraft are not sustainable in the sense that extraction cannot be economically viable indefinitely. Where extractions are consistently greater by volume than recharge, the water table falls and the elevation from which water must be extracted grows.

The costs of groundwater extraction include the costs of needed energy and those costs are highly sensitive to the depths from which the groundwater must be pumped. As the water table is drawn down through overdraft the costs of extraction rise. Ultimately, these costs rise to the point where it is no longer economically feasible to continue pumping and the extractor or extractors in question cease to pump. In some instances this will allow the aquifer to recover as recharge then exceeds extraction. There are other instances where the storage capacity of the aquifer is altered (consolidated) or rates of recharge are very small or nonexistent, that it is no longer economical for any extractor to withdraw water. At this point the aquifer is said to be economically exhausted. Economic exhaustion is not necessarily identical to physical exhaustion, however, because pumping depths from which extractions are no longer economically feasible can be significantly smaller than the pumping depths that would prevail if all of the water in the aquifer were extracted. These latter circumstances constitute physical exhaustion (Glennon, 2002; NRC, 1997).

Such an approach, however, should not be taken to imply that other facets of water scarcity are not also extremely important to human livelihoods.

Perhaps the most common metric of physical water scarcity, and certainly the simplest to calculate, is to take the average amount of water in a region and divide by the population (Falkenmark, 1989; Falkenmark and Lindh, 1974; Falkenmark and Widstrand, 1992; Falkenmark et al., 1989). These indexes usually define regions with more than 1,700 m^3 $person^{-1}$ yr^{-1} as water sufficient, while those below this threshold had some degree of water stress (<1,700 m^3 $person^{-1}$ yr^{-1}), chronic scarcity (<1,000 m^3 $person^{-1}$ yr^{-1}), or absolute scarcity (<500 m^3 $person^{-1}$ yr^{-1}). By this simple measure, Bangladesh, Bhutan, and Nepal are classed as water sufficient, and Pakistan and India are classed as water stressed. As noted above, these national averages hide important regional differences. Additionally, the thresholds are somewhat arbitrary, and this measure of water scarcity does not account for water that flows across a border and it ignores different uses of water in different climates.

Another common, but more descriptive, way to consider physical water scarcity is to look at the ratio of water withdrawals or consumption to total water available, which is defined as natural streamflow by Hoekstra and Mekonnen (2011). Figure 3.6 shows estimates of natural runoff and water consumption for the Brahmaputra basin, on a monthly time step. This river has very little water scarcity, except in February and March, and even then, water consumption does not exceed natural runoff. The large spike in water available in the period June to September corresponds to the monsoon period of the year.

The Ganges basin (Figure 3.7) has a similar annual pattern, but water consumption exceeds natural runoff for February and March. There is also a sharper peak in natural runoff in the single month of August.

Finally, the Indus Basin (Figure 3.8) has a much higher percentage of the natural runoff consumed over the whole year than the Ganges or the Brahmaputra basin, with the percentage highest in the period October to March. However, water consumption does not exceed natural runoff in any month for the Indus, in contrast with the Ganges.

More sophisticated measures of water scarcity are available in the literature. Sometimes measures of scarcity explicitly set aside a portion of available flow as an environmental flow (EF). Sometimes issues of water quality are also considered, which can be a limiting factor for many applications (McDonald et al., 2011a). Similarly, measures of water scarcity sometimes incorporate information on how well water is actually delivered to people. In many cities, for instance, a substantial fraction of people live in neighborhoods without consistent access to safe drinking water, simply because infrastructure is absent (UN-HABITAT, 2006).

Because data are sparse, it is not clear how increased glacial melt will affect total runoff. However, it could

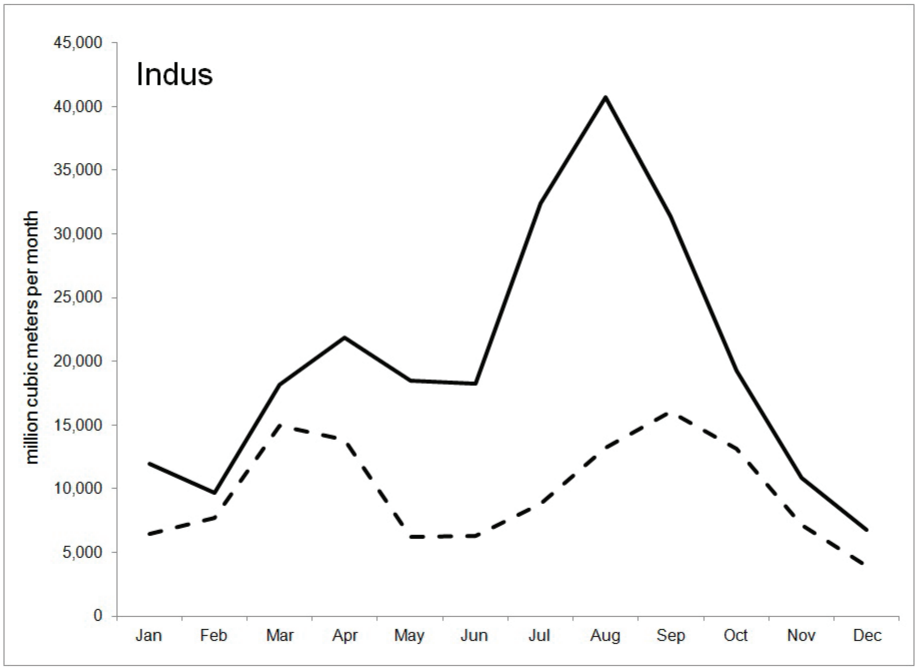

FIGURE 3.8 Natural runoff (solid line) and blue water consumed (dashed line) per month for the Indus. A higher percentage of the natural runoff is consumed than for the Ganges or the Brahmaputra basin, with the percentage highest in the period October to March. Water consumption does not exceed natural runoff in any month for the Indus. SOURCE: Based on data from Hoekstra and Mekonnen (2011).

affect the timing of runoff, which would in turn affect the ratio of water consumption to natural runoff. For example, in the Brahmaputra, if the change in runoff due to glacial melt occurs in February and March, there would be a larger change in the ratio. If the runoff were to change during the monsoon peak between June and September, there could also be issues with flooding.

WATER MANAGEMENT, INSTITUTIONS, AND HYDROCLIMATE CHANGE

The water-use patterns described above are mediated by institutions at multiple levels in the region — from international to national, state, and local water management, and from mountain headwaters to plains and coastal environments. In addition to multiple levels of management, water institutions span a range of subsectors from irrigation to domestic, industrial, and environmental uses that often have separate agencies housed under different ministries, and whose perspectives vary on hydroclimate change. Although a full description, let alone discussion, of these complex water management systems lies beyond the scope of this report, this section highlights patterns in the relationships between climate change and water management in South Asia. Institutions that focus more on disasters (e.g., devastating floods, droughts, and GLOFs), vis-à-vis water management more broadly, are addressed under the rubric of environmental security in Chapter 4.

Increasing International Assessment

Considerable progress has been made in assessing water resources implications of climate change in South Asia at international and national levels of analysis over the past decade. Some advances have come about through regional intergovernmental organizations (IGOs) such as the South Asian Association for Regional Cooperation (SAARC[6]), whereas others stem from multilateral donor-sponsored initiatives. Regional IGOs such as SAARC are devoting increasing attention to climate change, extreme events, and disaster risk reduction (e.g., SAARC; cf. also Regional Integrated Multi-Hazard Early Warning System for Africa and

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[6] *http://saarc-sdmc.nic.in/.*

Asia [RIMES],[7] which is an association of country hydrometeorological agency directors in the greater Indian Ocean region). Water management remains a sensitive topic that has historically been addressed through bilateral relations, although a 2012 SAARC-Chamber of Commerce and Industry conference dealt with climate, energy, and water, and SAARC is increasingly active in addressing hydroclimate disaster preparedness.

Comparative international water resources analysis is also advancing through the work of the South Asia Water Initiative which convenes countries in the region to analyze water management issues related to climate change (SAWI, 2011). The World Bank has conducted substantial analytical studies of water management and climate risk in several countries and basins in the region (Pahuja et al., 2010; Sadoff and Rao, 2011; Yu, 2010). These studies are helping increase awareness, analysis, and cooperation.

Among international nongovernmental organizations contributing to these advances, the Asia-Pacific Network for Climate Change organized an early study of water resources impacts of climate change in South Asia (APN, 2004). More recently, ICIMOD has supported cooperative international programs on snow and ice hydrology in the Himalayan region (e.g., ICIMOD's INDUS[8] and HKH-HYCOS[9] programs). Other international nongovernmental organizations (NGOs) have undertaken comparative case study analyses of water management in the context of climate change across the region (e.g., ISET, 2008; Moench and Dixit, 2004; see also the International Water Management Institute [IWMI] website[10]).

Formulation of National Water and Climate Policies

Several countries have articulated national water policies related to climate change. In 2012, India issued a new Draft Water Policy that includes numerous references to and a major section on adaptation to climate change (Government of India, 2012). The Ministry of Water Resources (2009-2011) earlier published a two-volume work that compiled *Comprehensive Mission Documents for a National Water Mission Under National Action Plan on Climate Change* (Government of India, 2009). Following a summary of recommendations, it presented supporting documents on the current policy context of water management, surface water, groundwater, and basin planning for climate change.

Bangladesh has joint concerns about the coastal hazards of climate change, inflows from major international rivers and tributaries, and domestic hydroclimate risks. To address these issues Bangladesh created an interagency Institute of Water Modeling chaired by the Ministry of Water Resources as a center of climate change modeling, and a Climate Change Cell[11] for adaptation and mitigation programs including irrigation agriculture under the Ministry of Environment.

The Government of Pakistan established a Global Change Impact Study Centre (GCISC) that prepared 16 research reports, including one on *Climate Change Implications and Adaptations of Water Resources in Pakistan* (Ali et al., 2009), which included a section on policy needs. The GCISC studies contributed to a Planning Commission *Task Force Report on Climate Change*. The federal cabinet adopted a climate change policy that has substantial water resources provisions and a new Ministry on Climate Change in 2012. These national actions occur at a time of constitutional devolution of authority for environment, agriculture, and other sectors to the provinces and political uncertainty.

Nepal has been an early leader in scientific assessments of climate change on water resources management (Gyawali, 2011). Nepal created a National Adaptation Programme of Action followed by a Nepal Climate Change and Development Portal,[12] which has a national branch of the Climate Action Network, youth alliances, and NGO associations. These efforts occurred within what has become a larger context of constitutional and governance uncertainties.

Bhutan has placed growing emphasis on climate change and hosted the SAARC meeting on climate change at Thimpu in 2010. Its water policy is situated under its Ministry of Agriculture, though it

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[7] *http://www.rimes.int/about_overview.php.*

[8] *http://www.icimod.org/?q=265.*

[9] See *http://www.icimod.org/?q=264.*

[10] See http://www.iwmi.cgiar.org/Topics/Climate_Change/default.aspx.

[11] See *http://www.climatechangecell.org.bd/.*

[12] See *http://www.climatenepal.org.np/main/.*

also has a substantial hydropower program under its Department of Energy.

Afghanistan is concentrating on reestablishing hydrological monitoring and water resources planning after a prolonged interruption. Water policy is addressed in the Ministry of Agriculture, Irrigation, and Land, which raises an interesting point of comparison across countries where water and climate policies are variously situated in ministries of agriculture, water resources, and environment.

Uneven Subnational, State, and Local Water Management Capacity

Recent decades have witnessed trends toward devolution of water governance from national or concurrent jurisdiction to state and local levels (i.e., the "subsidiarity principle" in the Dublin Statement on Water and Sustainable Development, 1992[13]). Irrigation departments in India and Pakistan are situated at the state and provincial level of government. In the case of Pakistan, although some recent annual plans for the provinces refer to climate change, provincial budgets and department plans for 2012 do not yet include major climate change adaptation analyses, programs, or policies analogous to those being developed at the national level.

In comparison with government, however, the past generation of social science research on local irrigation management by farmers in South Asia underscores their keen perception of and adjustments to hydroclimate variability (see, e.g., numerous IWMI field research studies of irrigation in South Asia;[14] IUCN, 2008; Kreutzmann, 2000).

It seems reasonable to summarize that at this time international and national water organizations are making significant advances toward water resources assessments of climate change that include snow and ice hydrology. National water agencies are devoting increasing emphasis to climate impact and adaptation assessment. It is less clear how these assessments affect management, policy, and interagency water coordination. Similarly, while devolution of water governance to states and districts is associated with increasing references to climate change in water sector planning documents at those levels, the actual implications for budgeting, management, and governance are less evident. The largest cities in South Asia are developing climate adaptation plans that include water systems, but the rapidly growing proportion of secondary and tertiary cities show limited evidence, capacity, or higher-level support for addressing hydroclimate effects on water supply, drainage, or wastewater management. At local scales of irrigation management, however, there is substantial practical experience with hydroclimate adjustment. The robustness of these local forms of adaptation in relation to longer-term and larger-scale trends in climate variability associated with snow and ice hydrology is less well known.

CONCLUSIONS

Key features of the human geography of the HKH region were identified at the workshop by the breakout groups on Hydrology; Water Supply, Use, and Management; and Demography and Security. Starting from those concepts, the Committee used its expert judgment, reviews of the literature, and deliberation to develop the following conclusions:

- Rural and urban poor may be most at risk, in part because the poor are least likely to be able to retrofit, move, or rebuild as needed when faced with risks. However, the environment is not the only driving factor for migration and other adjustments.
- Social changes in the region have at least as much of an effect on water demand as environmental factors do on water supply, leading to stress. Existing stress could be exacerbated by climate change in the future.
- Future population growth in specific watersheds or elevation zones is uncertain, but there is certainty that the region will become increasingly urbanized.
- Water resources management and provision of clean water and sanitation is already a challenge in the countries that share the Himalayan watersheds. The adequacy and effectiveness of existing water management institutions is a reasonable, if coarse, indicator of how the region is likely to cope with changes in water supply.

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[13] *http://www.wmo.int/pages/prog/hwrp/documents/english/icwedece.html.*

[14] *http://www.iwmi.cgiar.org/Publications/index.aspx.*

- Changes in seasonal streamflow could have significant impacts on the local populations by altering water availability patterns and affecting water management decisions and policies for irrigation, municipal, industrial, and environmental use.
- Average aggregate water-use data provide crude estimates of water supply, demand, and scarcity. Increasing the detail, consistency, and accessibility of water-use data (along with streamflow and aquifer data as discussed in Chapter 2) are key priorities for sound regional water assessment.
- Water management assessments have advanced over the past 5 to 10 years, although their implementation in water policies and programs is less clear; to date, there is limited penetration to lower levels of governance or support for local water managers who face the greatest risk.
- Water use has been increasing over time in both the Indus and Ganges/Brahmaputra basins, and this trend will continue for the next several decades, with irrigation by far the largest use.

4

Environmental Risk and Security

Hydroclimate hazards in the HKH region have the potential to affect the lives and livelihoods of large numbers of people. Although climate change may be just one of many elements in a complex system, it could also amplify existing political and security stress and push water systems over critical thresholds. In this chapter, we discuss risks and vulnerabilities related to natural hazards and provide an overview of water conflicts and political stresses in the region. Environmental change can contribute to violent conflict, especially where there is a history of such conflict and where governance institutions lack capacity or are still in the process of consolidating. It can also threaten political and social stability by creating obstacles to development, undermining public health, causing population displacement, creating problems for traditional livelihood and allocation systems, and affecting mediation tools.

NATURAL HAZARDS AND VULNERABILITY

It is useful to situate the risks associated with snow and ice hydroclimatology in the HKH region within the broader context of natural hazards patterns and trends in South Asia, which have varied in the region in both space and time. As of late 2011, some one-third to one-half of the populations of South Asian countries were reported to be food insecure[1] due in part to flood, drought, and complex emergencies (World Food Programme, 2011a). Monsoon flooding was affecting the plains and coastal areas of Bangladesh and India, cloudbursts and landslides were occurring in the mountains in northern India, floods and landslides were affecting Nepal, and monsoon flooding hit coastal Pakistan.[2]

In 2010, hydroclimatic hazards had a different spatial distribution in the region, but again with significant consequences. Twenty million people were impacted by what started as monsoon-related flash flooding in northern Pakistan and ballooned to one of the worst natural disasters in the history of the country as one-fifth of the country's land area was submerged. In the aftermath of this flooding it is estimated that 90 million people were food insecure, an increase from 83 million in 2009 (World Food Programme, 2011b).

Although few of these recent incidents directly involved snow and ice hydroclimatology, questions were raised about the possible linkages of mountain hydroclimate change to, and long-term implications for, perennial and pervasive hazards in the region. Moreover, food insecurity in some areas is a chronic hazard not associated with disasters as much as structural political, social, and economic forces (e.g., Pakistan National Nutrition Survey (AKU and UNICEF, 2012), which indicated no improvement in the percentage of the food-insecure population over the past decade). This section examines these wider patterns of natural hazards, in space and time, to establish the context in which mountain hydroclimate hazards are experienced.

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[1] The World Health Organization defines food security as "when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life."

[2] See *http://reliefweb.int/*.

Mountain Hazards

Twenty years ago, concerns arose about the perceived effects of upper basin deforestation (e.g., in Nepal) on catastrophic flood disasters in the Ganges River Basin downstream as far as Bangladesh, which are analogous to current concerns about Himalayan glaciers. A team of mountain scientists began to question these perceptions, and compiled a volume titled *The Himalayan Dilemma: Reconciling Development and Conservation* (Ives and Messerli, 1989). Research in *The Himalayan Dilemma* marshaled evidence that shed new light on processes of deforestation in the headwaters, refuted popular notions of mountain peoples' responsibility for lower basin flooding, and refocused attention on mesoscale relationships among land use, land cover, flood hazards, and economic development in the mountains, foothills, and upper piedmont settlement regions. The snow and ice hazards of concern in this report differ from the issues of 20 years ago, for example, in their attribution of responsibility to global rather than mountain societies, but the focus on the mountains as a source of downstream hazards invites analogies with the types of rethinking that are needed. To what extent, and in what ways, do the unfolding mountain snow and ice risks in the HKH region relate to other natural hazards in the region? Five propositions may be considered:

- Mountain hazards can *attenuate* with distance downstream.
- Mountain hazards can *cascade* and *amplify* downstream (e.g., because of increased downstream vulnerability or "associated disasters" triggered by those upstream).
- Mountain hazards can *concatenate* with other hazards downstream. They can attenuate while also being amplified by independent disasters downstream (Butzer, 1982).
- Mountain hazards can be *compounded* by independent disasters in different subregions that divert relief efforts from one disaster to another.
- Mountain hazards can be *eclipsed* by other crises downstream.

These five scenarios defy simple generalizations across the region. They may occur in succession with or adjacent to one another. One way of approaching them is to examine the historical geographic record of natural disasters in South Asia. The following analysis gives a sense of the magnitude of mountain hazards relative to those of the plains and coasts. It complements other discussions in this report regarding historical and future linkages among the hazards of mountains, plains, and coasts—and it is supported by information from a variety of disaster databases that are discussed in further detail in Appendix D.

Natural Disasters in South Asia

Natural disasters in South Asia can involve meteorological, hydrological, and geophysical phenomena that are obviously not unique to the HKH region. In 2010, hydrological disasters were more common than other types of disasters in the region (Munich RE NatCatSERVICE).[3] A similar pattern is observed over the past century, the frequency of natural disasters in the region being flood dominated when compared with other disasters (Figure 4.1), both in terms of the frequency of events and number of people affected by the occurrence of floods (Figure 4.2). However, the number of people killed over the past century by natural disasters was dominated by droughts and related famines; the number of people killed by floods in the 20th century is smaller (Figure 4.3).

It should be underscored that these national disaster data cover entire countries in the South Asian subcontinent over the past century, and not just the region affected by mountain hydroclimatology. This macroregional perspective over a century reflects the uncertainties of aggregate data analysis. For example, Several catastrophic drought and famine events occurred in South Asia during the first half of the 20th century. Thus, although the frequency of droughts and famines over the past century in the region is relatively low (Figure 4.1), Figure 4.2 and 4.3 reflect the major impacts of these events in terms of people affected and people killed.

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[3] The NatCatSERVICE database is a comprehensive natural catastrophe loss database. The statement in the text is based on statistics from this database on major global natural catastrophes in 2010. See *http://www.munichre.com/en/reinsurance/business/non-life/georisks/natcatservice/default.aspx*.

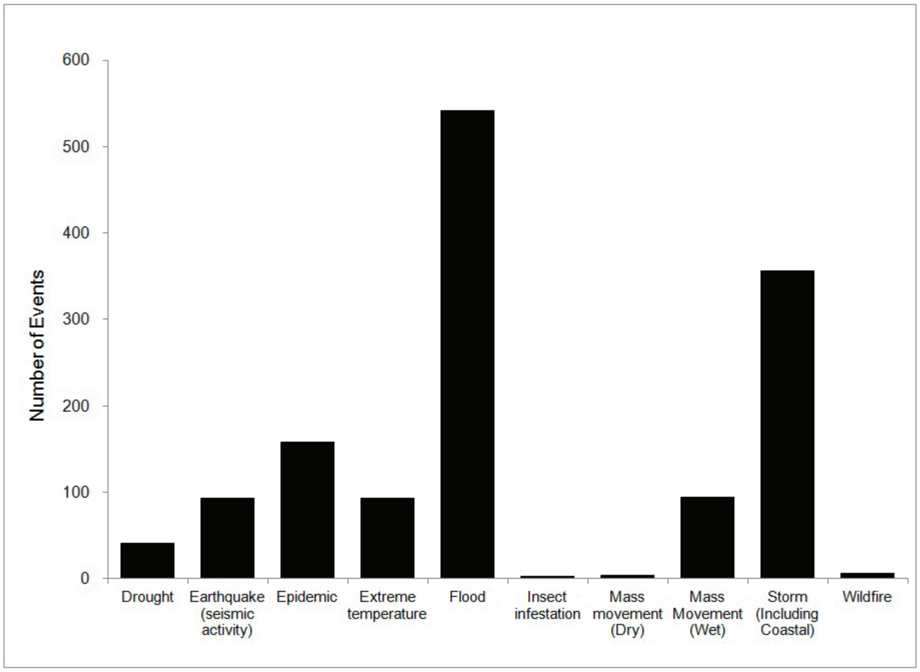

FIGURE 4.1 Disasters in the South Asia region have been dominated by floods over the past century (1900 to 2010) in Afghanistan, Bangladesh, Bhutan, India, Nepal, and Pakistan. SOURCE: Based on data from CRED (2011).

Focusing on the most recent 30-year period (i.e., the most recent climate "normals") provides additional insight, although the patterns and trends seem less clear. Floods have had increasing significance in the numbers of people affected (Figure 4.4) while earthquakes have been associated with the highest number of

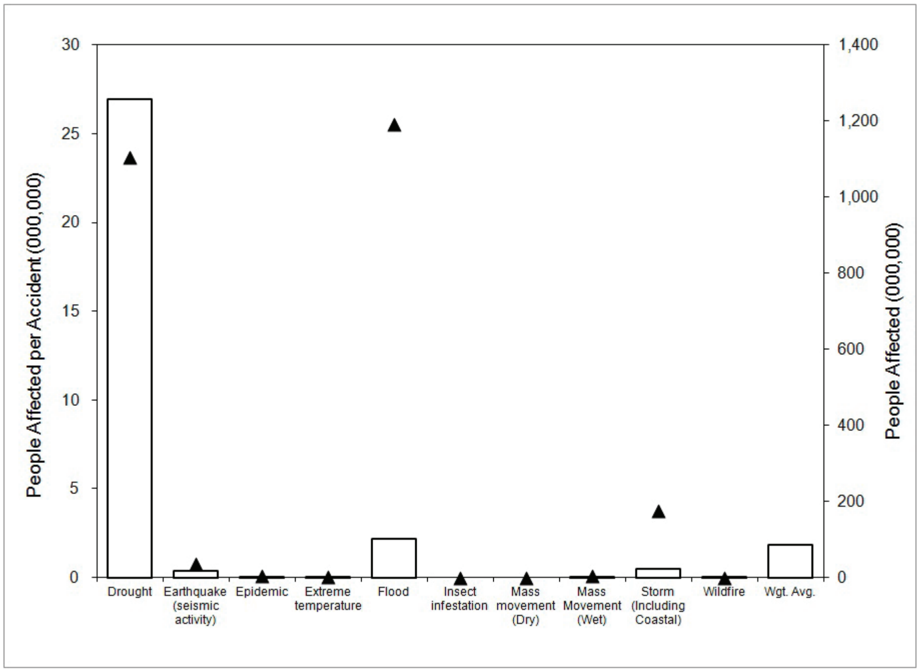

FIGURE 4.2 Number of people affected per event (bars; *y*-axis, left) and in aggregate (black triangles; *y*-axis, right) over the past century (1900 to 2010) in Afghanistan, Bangladesh, Bhutan, India, Nepal, and Pakistan. Floods have affected the most people, while droughts have affected the most people per event. SOURCE: Based on data from CRED (2011).

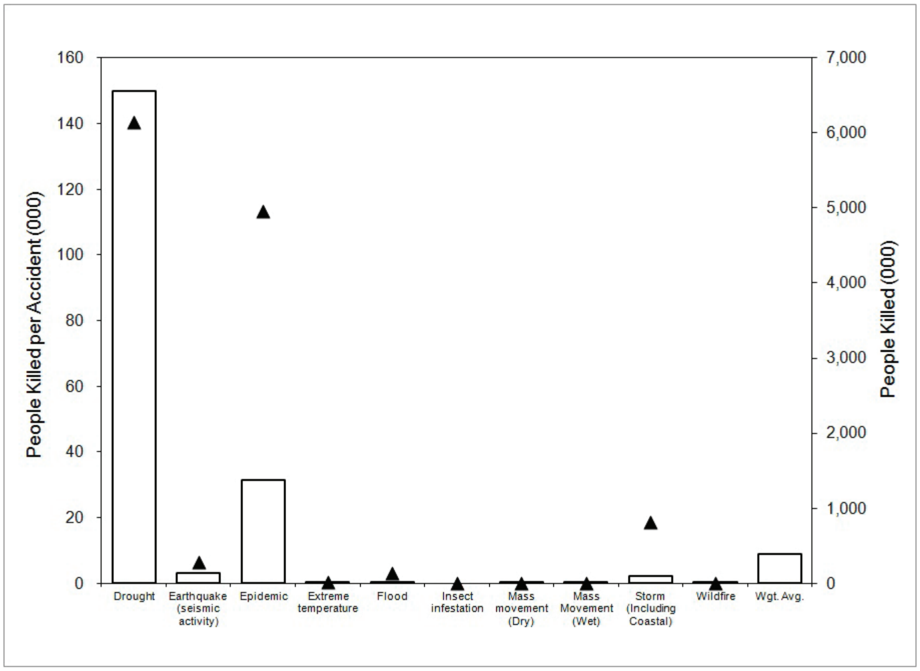

FIGURE 4.3 People killed per event (bars; *y*-axis, left) and in aggregate (black triangle; *y*-axis, right) by type of hazard over the past century (1900 to 2010) in Afghanistan, Bangladesh, Bhutan, India, Nepal, and Pakistan. Droughts and related famines have killed the most people in the region both in aggregate and per event. SOURCE: Based on data from CRED (2011).

people killed, including the 2005 Kashmir earthquake (Figure 4.5). On a yearly basis, the number of people killed and displaced spiked several times over the past 30 years due to significant flooding events such as the 2010 flood in Pakistan. Displacement of people in multiple countries appeared to start increasing in the

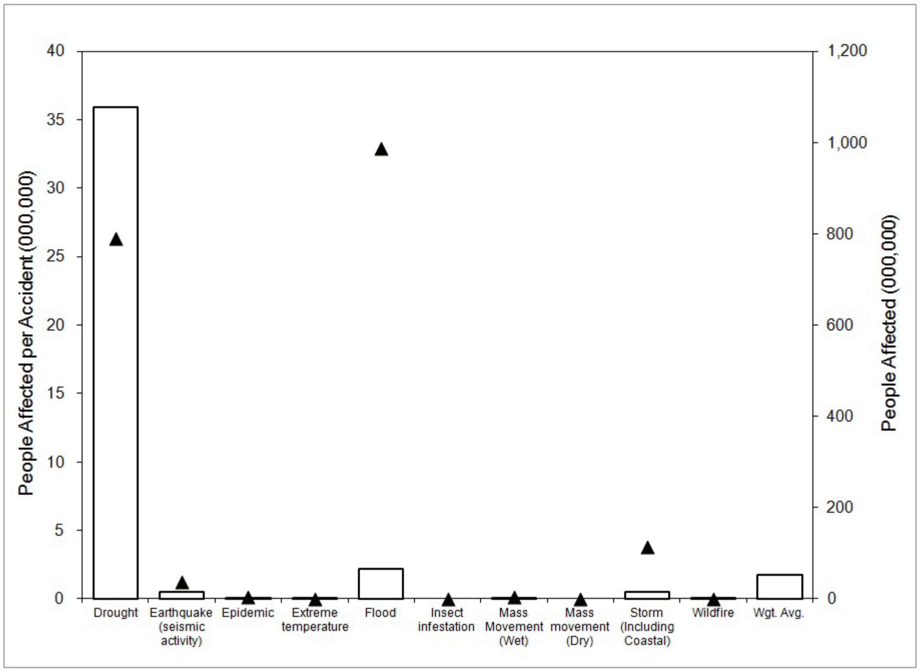

FIGURE 4.4 People affected per event (bars, *y*-axis, left) and in aggregate (black triangles; *y*-axis, right) by type of hazard over the past 30 years in Afghanistan, Bangladesh, Bhutan, India, Nepal, and Pakistan. In recent years, floods have been increasingly important in terms of the number of people affected. SOURCE: Based on data from CRED (2011).

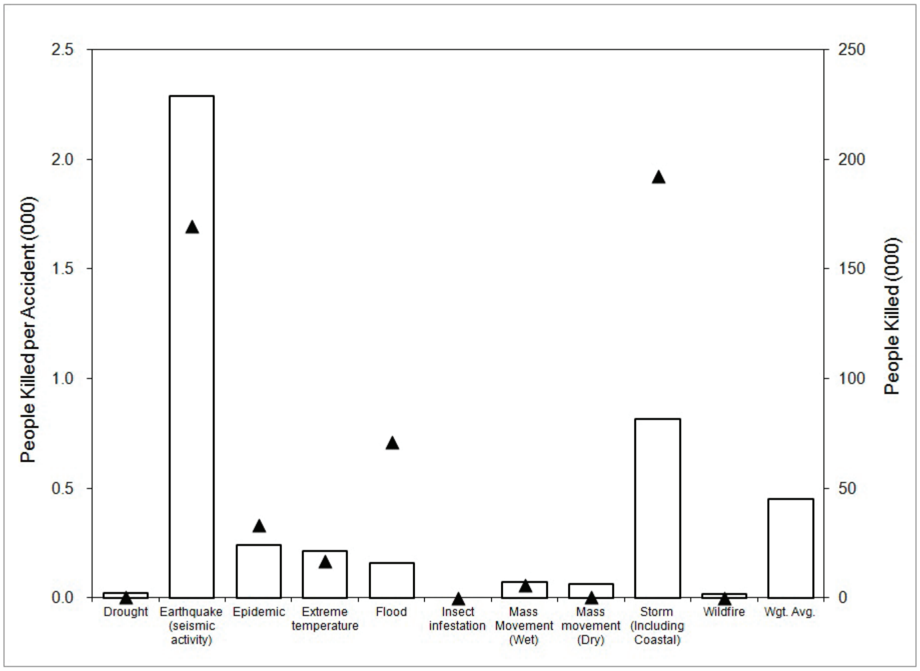

FIGURE 4.5 People killed per event (bars; *y*-axis, left) and in aggregate (black triangles; *y*-axis, right) by type of hazard over the past 30 years in Afghanistan, Bangladesh, Bhutan, India, Nepal, and Pakistan. In recent years, earthquakes have been associated with the highest number of people killed, mostly due to the 2005 Kashmir earthquake. SOURCE: Based on data from CRED (2011).

late 1990s, but then dropped. Even economic damages seem more variable in the region than the aggregate global trend (Dartmouth Flood Observatory, 2011).

Examining flood hazards over the past 25 years as they occur in the Dartmouth Flood Observatory Database (Appendix D) provides additional insight. Several patterns stand out: first, the frequency of reported events is increasing; second, a significant number of these events are two-country and presumably transboundary events, which is relevant for this study; but third, deaths and damages do not exhibit clear trends in individual countries. These observations raise questions about the extent to which increased frequency and impacts are a function of improved disaster reporting, changes in human exposure, and/or changes in vulnerability. Thus, while the above analysis brings forth information about the occurrence of natural hydroclimate hazards in the region, interpreting these data needs to be framed with additional points, including

- the number of people in risk zones has increased with population growth;
- the number of people affected by floods may be due to an increasing number of vulnerable people and increasing vulnerability of those people (e.g., by pressures to settle in hazardous floodplain and hill-slope areas);
- increasing flood hazards may be associated with land degradation in some settlements and watersheds; and
- the region is experiencing an increased reporting of disaster events.[4]

Mountain Environmental Hazards: An Examination of Nepal

To gain a more specific sense of mountain environmental hazards it is useful to examine Nepal. Nepal has the highest proportion of mountainous terrain among countries in the region, and thus the most pervasive exposure to and experience with mountain hazards. It is also the one country in the region that has a detailed national disaster database examining hazards by types and subregions, maintained by the Global Assess-

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[4] The last of these issues is partially addressed by data on losses per event. The other uncertainties are well recognized, though increased awareness has not yet led to more explanatory database development.

ment Report on Disaster Risk Reduction (GAR)[5] and described further in Appendix D. In this database, as in global ones, the frequency of disasters reported has increased from the 1990s onward, and so, looking at the impacts per disaster variable is important.[6]

Although the number of people killed by natural hazards in Nepal over the past 40 years has increased, the number of people killed per disaster has decreased somewhat. This could be due, in part, to improvements in medical care and disaster response. The number of people affected (in aggregate and per disaster) increased in the same time period, albeit with differently timed peaks and trends in response to specific events.[7] However, estimated economic damages increased from the 1990s onward in an obvious trend (Figure 4.6) reflecting the same global trend.

A subregional breakdown of disaster frequency and analysis of losses of life and damages by disaster type in Nepal indicates that

- damages are highest in the more populated central and eastern regions (Figure 4.7);
- losses of life are cumulatively highest from floods and landslides, although individual earthquakes have caused some of the highest mortality rates;
- droughts have limited recorded impact as compared with other countries in South Asia; and
- fires and floods have caused some of the greatest economic losses.

When contemplating these points, several important questions occur: How do the different countries of South Asia address these types of mountain hazards? Do low-frequency high-mortality disasters such as earthquakes have greater impact on disaster policy in the region than higher-frequency lower-magnitude flood hazards? How do societies address multiple hazards and transboundary hazards, including those in lowlands that may compound or eclipse mountain hazards? To consider these types of questions, the next

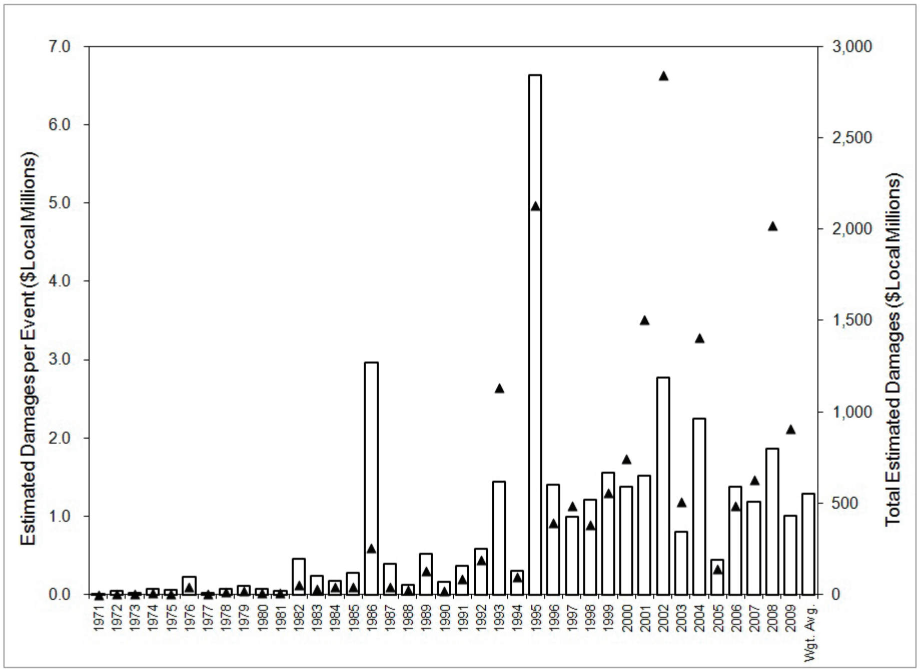

FIGURE 4.6 Estimated damages per event (bars; *y*-axis, left) and in aggregate (black triangles; *y*-axis, right) from natural hazards in Nepal in local currency by year (1971 to 2009). Estimated economic damages increased from the 1990s onward. SOURCE: Based on data from DesInventar Disaster Information System, *http://www.desinventar.net/DesInventar/profiletab.jsp?countrycode=np.*

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[5] Available at: *http://www.preventionweb.net/english/hyogo/gar/2011/en/what/ddp.html* and *http://www.desinventar.net/DesInventar/profiletab.jsp?countrycode=np*.

[6] It is worth noting that the GAR database does not separate glacial lake outburst floods (GLOFs) from the aggregate flood data.

[7] Analysis is based on data from the GAR database from 1971 to 2009.

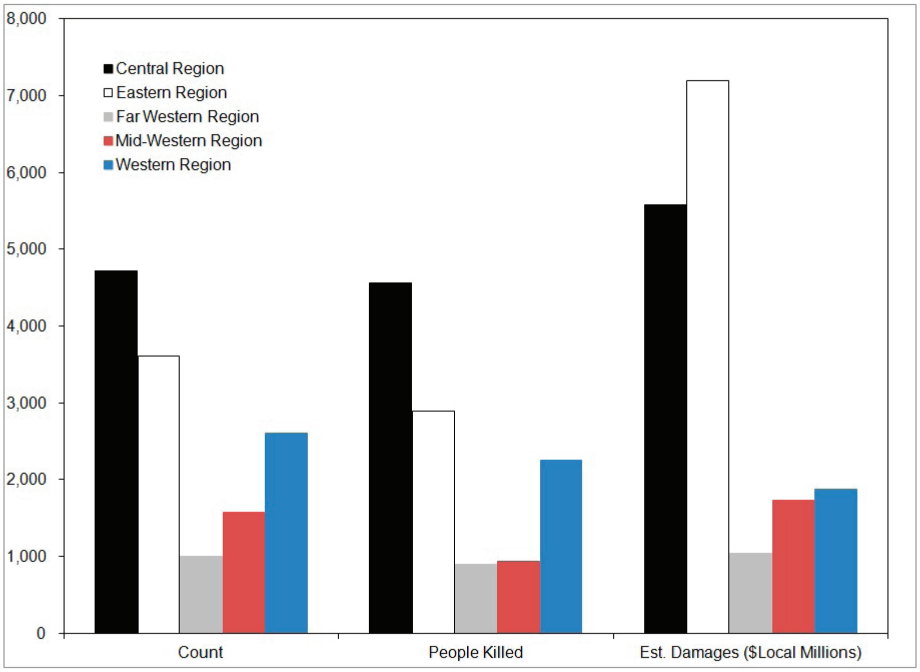

FIGURE 4.7 Number of people affected, number of people killed, and estimated damages (in local millions of dollars) for the five regions of Nepal, in aggregate for events occurring between 1971 and 2009. Number of people affected, number of people killed, and estimated damages are all highest in the more populated central and eastern regions. SOURCE: Based on data from DesInventar Disaster Information System.

section shifts from historical disaster data to current disaster risk reduction programs at the international and national levels.

Natural Disaster Mitigation, Management, and Response

It is important to consider the efforts that focus on natural hazards and disaster risk reduction in South Asia, as they offer different perspectives on and approaches to natural hazards across the region. This can also be useful when considering the specific impacts of glacial and snowmelt processes in the region. A variety of national, regional, and international intergovernmental organizations and programs and national disaster agencies exist that are relevant to this discussion. Each has differing missions, emphasis, and resources and thus different strengths and weaknesses in this context. Furthermore, geopolitical issues and governance structure have variable bearing on disaster management and response in the region. (For a more detailed discussion of these programs, see Appendix D.)

As a whole, regional organizations[8] give particular emphasis to international cooperation, information sharing, and capacity building. One important aspect of these regional programs is their increasing emphasis on linking climate change with disaster risk reduction. Another important observation is that increasing emphasis on community-based approaches and on capacity building by these organizations is creating an international professional cadre of regional disaster risk reduction expertise.

In addition to the military role in disaster relief in each country, national disaster management agencies are key sources of planning, coordination, and information on hazards management.[9] Most have had limited resources and capacity until recently, but that

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[8] Regional organizations discussed further in Appendix D include Asian Disaster Preparedness Centre (Bangkok); Asian Disaster Reduction and Response Network (Kuala Lumpur); Duryog Nivaran (Colombo); ICIMOD: Integrated Water and Hazard Management Programmes (Kathmandu); SAARC—Disaster Knowledge Network (New Delhi); and the U.N. ESCAP (Bangkok) Committee on Disaster Risk Reduction.

[9] National agencies discussed further in Appendix D include Afghanistan, Bangladesh, Bhutan, India, Nepal, and Pakistan.

has tended to change in the wake of high-magnitude events.[10] This is particularly the case in India, which is scaling up its public disaster management institutions and research centers (cf. Kapur, 2009, 2010).

The governance structures of nation-states have an important bearing on disaster management and response. In more centralized systems such as Bhutan, the national agency has primary jurisdiction, authority, and capacity. In parliamentary federal systems of government such as India and Pakistan, by comparison, states may have primary or concurrent jurisdiction, with support from national agencies to address disasters that are beyond their capacity.

Federal systems and their states can undergo processes of devolution or centralization over time that in turn can affect disaster response. In Pakistan, for example, devolution to local governments a decade ago has been replaced by devolution to provincial governments under the 18th Amendment to the Constitution of 1973 (an amendment passed in 2010). Under that amendment, many national agencies have been dissolved, and their authority devolved to provincial governments. For example, the Ministry of Environment, which might have advanced a national climate change policy, was devolved in 2011. The National Disaster Management Authority continues to operate at the federal level with an approach for devolving responsibilities to the provinces. Within this changing context, in March 2012 the federal cabinet division of Pakistan approved a national climate change policy, a new Ministry of Climate Change, and participation in the flood information program of the international Indus hydrology program convened by ICIMOD (KHK-HYCOS; Ghumman, 2012). It seems reasonable to consider in each country how policies for disaster risk reduction in the context of hydroclimatic and institutional change may be implemented. However, it is also reasonable to state that the general situation is one of uncertainty at the national level.

Although international, national, and state organizations are important, most disaster victims are rescued and assisted by their family members, neighbors, and local communities. This is particularly the case in remote and rural areas, whereas in urban disasters, reconstruction has historically been financed in part by national and external sources of capital as well (Vale and Campanella, 2005). The 2005 Kashmir earthquake marked an important benchmark for mobilization at multiple scales for mountain disaster relief (e.g., Halvorson and Hamilton, 2010).

Nongovernmental organizations have supported and helped shape an array of local, community-based approaches to disaster risk reduction in South Asia (see Appendix D for further discussion). Appraising the traditional coping and adaptive capacity of local organizations and communities, and the evolving efficacy of social media, cell phone, and humanitarian logistics technologies in modernizing regions are vital tasks (e.g., Gupta et al., 2010; IUCN, 2008). These technologies can provide people with very quick and accurate information about highly local conditions, facilitate mobilization and collaboration at different scales, and immediately connect affected people and their needs to friends and families. They can, however, also permit misinformation to circulate quickly and widely. Moreover, inexpensive and widespread access can result in systems being overwhelmed unless there is concomitant development of multiscale redundant social and information infrastructure for hazards mitigation, warning, emergency management, and vulnerability reduction.

Implications for Snow and Ice Hydroclimatic Hazards in South Asia

As in *The Himalayan Dilemma* (Ives and Messerli, 1989), the greatest vulnerability to mountain snow and ice hydrology hazards is for mountain people and their immediate downstream neighbors. Disasters are most severe at their source—that is, mountain and hill-slope (e.g., terai) communities are most at risk from blizzards, snow avalanche, glacial retreat, GLOFs, and related geophysical extremes. At the same time, upland communities are presumably adapted to historical ranges of hydroclimate variability, and the more remote communities have historically received limited assistance from the state (Macchi, 2011). For example, Kreutzmann (2000) documents impressive examples of cooperative water management across the Hindu Kush, Karakoram,

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[10] Resource allocation trends can be assessed through national budgets and plans at annual and interannual timescales. Although economic analysis of this sort was not conducted for this report, expansion of government programs was evident on disaster agency websites over the course of the study.

and Himalayan ranges. They underscore the changes in mountain human-environment relations brought about by transportation, tourism, and socioeconomic development that reduce some risks while amplifying others (cf. also Derbyshire and Fort, 2006).

Physical impacts of mountain floods tend to attenuate with distance from the source, but local losses can increase as they encounter concentrations of downstream people and property at risk (e.g., in the district and provincial centers in mountain and foothill regions). Headwater flood events can also concatenate and compound with other hydroclimate hazards, for example, with monsoon rainfall on the plains as occurred in the massive 2010 Indus Basin floods in Pakistan, or with coastal cyclones in Bangladesh and eastern India. The spatial extent and magnitude of these lowland disasters can eclipse more localized hazards in mountain areas. Another open question is how large drought losses on the plains may be affected by future temporal variability and regional trends in snow and ice hydrology.

Management of these types of situations can be confounded by several groups of factors. First, there are sometimes perverse incentives that constrain efforts to attenuate or eliminate the adverse consequences of the physical impacts of mountain floods. Upstream flood control or flood management actions produce downstream benefits that are public goods in the sense that those downstream benefits cannot be withheld from those who refuse to pay for them. This means that there is reluctance to invest in upstream flood control works and schemes because the full returns from them cannot be captured (Ostrom, 1990). Such disincentives need to be surmounted by some form of collective action which may not always be easily negotiated or constituted precisely because they would eliminate the benefits to so-called free riders. The problems of securing collective action may be particularly vexing in international and other transboundary situations.

A second confounding element stems from human vulnerability that is in many ways a function of exposure and sensitivity, which in turn are linked to structural inequalities and inequitable power relations among ethnic, gender, and class groups in a society (Wisner et al., 2003). These relationships vary over temporal and across spatial scales. Short-term disaster effects are most acute and longest lasting in local areas of rapid-onset disasters and deep social vulnerability, as in flash flood impacts on poor mountain floodplain occupants. As noted above, local events may attenuate, cascade, or concatenate over time; they may be compounded or eclipsed by larger-scale regional socioeconomic processes. For example, the short-term impacts of flooding in one growing season can be offset by the following crop (see Government of Pakistan [2012] for Pakistan and Yu et al. [2010] for Bangladesh). Long-term macroeconomic disaster impacts are in part a function of country size: small countries such as Nepal and Bhutan may have proportionately larger and longer-term socioeconomic impacts than larger countries such as India (Noy, 2009).

Modernization and globalization may reduce losses of life and long-term macroeconomic impacts of disasters, particularly when they include strong hazard mitigation policies (World Bank, 2010b). However, they can also increase the numbers of people affected and the economic damages they face. Macroeconomic disasters that stem from other causes can also increase vulnerability to hazards in and from the Himalayan region, especially for the poor and marginalized, upstream and down.

Multimethod and all-hazards research over multiple spatial and temporal scales will thus be increasingly important for analyzing these widening issues (e.g., Gearheard et al., 2011). New methods that are rapidly transforming the timeliness and efficacy of warning, evacuation, and relief include hydrometeorological services for flood warning (Hallegate, 2012; ICIMOD, 2012a); mass messaging (Coyle and Childs, 2005); near-real-time disaster GIS mapping and remore sensing;[11] real-time evaluation and adjustment (Active Learning Network for Accountability and Performance in Humanitarian Action);[12] civil-military coordination and the expanding humanitarian logistics cluster.[13]

Perspectives on Vulnerability and Risk of Natural Disasters

The preceding sections have discussed the physical and human dimensions of hydroclimate hazards in the wider Himalayan region.

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[11] See *http://reliefweb.int/updates/thumb.*

[12] See *http://www.alnap.org/about.aspx.*

[13] See *http://www.logcluster.org/.*

These processes cannot be forecast on interannual or decadal timescales with any level of confidence at present, but they pose credible risks that can be analyzed with basic methods of scenario and sensitivity analysis (Wescoat and Leichenko, 1992; Yu et al., 2010). Returning to the natural hazards propositions outlined above, it is important to anticipate and explore alternative perspectives on compound physical and social processes that can amplify individual hazards. These could include combinations of high-snowfall years with high temperatures, rapid runoff, and major monsoon storms in the foothills—as occurred in the Indus Basin floods of 2010 in Pakistan (Asian Development Bank and World Bank, 2010; OCHA, 2010). A glacial lake could breach and cascade downstream, triggering river channel change, levee failure, and inundation, for example, on the Kosi River alluvial fan or Indus River main stem (Hewitt, 1983). High flows in the Ganges/Brahmaputra Basin could coincide with large-scale processes of sedimentation, erosion, and coastal storm surge.

These complex geophysical events may become more common than isolated single-variable extremes, and require greater research and planning attention. Moreover, they always coincide with social processes that create, amplify, and/or mitigate environmental security risks (Wisner et al., 2003).

As illuminated throughout this report, to anticipate future hydroclimatic hazards and disasters in the Himalayan region, three major challenges need to be addressed: (1) high levels of different types of uncertainties about the measurement, modeling, forecasting, explanation, and capacity for reducing and responding to future hazards; (2) high levels of spatiotemporal variability in hazard losses at multiple scales; and (3) alternative frameworks for understanding social vulnerability and resilience. This section briefly describes these challenges, reviews a progression of models for addressing them, and analyzes several lines of evidence as first steps along what needs to become a long path of scientific inquiry, policy development, and effective hazards mitigation for the peoples and places that face these risks.

Himalayan hydroclimatology encompasses all of the forms of uncertainty described in the NRC report on *Risk Analysis in Flood Damage Reduction Studies* (NRC, 2003b). When these uncertainties of data, models, and knowledge are aggregated—and when analogous uncertainties of social processes and damage datasets are included—they raise profound questions about the prospects for long-term scenario-driven simulation, let alone forecasting, of future hazards.

This is not to dismiss scenario analysis, but rather to say that it must be complemented by other types of risk assessment and risk reduction. In the field of scenario analysis, the Intergovernmental Panel on Climate Change (IPCC) has recently summarized the state of scientific evidence, agreement, and perceived likelihood of extreme events and losses associated with climate change at the global and regional scales (IPCC, 2012; Climate and Development Knowledge Network, 2012). Selected trends and projections relevant for this report include

- *Climate extremes and impacts*: (a) medium confidence in a warming trend in daily temperature extremes over much of Asia; (b) low to medium confidence that droughts will intensify; (c) limited to moderate evidence regarding “changes in the magnitude and frequency of floods at regional scales,” low agreement, and low confidence regarding these changes.
- *Disaster losses*: (a) high confidence about increasing economic losses; (b) high confidence that losses as a proportion of GDP are greater in small and middle-income countries; (c) high confidence that increased exposure of population and settlements has been the major cause for increasing losses; and medium confidence that future economic losses related to climate extremes will be socioeconomic in nature.
- *Disaster management and adaptation to past events*: (a) high confidence about the major role of exposure and vulnerability; (b) high confidence about the aggravating impact of flawed development practices and policies; (c) high agreement about the inadequacy of local disaster data for vulnerability reduction; (d) high agreement about the aggravating effects of socioeconomic inequalities on adaptation; (e) high agreement about the need for humanitarian relief in small and less-developed countries; (f) high agreement about the importance of postdisaster opportunities for increasing adaptive capacity through long-term planning and reconstructions; and (g) medium confidence about the role of risk-sharing mechanisms at multiple scales; and (h) high agreement about the need for inte-

grated disaster risk management, climate adaptation, and development.

- *Future climate extremes, impacts, and disaster losses*: (a) very likely that heat waves will increase in most regions; (b) likely that heavy precipitation events will increase; (c) likely that tropical cyclone wind speeds will increase but that cyclone frequencies may decrease or remain unchanged; (d) low confidence in future drought projections; (e) low confidence in future flood projections at a regional scale; (f) high confidence that current coastal hazards would be aggravated by future sea level rise; (g) low confidence in projections of changes in monsoons.
- *Human impacts and disaster losses*: (a) high confidence that climate change could seriously affect water systems; (b) medium confidence that socioeconomic factors will be the main drivers of future losses; (c) medium agreement that future climate extremes would affect population mobility and relocation (IPCC, 2012).

These conclusions indicate the currently limited ability to project future hazard losses, or resilience in quantitative terms, especially at local to regional scales or on timescales on the order of decades, and at the same time, increasing scientific agreement about the types of hazards likely to be faced in different contexts in qualitative terms. This combination of findings underscores the importance of examining a broad range of historical evidence, current plans, and plausible analogies for anticipating possible futures.

One approach focuses on "critical water problems" as currently defined and asks how past variability, climate change scenarios, and plausible future hazards such as the probable maximum flood affect the range of future choices for redefining and addressing those critical water problems (Brown, 2012; Wescoat, 1991). Comparing losses in one place, time, and context with the current situation in another context, and with a range of possible futures in other places can benefit from the analysis of hydroclimate "analogues and analogies" (Glantz, 1998; Meyer, 1998). For example, Hewitt (1983) examines the historical record of flood disasters on the Indus, including a 19th century GLOF event that cascaded into the middle reaches of the river, within a human ecological framework for assessing the changing character of disaster losses and management, which can be useful for water managers today. One issue with such an approach is whether contemporary social structures, populations, and capacities have useful working historical analogues.

Impacts from the Attabad landslide-impounded lake in the Hunza Valley of northern Pakistan in 2010 were vastly compounded by monsoon rains in northern plains later that year, which cascaded in river flooding downstream to the delta. The latter event eclipsed the former and disrupted relief supply chains as well as funding for resettlement and reconstruction. The 2011 monsoon, by comparison, was normal in the northern plains but caused severe rainfall damages in the lower delta. Analysis of the similarities, differences, comparability, and linkages among these damage and recovery processes—as well as their implications for future disaster risk reduction policies and programs at different scales—is still under way. Independent of these events, however, disaster management is being devolved along with many other federal ministries to the provincial level of government, which will make analogies, vis-à-vis strict comparability, between past and future hazards all the more important.

Two major advances in disaster research in recent years have focused on vulnerability and resilience (Adger, 2006; Cutter, 2006; Cutter et al., 2010). "Vulnerability" can be as much a characterization of potential future losses, as it is an assessment of documented historical losses. When used as a planning or policy concept, "resilience" can also be projective, imagining alternative pathways for relief, recovery, reconstruction, and mitigation.

Insight into these possible futures can be gleaned in part from critical research on historical and contemporary hazards. For example, Kapur (2009, 2010) has prepared major reviews of disaster research and policy in India that document the rich cultural heritage of ideals and practices for adjusting to hazards, while lamenting the belated development of modern hazards research and policies in the late 20th century. Those studies indicated the highest levels of vulnerability in the extreme northeast and northwest districts of India (e.g., Arunachal Pradesh and Ladakh, due primarily to inadequate infrastructure and access to services), followed by subareas of northern Bengal, Bihar, and Uttar Pradesh (due more to disadvantaged groups and fragile living conditions). Recent Indus Basin hazards research has likewise shed light on conditions of social vulnerability related to unequal and marginalizing power relations that have been driving forces of past, present, and likely future losses (e.g., Halvorson, 2003; Mustafa and Wrathall, 2011).

Resilience research focuses on the complementary processes of coping, recovery, and reconstruction. In physical terms, the concept of resilience draws upon ecosystem and systems analysis by analyzing the time required for human-environmental systems to rebound to their predisaster status; in recent years, however, the definition of resilience has been expanded to include the possibility of learning, reorganizing, and redeveloping into an improved state in the longer term. However, much more is intended in the hazards field where resilience also connotes preparedness, capacity building, and ways for “building back better” in the future. For application across South Asia, Moench and Dixit (2004) provide an array of examples in an edited volume on *Adaptive Capacity and Livelihood Resilience: Adaptive Strategies for Responding to Floods and Droughts in South Asia*. Other studies of community-based planning methods for multihazard resilience in the HKH mountains can serve as blueprints for future planning, as well as assessments of past losses (e.g., ICIMOD, 2012b; Interworks LLC, 2010).

In light of these critical perspectives on patterns of vulnerability, challenges of resilience, and the limitations of historically technocratic approaches to hazard mitigation in South Asia, it is also worth mentioning here the perspective of sociologist Ulrich Beck on “risk societies.” Beck (1992, 2009) argues that developed countries in the West have placed ever-increasing emphasis on risk, but not on its root causes (e.g., poverty, social inequality, governance failures, and domination and marginalization of some groups by others). These “risk societies” are destined to be evermore anxious about and adept at managing symptomatic, sometimes catastrophic, losses, but not in ways that dramatically reduce the driving causes and experience of vulnerability. Under conditions of uncertainty, governments may prefer a combination of decentralizing risk toward the individual and the private sector and then paying for rescues and bailouts when required, as opposed to a society-wide strategy of building resilient capacity and safety nets. The economics and the political economy of these options require further attention, because at almost any given time, building resilience may seem like the more expensive, and hence less politically attractive, choice.

In assessing the hydroclimate risks of the Himalayan region, it seems vital to understand regional traditions, adaptation, and innovations for addressing the root causes of climate, water, and food insecurity (Moench and Gyawali, 2008; Ul Haq, 2007), as well as the frontiers of international scientific and technical risk management. An area that is understudied and perhaps of critical value is understanding local adaptation and innovation, and hence what local mechanisms could be supported and scaled up, and additionally, which actions at different scales may actually be counterproductive when viewed from a broader perspective and should therefore be replaced.

SECURITY DYNAMICS AND WATER CONFLICT

Although water conflict per se has historically been kept within bounds, the region is characterized by a high level of risk for political security problems, compared with other parts of the world. It has a mixture of political regimes ranging from strongly and consistently democratic (India) to strongly and consistently autocratic (China), with many regimes (Afghanistan, Bangladesh, Bhutan, Nepal, and Pakistan) exhibiting high levels of instability in their domestic political systems and failing to consolidate as either strongly democratic or autocratic. Regime type may be a significant variable conditioning war proneness, with evidence suggesting that emerging or unconsolidated democracies (e.g., Afghanistan and Nepal) may be particularly vulnerable to initiating conflict (Gartzke, 2007; Krain and Myers, 1997; Mansfield and Snyder, 2005).

The region also has several ongoing international security problems. China, India, and Pakistan have nuclear weapons, with India and Pakistan doing so primarily as part of an international rivalry involving each other. The China-India border is under dispute, with territory in Aksai Chin and Arunachal Pradesh claimed by both countries; a war was fought in 1962 over this territory. India and Pakistan also contest their border, with conflicting claims to Kashmir; they have engaged in military conflicts over this border in 1947 and 1948 at partition, and in 1965 and 1999. The two countries maintain a military presence on the Siachen Glacier and have engaged in armed combat there. Afghanistan and Nepal are both emerging from war and in a fragile peace-building phase in which the probability of conflict recurrence is significant. Collier et al. (2003) provide extensive statistical data showing that past conflict is a good predictor of future conflict. Past conflict combined with growing environmental stress may be a particularly volatile combination (Collier, 2007).

As the 21st century unfolds, concerns over the real and imagined risks of conflict over environmental problems and access to resources have risen on the global list of security challenges (e.g., Deudney and Matthew, 1999; Homer-Dixon, 1999).[14] These concerns now include the area of water resources, requiring experts and policy makers to consider and evaluate the connections between water resources and conflict—and to do so against the backdrop of existing political and security risks and vulnerabilities. Water supply and treatment in modern and developing countries is dependent on complex water infrastructure. Yet access to reliable water is vulnerable to disruptions from intentional human actions or from changes in natural conditions, including climate changes. In the HKH region, water resources are already a scarce and valuable resource in many communities. Because water is such a fundamental resource for human and economic welfare, threats to water availability and water management systems or conflicts over access to water need to be viewed with concern, and care taken to both understand and reduce those risks (cf. the various perspectives of Falkenmark, 1990; GCISC, 2007; Gleick, 1993, 2000, 2006; Lal et al., 2011; Michel and Pandya, 2009; Moench, 2010; Monirul Qader Mirza and Ahmad, 2005; Postel, 2000; Postel and Wolf, 2001; Ringler et al., 2010; Swain, 2004; Uprety and Salman, 2011; Yu et al., 2010). Such conflicts can occur at international, subnational, and local levels.

Political boundaries rarely coincide with watershed boundaries, often bringing politics into water policy. Indeed, approximately half of the land area of the planet is in an "international river basin"—shared by two or more nations (Wolf, 2007), and almost all of the watersheds of the HKH region are international in nature.

At the international scale, water disputes are often addressed at the political and diplomatic level, and water can be an effective source of international cooperation and negotiation through bilateral or multilateral treaty agreements or standards of international law. Hundreds of water treaties have been negotiated and implemented around the world (Oregon State University, 2012b). Wolf (2007) argues that these are often highly effective at reducing the risks of water conflicts, although few of these agreements have incorporated new concerns that might be caused by climate changes or other pressures. Moreover, the overwhelming majority of agreements were crafted at a time when the world population was much smaller and there were far fewer states and other political actors. Most bargaining theory suggests that strong and effective agreements are more difficult to reach as the number of actors increases (e.g., Oye, 1986).

There have been a range of promising multitrack initiatives that focus on transboundary water issues in South Asia (cf. the various perspectives of Aman Ki Asha, 2012; Bandyopadhyay and Ghosh, 2009; Crow and Singh, 2008; Gyawali, 2011; Iyer, 2003, 2007; Jinnah Institute, 2012; Moench and Dixit, 2004; Verghese, 2007). These have broadened in scope and significance over time, with the leadership of influential water experts from the region. Their effect on relationships and negotiations is difficult to discern, but has potential in light of the substantial water policy experience, public intellectual, and civil society roles of leading participants.

Cooley et al. (2012) argue that even in areas with a precedent of cooperation, population growth, economic factors, and climate change could increase tensions over water. As they note:

> For countries whose watersheds and river basins lie wholly within their own political boundaries, adapting to increasingly severe climate changes will be difficult enough. When those water resources cross borders, bringing in multiple political entities and actors, sustainable management of shared water resources in a changing climate will be especially difficult (Cooley et al., 2012).

There are clear needs for regionally coordinated planning for water sharing, management, and storage in the HKH region. Yet the political, economic, and

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[14] These authors were pioneers in raising the issue of possible links between conflict and the environment, but the issue remains one of active debate in the literature.

social conditions in various countries and places have historically impeded such integrated planning and management. Upstream countries such as China and India have implemented and proposed dam projects, for instance, that affect the timing and amount of flow to downstream countries such as Pakistan and Bangladesh. Even the sharing of data on water faces political constraints; the Indus Waters Treaty provides for data exchange (Article VI), though some data remain classified by countries or otherwise not available for regional analysis or use. With a few partial exceptions, such as the Indus River Treaty signed over half a century ago,[15] countries in the region have not had a history of working together on shared problems. And, even that treaty is the subject of considerable tension between India and Pakistan these days. Recent failed discussions, such as over the Wullar Barrage (see Bhutta, 2011), suggest that tensions are far from being managed completely effectively. Climate change adds another complex layer of stress to this and other treaties. As noted above, however, the Indus Waters Treaty has provisions for exchange of data (Article VI) and future cooperation (Article VII) that have considerable potential. Although Nepal alone has four treaties with India,[16] those agreements do not say anything about climate changes or address the uncertainty posed by potential effects of changing melt dynamics from glaciers of the HKH. However, Bhutan and India have a long-standing agreement for cofinancing and benefits dating back to the Chukka Power Plant. It will be interesting to see whether and how emerging international private and public-private power investment agreements in the region address hydroclimate variability (see discussions in World Bank [2008] and USAID [2012], which examine power trade potential and constraints among Bhutan, India, Nepal [the so-called "eastern" market] and also Afghanistan and Pakistan [the "western" market]). Bangladesh and India established a treaty on sharing Ganges water in 1996, which superseded less formal agreements. They recently set aside a proposed treaty to share the waters of the Teesta River but that was reportedly due to federal-state politics in India (India Water Review, 2011). Another difficulty with many of the treaties in the region is that they do not include all riparians.[17] For example, the Indus Treaty does not include Afghanistan (the Kabul River is a tributary of the Indus). The Ganges Treaty with Bangladesh does not include Nepal.

Other important factors related to climate risks are left out of almost all international water agreements as well. Groundwater is typically ignored or excluded, and for India and Pakistan, finding a way to manage transboundary groundwater may be a critical issue. Many agreements that address water allocations do so using fixed volumetric allocations rather than proportional or percentage allocations, and they typically are inflexible in the face of shortages. Few agreements include standards for water quality. Many transboundary agreements lack monitoring, enforcement, and conflict resolution procedures. Overcommitment of river waters leads to disputes; a 2007 assessment included the Indus River in the list of rivers that are "severely overcommitted" (Molle et al., 2007).[18] This points again to the need for flexibility in any water management agreements, as stated above. The Indus agreement, however, does at least divide the river entirely by tributary, and the Ganges agreement has varying allocations depending on flow.

Fischhendler (2004), McCaffrey (2003), and Tarlock (2000) identify some mechanisms that can add flexibility in the face of climate change to existing treaties, and Cooley et al. (2012) extend these mechanisms. Among the leading recommendations are as follows:

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[15] With extensive irrigation systems, the Indus River Basin was already the subject of contested water management by Indian states when the new countries of India and Pakistan were created in 1947. In April 1948, India cut off water to several major canals, However, this was followed by extended negotiations under the auspices of the World Bank and a consortium of donors, leading to the Indus River Treaty of 1960 (Michel, 1967; Wolf and Newton, 2008). Indus Waters Treaty provisions for appointment of a neutral expert (Annexure F) and an international court of arbitration (Annexure G) have recently been tested. The full text of the treaty is available at: *http://web.worldbank.org/WBSITE/EXTERNAL/COUNTRIES/SOUTHASIAEXT/0,,contentMDK:20320047~pagePK:146736~piPK:583444~theSitePK:223547,00.html*.

[16] The Kosi River agreements of 1954, 1966, and 1978, and the Gandak Power Project agreement of 1959 (Hamner and Wolf, 1998). The full text of the agreements are available at: *http://ocid.nacse.org/tfdd/treaties.php*.

[17] A riparian area is the area along a river bank.

[18] India's Cauvery River, not part of this study and not fed by glacial melt, has also been the subject of dispute because of overallocation.

- Address how water allocations can be made more flexible in the face of altered timing and availability of flows.
- Incorporate water quality provisions.
- Develop explicit water management strategies for extreme events, including floods and droughts.
- Provide clear amendment and review processes for changing conditions.
- Create joint institutions to facilitate adaptation to climate change, including technical committees and shared models and data.

Recently, Chellaney (2011) has suggested that the extensive technical boards and task forces, public engagement processes, and voting procedures employed by the International Joint Commission between Canada and the United States offer promising precedents for expanding the scope, capability, and efficacy of the presently small bilateral treaty commissions in South Asia (cf. Article VIII of the Indus Waters Treaty on the Permanent Indus Commission, in which Article VIII(10) states that "the Commission shall determine its own procedures," as well as Article VII on "Future Cooperation," which support the view that there is flexibility even in the most detailed agreements).

Similarly, Wolf and Newton (2008) provide analyses of international water agreements, including historical details, the principal actors, and "lessons learned" about the resolution of conflicts. The major lessons learned from the Indus River Treaty case study (Oregon State University, 2012a), for example, include the following:

- Power inequities may delay the pace of negotiations.
- Positive, active, and continuous involvement of a third party is vital in helping to overcome conflict.
- Coming to the table with financial assistance can provide sufficient incentive for a breakthrough in agreement.
- Some points may be agreed to more quickly if it is explicitly agreed that a precedent is not being set.
- Shifting political boundaries can turn intranational disputes into international conflicts, exacerbating tensions over existing issues.
- Sensitivity to each party's particular hydrological concerns is crucial in determining the bargaining mix.
- In particularly "hot" conflicts, when political concerns override, a suboptimal solution may be the best one can achieve.

Other considerations include designing upstream interventions that minimize downstream impacts and the importance of advance notice about such interventions.

Extensive research and policy discussions around water security have also taken place within the countries of South Asia. In India, for example, analysts have suggested that water issues with Pakistan and China have the potential to become catalysts for conflict, but that political deadlocks with Nepal and Bangladesh could be broken through sensible water-sharing arrangements and resource development (IDSA, 2010).[19] Within Pakistan, it has been suggested that while Kashmir is the major source of tension between the two countries, discord over several upstream river projects being constructed by India has the potential to provoke increasing conflict between the two countries.

Increasingly, however, conflicts over water are not only the result of international disputes, but are also subnational. The challenges can be even greater at the subnational level, where frameworks and strategies for reducing conflicts over water as a development issue are protracted (e.g., Iyer, 2003; Joy et al., 2008; Mohan et al., 2010). Regional and local legal and water management institutions are often weak, and water infrastructure can be insufficiently developed, poorly maintained, or ill-suited to needs. Dams, for instance, are sometimes purportedly built because they are large infrastructure projects that have symbolic, political, and financial benefits, rather than because they solve water supply problems effectively, although there is debate about this issue (e.g., Briscoe and Malik, 2006; Gyawali, 2011; Iyer, 2007). Dams may also raise distributional conflicts and spur political tension as downstream and upstream communities receive unequal benefits, or as one community benefits at the expense of the other (Beck et al., 2012; Duflo and Pande, 2007).

Improvements in water management are more likely to occur at the national and subnational levels than the international level; therefore, a focus on management at these levels is more likely to be successful

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[19] Malhotra (2010) provides another perspective from India on water issues.

than efforts to create optimal, regionwide agreements. However, channels of cooperation relating to cross-boundary scientific assessment could open up if science is seen as neutral ground and new data are regarded as being of mutual benefit.

Table 4.1 lists selected entries from the Water Conflict Chronology (Gleick, 2011) from the HKH region through 2010. Not all of these entries involve watersheds that derive water from glacial melt, but they are indicative of the kinds of regional conflicts over water that have occurred over the past four decades and that are relevant to this study. All but one of the 23 conflicts are national or subnational, and 21 are development disputes[20]—although 6 of those 21

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[20] "[W]here water resources or water systems are a major source of contention and dispute in the context of economic or social development" (Gleick, 2011).

TABLE 4.1 Examples of Water Conflicts in the Hindu-Kush Himalayan Region

Date	Parties Involved	Basis of Conflict	Description
1970	Chinese citizens	Development dispute	Conflicts over excessive water withdrawals and subsequent water shortages from China's Zhang River have been worsening for over three decades between villages in Shenxian and Linzhou counties. In the 1970s, militias from competing villages fought over withdrawals. (See also entries for 1976, 1991, 1992, and 1999.)
1976	Chinese citizens and government	Development dispute	In 1976, a local militia chief is shot to death in a clash over the damming of Zhang River. Conflicts over excessive water withdrawals and subsequent water shortages from China's Zhang River have been worsening for over three decades. (See also entries for 1970, 1991, 1992, and 1999.)
1991	Chinese villages of Huanglongkou and Qianyu	Development dispute	In December 1991, the villages of Huanglongkou and Qianyu exchange mortar fire over the construction of new water diversion facilities. Conflicts over excessive water withdrawals and subsequent water shortages from China's Zhang River have been worsening for over three decades. (See also entries for 1970, 1976, 1992, and 1999.)
1991-present	Karnataka, India	Development dispute	Violence erupts when Karnataka rejects an Interim Order handed down by the Cauvery Waters Tribunal, set up by the Indian Supreme Court. The Tribunal was established in 1990 to settle two decades of dispute between Karnataka and Tamil Nadu over irrigation rights to the Cauvery River.
1999	Bangladesh	Development dispute, political tool	Fifty are hurt during strikes called to protest power and water shortages, led by former Prime Minister Begum Khaleda Zia.
1999	China	Development dispute, terrorism	Around the Lunar New Year, farmers from Hebei and Henan Provinces fight over limited water resources. Heavy weapons, including mortars and bombs, were used and nearly 100 villagers were injured. Houses and facilities were damaged and the total loss reached one million US dollars.
2000	Hazarajat, Afghanistan	Development dispute	Violent conflicts break out over water resources in the villages of Burna Legan and Taina Legan, and in other parts of the region, as drought depletes local resources.
2000	Gujarat, India	Development dispute	Water riots are reported in some areas of Gujarat amidst protests against authorities' failure to arrange adequate supplies of tanker water. Police are reported to have shot into a crowd at Falla village near Jamnagar, resulting in the death of three and injuries to 20 following protests against the diversion of water from the Kankavati dam to Jamnagar town.
2001	Pakistan	Development dispute, terrorism	Long-term drought and water shortages lead to civil unrest in Pakistan. Protests begin in March and continue into summer, leading to riots, 4 bombings, 12 injuries, and 30 arrests. Ethnic conflicts erupt as some groups "accuse the government of favoring the populous Punjab province (over Sindh province) in water distribution."
2002	Kashmir, India	Development dispute	Two people are killed and 25 others injured in Kashmir when police fire at a group of clashing villagers. The incident takes place in Garend village in a dispute over sharing water from an irrigation stream.
2002	Nepal	Terrorism, political tool	The Khumbuwan Liberation Front (KLF) blows up a hydroelectric powerhouse in Bhojpur District on January 26, cutting off power to Bhojpur and surrounding areas. By June 2002, Maoist rebels had destroyed more than seven micro-hydro projects as well as an intake of a drinking water project and pipelines supplying water to Khalanga in western Nepal.
2002	Karnataka, Tamil Nadu, India	Development dispute	Violence continues over the allocation of the Cauvery (Kaveri) River between Karnataka and Tamil Nadu, including riots, arrests, property destruction, and more than 30 injuries.

TABLE 4.1 Continued

Date	Parties Involved	Basis of Conflict	Description
2004	India	Development dispute	Four people are killed in October and more than 30 are injured in November in ongoing protests by farmers over allocations of water from the Indira Gandhi Irrigation Canal in Sriganganagar District, which borders Pakistan. Authorities impose curfews on the towns of Gharsana, Raola, and Anoopgarh.
2004	China	Development dispute	Tens of thousands of farmers stage a sit-in against the construction of the Pubugou Dam on the Dadu River in Sichuan Province. Riot police are deployed to quell the unrest, and one policeman is killed. Witnesses also report the deaths of a number of residents. (See China 2006 for follow-up.)
2007	India	Development dispute	Thousands of farmers breach security and storm the area around the Hirakud Dam in the east Indian state of Odisha (Orissa) to protest allocation of water to industry. Minor injuries are reported during the conflict between the farmers and police.
2008	Pakistan	Terrorism	In October, the Taliban threatens to blow up Warsak Dam, the main water supply for the city of Peshawar during a government offensive in the region.
2008	China, Tibet	Military tool, development dispute	China launches a political crackdown in Tibet. At least some observers have noted the importance of Tibet for the water resources of China, although the political complications between Tibet and China extend far beyond water. As noted: "Tibet is referred to in some circles as the 'world's water tower'; the Tibetan Plateau is home to vast reserves of glaciated water, the sources of 10 of the largest rivers in Asia, including the Yellow, Yangtze, Mekong, Brahmaputra, Salween, Hindus and Sutlej among others. By some estimates, the Tibetan plateau is the source of fresh water for fully a quarter of the world's population."
2009	India	Development dispute	On December 3, police clash with hundreds of Mumbai residents protesting water cuts. One man is killed and a dozen others injured. Mumbai authorities are faced with rationing supplies after the worst monsoon season in decades.
2009	India	Development dispute	A family in Madhya Pradesh state in India is killed by a small mob for illegally drawing water from a municipal pipe. Others ran to collect water for themselves before the pipe ran out. Drought and inequality in water distribution lead to more than 50 violent clashes in the region in the month of May, and media reports more than a dozen people killed and even more injured since January, mostly fighting over a bucket of water.
2009	China and India	Military tool, development dispute	China claims a part of historical Tibet that is now under Indian control as part of the state of Arunachal Pradesh. To influence this territorial dispute, China tries to block a $2.9 billion loan to India from the Asian Development Bank on the grounds that part of this loan was destined for water projects in the disputed area.
2010	Pakistani tribes	Development dispute, military tool	More than 100 are dead and scores injured following 2 weeks of tribal fighting in Parachinar in the Kurram region of Pakistan, near the Afghanistan border. The conflict over irrigation water began as the Shalozan Tangi tribe cut off supplies to the Shalozan tribe. Some report that the terrorist group al-Qaida may be involved; others claim sectarian violence is to blame as one group is Sunni Muslim and the other Shiite.
2010	Mangal and Tori tribes, Pakistan	Development dispute	A water dispute in Pakistan's tribal region leads to 116 deaths. In early September, the Mangal tribe stopped water irrigation on lands used by the Tori tribe, leading to fighting.
2010	India	Development dispute	A protest about water shortages leads to violence. Erratic water supply, and eventually a complete cutoff of water in the Kondli area of Mayur Vihar in east Delhi, causes a violent protest and several injuries.

SOURCE: Gleick (2011).

also have another basis (political tool,[21] terrorism,[22] or military tool[23]). Scarcity and unequal allocations of water are the usual immediate causes of violence. In general, these results confirm the notion that countries are more likely to cooperate—or at least negotiate—than to go to war over water, but that there could be violence and instability at the substate level. In addition, water may be the occasion for violence but not a sufficient basis in itself. Climate change, accordingly, might be best thought of as a "stress multiplier."

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[21] "[W]here water resources, or water systems themselves, are used by a nation, state, or non-state actor for a political goal" (Gleick, 2011).

[22] "[W]here water resources, or water systems, are the targets or tools of violence or coercion by non-state actors" (Gleick, 2011).

[23] "[W]here water resources, or water systems themselves, are used by a nation or state as a weapon during a military action" (Gleick, 2011).

A similar analysis may be undertaken for the Indus and Ganges-Brahmaputra-Meghna basins using the Transboundary Freshwater Dispute Database's *International Water Events Database,* which codes events reported in news sources on a 14-point scale from −7 (formal declaration of war) to +7 (voluntary unification) from 1948 to 2008. Although the mixed sources of records, challenges of coding them, and relationships between reports and reality need to be considered, four rough patterns seem apparent in these data:

- No events are reported at the −7 level (formal declaration) of water war (and only 1 or 2 are at the −6 to −4 levels of water conflict).
- Both the Indus and the Ganges/Brahmaputra basins have a bimodal distribution of relatively lower levels of conflict and cooperation.
- Both basins appear to have a somewhat higher frequency of cooperation than conflict.
- There are several examples of significant international agreements (+6 level).

Each of these databases and others like them have significant limitations. They do not, for example, convey shifts in international relations that may be associated with major constitutional transitions, and which can include water governance, for example, in countries such as Nepal and Pakistan. They do however offer partial perspectives on the types and trends of water-related conflict and cooperation.

Future Political Stresses and Water Conflicts

Traditional political and ideological questions that have long dominated international discourse and contributed to international and subnational conflicts are now involving other factors that were less important in the past. These include population growth, transnational pollution, resource scarcity, and inequitable access to resources and their use (Gleick, 1998). As the climate changes, shifts in the timing, availability, or quality of water resources in parts of the region may play an increasing role in political tensions, either directly through disputes over access to water, or indirectly through changes in agricultural production and food security or other concerns.

The history of international river disputes and agreement suggests that cooperation is a more likely outcome than violent conflict. However, the relevance of this history may be attenuated by the dramatic increase in the number of state and nonstate actors, larger populations, changes in patterns of economic growth, and the complexity of the challenges. Because of changes in political and social conditions, historical patterns may not be able to provide insight into current and future challenges.

Moreover, if trends combine in especially dangerous ways, conflicts might outstrip the ability of existing institutions to cope along normal lines, thereby escalating national security crises. For example, major deterioration in international relations might coincide with dramatic fluctuations in transboundary flows, rising flood risks perceived to result from mismanagement by upstream nations, social media allowing misperceptions to be widely diffused and used as a basis for mobilizing action regardless of official attempts to control the narrative, or heightened conditions of general water scarcity driven by rising demand and declining groundwater resources. Monitoring the conditions that drive these potential situations would be worthwhile.

In addition to transboundary and international threats to security, there is a growing risk of internal conflict over water resources. Increases in floods, especially floods that are larger than those that have been experienced in recent history, can kill and injure many people, destroy property and livelihoods, and pressure governments in ways that trigger legitimacy problems. If such floods repeat in the same area over short periods, downward spirals in livelihoods and legitimacy could occur. Similarly, water scarcity problems—whether triggered by shifts in rainfall or runoff patterns, changes in groundwater recharge rates and availability, or alterations in water demands—could trigger similar crises if they endure over long periods in areas of significant vulnerable populations and weak water management institutions. In addition, the threat posed by continuing overdraft of groundwater resources may be even more important than consequent changes in glacial melt and its contribution to the rivers of South Asia (Darnault, 2008; Shah, 2009). Whether or not water stresses escalate into security crises will depend in part on governmental capacity; therefore, the most dangerous situations are those that combine high water stress and state fragility.

Some historical analysis suggests that societies can be very slow to act upon strong signals from environmental change, resulting in breakdowns that, from a historical vantage, are shocking (e.g., Diamond, 2004). The frequency with which breakdowns occur due to environmental stress have led some analysts to argue that societies should consider carefully how they will rebuild (Homer-Dixon, 2006).

Even in the absence of catastrophic events, existing water management institutions and treaty arrangements would need to evolve in order for cooperation to be a more likely outcome than conflict. The web of economic and social relationships in the region has become increasingly complex and intricate, and the numbers of stakeholders and interested parties in water resource management have multiplied. This creates new sets of challenges for governance and stability. International treaties may also have to adopt a more integrated ecological approach so that water issues are not considered in isolation from the management of land, energy, and other resources. This creates a greater role for scientific knowledge and makes international collaboration on scientific issues all the more important.

More generally, regional—as opposed to bilateral—frameworks for resource management may become increasingly necessary (and if robust regional governance mechanisms emerge, then new forms of early warning and response will become possible). Historically, large regional powers throughout the world have tended to favor bilateral arrangements, which have been the norm, while small and medium powers have enjoyed greater leverage within multilateral institutions (see Naidu [2009] and Singh [2011] for a discussion of the shift in India's position in favor of multilateralism). Moving forward, however, as countries such as India play a more prominent role on the world stage, they may be increasingly willing to embrace regional and multilateral arrangements and try, to the extent possible, to structure these institutions to their advantage.

CONCLUSIONS

Key features of the environmental security of the HKH region were identified at the workshop by the breakout groups on Demography and Security and Risk Factors and Vulnerabilities. Starting from those concepts, the Committee used its expert judgment, reviews of the literature, and deliberation to develop the following conclusions:

- Natural disasters in South Asia involve meteorological, hydrological, and geophysical phenomena that are not unique to the HKH region. Current efforts that focus on these natural hazards and disaster reduction in South Asia can offer useful lessons when considering and addressing the potential for impacts resulting from changes in snowmelt processes and glacial retreat in the region.
- Current international datasets indicate that over the past century, natural disasters in the region have been flood-dominated in terms of the frequency of events and number of people affected. However, the number of people killed over the past century by natural disasters was dominated by droughts and related famines. Over the past 30-year period the patterns and trends are less clear. Floods have had increasing significance in the numbers of people affected, while earthquakes have been associated with the highest number of people killed.
- Modernization and globalization may reduce losses of life and long-term macroeconomic impacts of disasters, but they can also increase the numbers of people affected and the economic damages.
- At the regional level of disaster management, organizations give particular emphasis to international cooperation, information sharing, and capacity building, as well as an increasing emphasis on linking climate change with disaster risk reduction. At the national and state levels, processes of devolution or centralization over time can affect disaster response. An increased focus on vulnerability and resilience within the disaster research community could lead to improved disaster management.
- Changes in transboundary water flows can generate or increase conflicts of interest among riparian countries, and these climate-induced changes will further complicate changes driven by economic, demographic, and political factors.
- Among the most serious challenges, even in the absence of climate change, are the magnitude of conflicting demands for limited water resources, the lack of corresponding institutional capacity to cope

with such conflicts, and the current political disputes among regional actors that complicate reaching any agreements on resource disputes. Water management institutions need to think systematically about integrating climate change risks in water resources policy, and they need to function in ways that are flexible and take account of the interests of all parties.

- The most dangerous situation to monitor for is a combination of state fragility (encompassing, e.g., recent violent conflict, obstacles to economic development, and weak management institutions) and high water stress.
- Although the history of international river disputes and agreements in this region suggests that cooperation is a more likely outcome than violent conflict, social conditions may have changed in ways that make historical patterns less informative about current and future challenges. Changes in the availability of water resources may still play an increasing role in political tensions, especially if existing water management institutions do not evolve to take better account of the social, economic, and ecological complexities in the region. Agreements will likely reflect existing political relations more than optimal management strategies.
- Changes to the hydrological system are inevitable, and adaptation is needed at all levels of governance. Lessons can be learned from developed countries, but these arrangements will not operate in the same way, and the time horizon for these solutions to bear fruit might be significant. Adaptation approaches need to be flexible enough to change with changing conditions, for example, smaller-scale and lower-cost water management systems, because of uncertainty in impacts and the dynamic nature of coming changes. There is a need to think through adaptation protocols now rather than when fear and urgency have become widespread.

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Conclusion

The climate and hydrology of the HKH region are changing. There are many important uncertainties about the current state of physical and social systems in the region in addition to the uncertainties about the future. However, not everything is uncertain or unknown. It is important to consider the impact of glacial retreat on regional water resources in the larger, hydroclimatic and social context of the HKH region. The effects of climate changes on glacier dynamics will affect both the supply and demand for water in the Himalayan region, and these changes will, in turn, affect the vulnerability of key populations to freshwater problems. Glacial retreat is only one factor that contributes to changes in the hydrological cycle, and the relative importance of glacial meltwater varies across the region and between seasons. In most instances, the contribution to surface-water discharge of snowmelt exceeds that of glacial melt. Glacial melt does contribute to the water flow in major rivers such as the Ganges and Indus, but for low-lying areas such as the Gangetic Plain, at much lower percentages than thought several years ago. The effect of glacial retreat will be most evident during the dry season, particularly in the west. In all seasons, changes in many regions are likely to be dominated by shifts in the location, intensity, and variability of precipitation (both rain and snow) rather than glacial retreat. Glacial meltwater is not a major contributor for river systems to the east but is more important for river systems to the west. Kaltenborn et al. (2010) conclude that,

> In general, the impact of melting glaciers on the seasonal distribution of river flow is greatest where (i) ice melt occurs during a dry season; (ii) glacier meltwater flows into semi-arid areas; and/or (iii) small annual temperature cycles mean that there is little seasonal variation in snow cover. Conversely, the seasonal effect is smaller where there is significant precipitation during the melt season, such as the monsoonal central and eastern Himalaya.

Melting of glacial ice plays an important role in maintaining water security during times of drought or similar climate extremes. For example, in the European Alps during the drought year of 2003, glacial melt contributions to August discharge of the Danube River were about three times greater than the 100-year average (Huss, 2011). Thus, water stored as glacial ice is the region's hydrological "insurance," acting as a buffer against the hydrological impacts brought about by a changing climate, releasing the stored water to streams and rivers when it is most needed.

There may be normal, even increased, amounts of available meltwater to satisfy dry season needs because of the release of "insurance" water from storage in retreating glaciers for the next several decades (Barnett et al., 2005). To illustrate, the role of glacial wastage contributions to discharge under future warming scenarios was investigated for three highly glacierized catchments in the Alps that have long-term climate and discharge records (Huss et al., 2008). Annual runoff from the drainage basins shows an initial increase which is due to the release of water from glacial storage. After some decades, depending on catchment characteristics and the applied climate change scenario, runoff stabilizes and then drops below the current level. Retreating glaciers of the HKH in the short term (decadal time frame) will subsidize surface flows by melting water held in storage, mitigating immediate losses to discharge by retreating glaciers (Kaser et al., 2010).

As noted in Chapter 2, paleoclimate records suggest a mixed record of wetness and dryness during the 20th century in the monsoon-dominated eastern HKH and hydrological modeling indicates that glacial melt is not a major contributor to river systems in the east (i.e., the Ganges, Yangtze, and Yellow). Thus, for the eastern HKH, these factors could result in little change to annual surface-water discharge, but could result in the loss of "insurance" water that glacial melt provides for water security during times of drought. In the western HKH, paleoclimate records indicate a trend toward wetter conditions in the 20th century and hydrological models indicate that glacial melt is much more important in the west (i.e., the Indus Basin). Thus, the consequences of climate change to water security could be large if a reduction in available surface water either annually and/or seasonally occurs in the western HKH. However, the trend toward wetter conditions in the western HKH confounds this assessment.

During situations such as these, groundwater, a significant amount of which is supplied to the major river plains of the region by the Himalayas, will be looked to as a source to offset water scarcity. Thus, water security issues for lowland populations over the next decade are more likely to come from overdrafting of groundwater resources than changes in discharge from retreating glaciers.

Although a greater understanding of the glaciers of the HKH region will inform knowledge about water security in the region, improved understanding of the science of the glaciers is itself not sufficient to answer all questions about the relationship between the hydrology, the population, and the policies and politics of the region. As discussed in Chapter 3, social changes are affecting water use at a greater rate than environmental factors are affecting the availability of water. For example, rising standards of living, including improving and changing diets and greater energy use, will have a significant effect on water-use patterns over the coming decades. Even if streamflow remains relatively stable in the short term, human factors could lead to water scarcity. Changing standards of living could also influence vulnerability to natural hazards. Although economic development could reduce adverse outcomes, including loss of life, monetary loss could increase.

A WAY FORWARD

When considering the link between humans and the environment in the context of water security in the HKH region, four themes emerge: (1) there is significant variability in the climate, hydrology, and glacier behavior as well as the demographics and water-use patterns of the region; (2) uncertainties exist and will continue to exist in both the physical and social systems; (3) to reduce and respond to this uncertainty there is a need for improved monitoring of both the physical and social systems; and (4) in the face of uncertainty, the most compelling need is to improve water management and hazards mitigation systems.

Theme 1: There is significant variability in the climate, hydrology, and glacier behavior in the region as well as the demographics and water-use patterns within the region. The retreat rates of Himalayan glaciers vary over time and space, with the rate of retreat being higher in the east than the west. There are confounding factors such as dust and black carbon that will affect glacial melt and in some cases increase glacial wastage. Changes in the monsoon will probably be more important than changes in glacial wastage at lower, downstream elevations. Rates of urbanization vary across the region, as does the portion of the population with access to improved water and sanitation.

Theme 2: Uncertainties exist and will continue to exist in both the physical and social systems. The impact of future climate change is uncertain but will probably accelerate rates of glacial retreat. Accelerated glacial retreat rates will have significant impacts in local, high-mountain areas but will probably not be very important downstream. As the region's population becomes more urbanized and standards of living change, water-use patterns will also change in ways that will be difficult to predict. Existing demographic methods to not allow for projections at sufficient spatial resolution to determine whether, for example, certain basins and elevation zones will experience higher rates of population growth than others and how the demographic composition of those specific areas will change. In both the physical and social systems, stationarity—the assumption that the systems will fluctuate within a known range of variability—will no longer apply. In other words, the past is not a good basis for prediction, and past trends in the climate, hydrology, glaciers, and population of the region will not be a viable guide for the future (e.g., Milly et al., 2008).

Theme 3: To reduce and respond to this uncertainty, there is a need for improved monitoring of both the physical and social systems. Monitoring will need to occur on a more extensive and consistent basis. Without enhanced monitoring, the information needed to respond to changing environmental and social conditions will be unavailable. Monitoring and research will further understanding of both the physical and human systems in the region, and identify the various options available to respond to change in the face of uncertainty.

Theme 4: In the face of uncertainty, the most compelling need is to improve water management and hazards mitigation systems. Existing patterns of water use and water management need improvement. As discussed in Chapter 3, some progress has been made in improved assessments in the recent past. Going forward, improved implementation of lessons from these assessments in water policies and programs will be necessary. Options for adapting to climate change are discussed in greater detail in the next section. However, the people most likely to be affected by changing water security in South Asia are the rural and urban poor who have the least capacity to adapt to changing environmental and social conditions and hazards. Management of groundwater and demand-side management are among the areas where improvements can be made.

RESEARCH AND DATA NEEDS

Anticipating future conditions in the HKH region is hindered by an incomplete understanding of current conditions and of both the extent to which natural feedback mechanisms will generate new equilibria and human systems will adapt to signals of stress and change. As discussed throughout the report, many open scientific questions remain about the physical and social systems of the region, which, if addressed, could lead to a greater understanding. These research and data needs are presented in roughly the same order as the topics appeared in the report, and the order does not indicate priority. These needs are critical to more fully address the questions in the Committee's charge.

Physical Geography

The HKH is one of the least-observed regions on Earth. Currently available data lack the necessary spatial and temporal resolution, as well as quality, to fully understand the region. There is a need for carefully designed surface observing systems (including temperature, precipitation amount and type, streamflow, glacial mass balance, glacier albedo, groundwater, paleoclimate proxies) that are integrated with satellite observations to provide comprehensive monitoring of the region. In addition to new data, pooling of existing data and resources, including release of relevant classified or restricted satellite imagery or water data, and sustained international cooperation and data sharing are critically important to advance understanding and reduce uncertainties. Comprehensive monitoring and data sharing would help answer the following questions:

- *Climate, meteorology, and aerosols:* What are the effects of greenhouse gas warming and black carbon radiative forcing on winds, temperature, precipitation variability, and trends in the summer monsoon and mid-latitude westerlies? How much of the regional atmospheric aerosol loading is driven by local emissions compared with transport from remote sources? How do black carbon deposition, snowfall, and snow turnover processes combine to affect the albedo of glaciers and snowpack? How has the temperature in the mid and lower troposphere changed? How do current changes in the regional climate compare to natural climate changes that occurred in the past? How will the monsoon change in the future?
- *Glaciers*: What is the relationship between climate changes and the mass balance of the HKH glaciers? What is the response time of individual glaciers to climate forcing, and how does this response time vary among glaciers in the region? Have temperature changes in the mid and lower troposphere affected the equilibrium line altitude or the ratio of snow to rain? How does snow cover change seasonally?
- *Hydrology*: What is the relative contribution, seasonally and annually, of glacial wastage and meltwater to total streamflow in the major rivers of the

HKH region? What are the surface water-groundwater recharge mechanisms in the region? How will climate change affect groundwater supply? How can hydrological data become more widely accessible to the science and management communities? How can remote sensing be used in conjunction with well data to increase understanding of groundwater in the region?

Human Geography

Currently available demographic compositional data do not conform to geophysical parameters and lack the necessary spatial resolution to determine whether, for example, certain basins and/or elevation zones will experience higher rates of population growth than others. Current understanding of water usage is poor because of a lack of regional datasets. Remote sensing advances may address some of these deficiencies, particularly in the plains. Improved measurement of water withdrawals from surface water, and even more so groundwater pumping, will be crucial for developing, monitoring, and managing regional water budgets, hazards, and stresses. As lowland water and energy scarcity may increase demand for mountain water storage, advances in water use analysis will have increasing importance. Improved datasets and monitoring would help answer the following questions:

- *Demographics*: How will populations change in areas with water scarcity as compared with areas with sufficient water supplies?
- *Water-use patterns*: How can major improvements in water-use data collection, access, and utilization be accelerated? How do changing lifestyles, standards of living, and demographic trends affect water supply, demand, and management?
- *Water management*: What dams are planned in the region, and how will they affect water management and hydrology? How can the results of international- and national-level climate assessments be incorporated into water management and policy at the subnational level?

Environmental Risk and Security

Hazard datasets remain inconsistent and not coded in ways that enable causal analysis of large-*N* samples of floods, droughts, heat waves, and secondary impacts associated with climate variability. Although deaths and numbers of persons affected are regularly reported, and to a lesser extent physical damages (e.g., houses and infrastructure destroyed), rigorous economic damage and need estimation are a priority for policy research. Disaster resilience, recovery, and reconstruction processes are less well documented than initial impacts, in part because they occur when postdisaster attention wanes. The human dimensions of loss and reconstruction require intensive field research, and strong relationships between research and practice. New methods of postdisaster mobile phone survey data transfer and mapping have considerable promise for advancing socioeconomic lines of research on a regional scale. Improved economic, social, and political datasets would help answer the following questions:

- *Natural hazards and vulnerability*: Which populations in the region will be most vulnerable to a changing climate? What are the proximate and root causes of vulnerability in the HKH region? How do alternatives for secure and sustainable livelihoods differ for populations in the mountains more dependent on glaciers and larger downstream populations on the plains? How can the results of collaborative research on exemplars of disaster-resilient settlement, infrastructure, and housing in mountain environments of the HKH region complement initiatives to increase collaboration on climate change, glaciology, glacial lake outburst flood monitoring, and flood warning—and help increase the prospects for successful adaptation to changes in climate and hydrology in the region? How can early-warning systems be used to minimize deaths from hazards such as GLOFs?
- *Security dynamics and water conflict*: What is the current and future institutional capacity to absorb change at the local, national, and international levels? How can the research community design appropriate metrics to monitor the capacity of governmental institutions to address water stress? Does water stress, among other stressors, affect state stability? Through what mechanisms? What are the possibilities for better incorporation of scientific information about glaciers, hydrology, and climate change into international water-sharing treaties? Will climate change impacts on glacial melt and hydrology be severe enough to

constitute a threat to water and food security and/or political stability?

OPTIONS FOR ADAPTING TO CHANGES IN CLIMATE, HYDROLOGY, AND WATER AVAILABILITY

There are some potential adaptations that governments, communities, or individuals may consider in response to climate change's effects on the hydrologic system. Even with significant international progress toward mitigating greenhouse gas emissions, with current levels of carbon dioxide and other greenhouse gases in the atmosphere, there will be significant climate change over the next few decades, and thus some adaptation, particularly to strengthen water management systems, will be necessary.

It can be difficult to make decisions about which adaptation strategies to pursue in the face of uncertainty about the magnitude of climate change's hydrological impacts. Also, there are significant uncertainties about the effectiveness of various adaptation options. Some adaptation options have been shown to be effective in adapting to variability under current climatic conditions, but it is not known whether they will hold up under a changing climate (NRC, 2010a). Additionally, implementation of adaptation strategies can be challenging in developed countries:

> Numerous attempts have been made to develop and implement adaptive management strategies in environmental management, but many of them have not been successful, for a variety of reasons, including lack of resources, unwillingness of decision makers to admit to and embrace uncertainty; institutional, legal, and political preferences for known and predictable outcomes; the inherent uncertainty and variability of natural systems; the high cost of implementation; and the lack of clear mechanisms for incorporating scientific findings into decision making. Despite all of the above challenges, often there is no better option for implementing management regimes. . . . (NRC, 2011b)

And developing countries are likely to face as many challenges.

Good first adaptation strategies to pursue are generally flexible (i.e., they do not lock a country or other entity into a long-term commitment to the strategy), are relatively low-cost and are "no regret" strategies (i.e., they would be good strategies to take regardless of how severe climate change's impacts become). In general, many strategies that encourage good management of water resources under current climate could serve as useful adaptation strategies in a world with altered climate. Similarly, because people with fewer resources are often more vulnerable to climate change disruptions, many strategies that promote sustainable economic development could also be useful adaptation strategies in the face of climate change.

There is a large literature on the topic of adaptation, and the Committee can only briefly describe a few potential adaptation options in this section. Adaptation was discussed previously in the context of water management institutions and disaster agencies in Chapters 3 and 4, respectively. Here, the Committee describes options that affect the supply or timing of water available to users, followed by options that affect the demand of water by users. Then the Committee discusses integrated watershed management and river basin management, which often consider both supply and demand. Finally, the Committee discusses adaptation options to decrease the risk of negative impacts from flooding.

Adapting Under Uncertainty: The Need to Monitor

As discussed above, and throughout this report, lack of understanding and a paucity of data about current and emerging conditions of glacial melt and the hydrological system more generally are major sources of uncertainty in the region. Adaptive management[1] of water resources depends critically on observations of changes that are occurring. Therefore, adaptation options will rely on expanding the monitoring programs in the region, including increased hydrometeorological data; measurements of glacial mass balances, seasonal snow cover, black carbon on snow and ice; assessment of GLOF risks; streamflow data (i.e., discharge); water quality; and demographic patterns of water use. Both remotely sensed and in situ data are valuable for such monitoring programs (USAID, 2010).

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[1] Adaptive management is a flexible approach designed to meet management goals under a variety of future climate conditions and requires a nonstationary view (e.g., Milly et al., 2008; NRC, 2010a, 2012b).

In addition to uncertainties in the physical systems of the region, there are also uncertainties in the social systems. Adaptive management of the region's water resources will require a greater understanding of how each option will affect downstream users, the potential negative consequences of each option, and whether an option may prove to be maladaptive. In addition, it will be necessary to monitor the impacts of adaptation policies, and make adjustments to the policy as required. Interventions that can be repurposed and customized are especially desirable when operating under conditions of uncertainty and change. The capability to support and integrate interventions into local innovations that are effective is also of great value. Effective program evaluation, something that is often overlooked, is especially important when designing and implementing interventions under conditions of uncertainty. A central concern with adaptation strategies is their potential for changing power relationships and introducing conflict, and for creating unrealistic expectations that can become difficult to manage and a source of significant social tension. Some management and adaption options in the face of hydrological change may themselves detrimentally affect water availability for downstream riparians, possibly sparking or exacerbating water conflicts or political tensions. In other words, the rational pursuit of otherwise reasonable adaptation options (e.g., the construction of more water storage or the expansion of irrigation) as insurance against prospective climate-induced shortfalls or volatility in future supply could have negative consequences.

Supply-Side Strategies

One potential impact of climate change on the region's hydrology is to increase the frequency of both high-flow events and low-flow events. One adaptation option is to try to increase storage, so that water can be stored during wet periods for use during dry periods. Three approaches to this effort are improved water supply forecasting, dams, and catchment systems. In each approach, the need for flexible systems that can adapt in a range of uncertain futures suggests that small-scale and low-cost systems may be the best options for at least the planning horizon of most countries and donors.

New dams, either at a large or a small scale, are one way to increase hydropower and/or storage in both the Indus and the Ganges/Brahmaputra, although any new dam construction would likely be a politically controversial decision, both within a country and between countries. Because climate will be changing over the long term, dam planning needs to include multiple scenarios over the projected life of the dam to ensure its usefulness under climate change. As well as the potential for being maladaptive over time, dam construction could also have unintended and cumulative negative consequences on the regional ecology, settlements, and downstream sediment supply (e.g., NRC, 2011a). Additionally, geological instability limits the stability of major dams and reservoir development in the region and adds risk from dam failure. In any event, dam management regimes at existing dams will need to be altered, so that, rather than being operated on the basis of historical distribution of streamflow events, dam operation is based on the current (altered) climate. Because changes in dam management will affect the availability of water to downstream users, either in the same country as the dam or a different one, such changes may have the potential for conflict if decisions are not made cooperatively with all affected parties.

More local-scale catchment systems can store water in wet seasons for use in dry seasons. Catchments are often constructed and managed at the local level. They are relatively less expensive, lower impact, and easier to change than large dams.

Another adaptation option sometimes used in the face of water shortages is to construct a system for interbasin water transfers, moving water from a relatively wet place to a relatively dry place. Such systems are often extremely expensive to construct, such as the Chinese plan to divert water from south China to the north, the South-North Water Diversion Project, which is estimated to cost around $62 billion dollars (Wong, 2001). Moreover, any plan by upstream countries for an interbasin transfer in the Ganges/Brahmaputra Basin would likely have international political repercussions and could be the basis for a conflict. Interbasin water transfer is further complicated by the lack of understanding of the impact of climate changes on the hydrology of the region. Changes in the flow of rivers in the relatively wet areas could impair their ability to adequately provide water for the dry areas, decreasing the effectiveness of a very expensive project. For these reasons, proposals for interbasin water transfers are generally controversial among hydrologists, policy analysts, NGOs, and the courts.

Usually, climate change adaptation is considered a separate topic from climate change mitigation (i.e., the reduction in emissions of pollutants that cause climate change). Greenhouse gas emission mitigation is by necessity a global challenge, because most greenhouse gases are well mixed in the atmosphere. However, for South Asian countries the control on the emission of aerosols and particulate matter could help mitigate the regional pattern of climate change, because these pollutants play an important regional role in, respectively, the monsoon cycle and the rate of snowmelt and icemelt. Although the exact scientific relationship between these pollutants and regional climate is still an area of active scientific exploration, there is potential that countries could cooperate to maintain traditional climate patterns to some extent by limiting emissions of aerosol and particular matter. Because actions by a small set of countries could significantly change the regional concentration of these pollutants, such an agreement could avoid the problem facing many global agreements about greenhouse gas pollutants, where there are many actors who have to approve an agreement. Reducing aerosol emissions is also a resilience-building strategy, in that it has the co-benefit of reducing respiratory diseases and premature deaths, especially among women and children (NRC, 2010b).

One common adaptation strategy used to address short-term water shortages is to withdraw groundwater. Groundwater is a form of water storage, and can be sustainably used as long as withdrawal rates do not exceed recharge rates of the aquifer. However, changes in the regional hydrology could affect the recharge rate, leading to uncertainties in the amount of water that can be sustainably withdrawn. Increased use of groundwater may be one adaptation to climate change, but some major aquifers are already being depleted by excess withdrawals, so there are (often uncertain) limits to how extensively increasing withdrawal from groundwater can be a long-term adaptation to climate change. In addition, groundwater withdrawal in delta regions could lead to increased subsidence, which in turn leads to increased sea level rise. Increased use of the traditional *karez* or *qanat* system of channeling groundwater (Box 3.1) may serve as a climate change adaptation, but success depends on the level of community cohesion and will be limited unless enough groundwater is available for the system. Because available data indicate the groundwater is currently being used unsustainably in the region, this adaptation option, by itself, is likely not realistic; however major advances in conjunctive management of surface and groundwater will be a high priority.

There are also options for local water storage. For instance, some high-altitude communities in the HKH region have experimented with building small ponds that freeze in the winter into miniglaciers (ICIMOD, 2000b). These miniglaciers then melt slowly over the growing season, providing farmers and towns with water. Larger reservoirs could potentially become a hazard due to earthquake-induced failure, or change the energy balance of snow-covered basins. Additionally, there are emerging technologies that harvest water from humid air (ICIMOD, 2000a). An increasing number of cities in South Asia are adopting harvesting requirements in building and development codes (Agarwal et al., 2001). Another way to increase water supply at the local level is to reuse treated wastewater (e.g., Kumar et al., 2005), particularly for irrigation.

Given the uncertainty in the future magnitude of climate change impacts, one general adaptation option is to expand the diversity of techniques that are used to obtain water. The idea is that instead of just one source, which could be critically affected by climate change, multiple sources would be relatively less sensitive to disruption by climate change, unless climate change were to impact all the sources simultaneously and synchronously.

Demand-Side Strategies

Any strategy that increases water-use efficiency can serve as a potential climate change adaptation, but can also increase a population's vulnerability if users do not see the value in using less water. Because users sometimes expand their use to take advantage of increased water availability, efficiency gains do not always translate into reductions in total water use. These gains may still increase the productivity of a given water use per unit of water withdrawn and hence a sector's resiliency to climate change. The agricultural sector is the biggest user of water, and the one with the greatest potential for increases in water-use efficiency to serve as an adaptation. For instance, cotton, rice, and sugarcane irrigation in the Indus Basin use a large volume of water, and small reductions in the amount of water used per hectare could significantly reduce water use by these crops. Another sector where gains in water-use efficiency may be helpful in adapting to climate change would be the energy sector. Thermoelectric power plants that use once-through cooling systems withdraw significantly more water than recirculating cooling systems. Although most of this water is discharged to the stream after use, there can be local thermal impacts. A switch from once-through cooling to recirculating cooling can significantly reduce water withdrawals by the sector. However, recirculating systems have higher consumptive use than once-through systems, so trade-offs are necessary (NREL, 2003). Municipal water systems also could improve technological efficiency, perhaps as part of extending their coverage to growing populations. Such adaptation strategies require large infrastructure investments, which affect their feasibility.

There are a number of tools available to affect demand management. Some of these are technology based and include flow restrictors, low-flush toilets, closed conduit irrigation systems—sprinkler and drip systems—and water metering, either by itself or in connection with rational regimes of water pricing. In general, the relatively high capital costs of these technologies make their adoption prohibitively expensive for much of the water-using population in the region. More decentralized demand management techniques include water pricing and water rationing. Shah (2009) describes how the availability of complementary inputs such as energy for pumping groundwater have been used successfully to manage demand for irrigation water in some areas. This is accomplished by making energy available only during certain periods of the day. These decentralized demand management techniques have the advantage of allowing each user to adjust consumption according to their circumstances.

More significant climate change impacts on hydrology might necessitate changes in land use over time. For instance, farmers might adapt to climate change by shifting from a water-intensive crop that requires significant irrigation to a less intensive, perhaps rainfed, crop. Such a strategy would require periodic adjustments to account for further changes in precipitation patterns. The focus of adaptation strategies might also be how to reduce irrigation demands during extreme low-flow periods of the year. Although forgoing irrigation during low-flow events imposes an economic cost on farmers, it may leave enough water in surface water and groundwater for downstream users. However, this may have a negative impact on regional food security, again demonstrating the complexities of adaptation options.

River Basin Management

The ideal model for river basin management and the processes its development, management, and maintenance have been given considerable thought and have evolved through time (Molle et al., 2010; NRC, 2010c). Embedded within this discussion is the concept of environmental flow (EF) that describes the water regime (quantity, timing, and quality) within a system that is required to maintain the surrounding ecosystem and human livelihood. Most EF assessments have been developed and performed in developed countries. Yet assessment of EFs in developing countries, such as those in the HKH region, is a necessary step toward successful river basin management, and some progress has been made (Smakhtin et al., 2006).

Often, water managers implement minimum EF requirements based on system objectives such as maintaining populations of fish at a given level or supplying local communities and/or agriculture with a given volume of water (NRC, 2010d). When a river basin is at the point where there is no more utilizable flow in a given year, the basin is said to be “closed” (Falkenmark and Molden, 2008). If a basin is closed and utilization continues, an unsustainable situation ensues. The waters of the Indus and the Ganges are already said to be overallocated or nearing overallocation, thus “closed” basins (Falkenmark and Molden, 2008; Smakhtin, 2008).

Efforts to effectively manage river basins attempt to avoid this type of situation and the associated impacts such as a decrease in water quality or inequitable sharing of the resource. It is increasingly being realized that the biological and social systems supported by water are not adequately described by a single minimum flow requirement or a set of flow requirements, but a more comprehensive assessment of water management is needed that accounts for hydrological change (NRC, 2012b). This would include, for example, basic strategies such as demand management, increased storage, establishment of EFs, and operational flexibility (NRC, 2012b).

One option, integrated watershed management (IWM), attempts to consider both demand- and supply-side strategies for managing water in a basin to find a solution to any water problems in the basin. Although definitions of IWM vary, the general focus of management is on looking at all uses of water simultaneously when making policy decisions. For the Ganges/Brahmaputra and the Indus, there is a clear need, for example, to link management of surface-water resources more closely with management of groundwater resources. There is also a need for management decisions to be made that consider the needs of water users in different countries. This is often a difficult task politically, but the existing international agreements (e.g., Indus Water Treaty) illustrate that agreements about water allocations can be achieved.

Many of the international agreements in the region are not yet fully integrating climate change considerations into their decision making, and any progress on this front could serve as a climate change adaptation, by ensuring that basin water resources are managed efficiently and equitably in a changing climate. Climate change planning at the national level is important. Even if many national hydrological agencies are considering the potential impacts of climate change, many other national government agencies are not. If, for instance, agencies deciding on the construction of new irrigation systems are not adequately considering the effect of climate change in their decisions, then countries may commit significant resources to irrigation that will not be useful in a future climate.

At national and subnational levels, opportunities exist to provide knowledge and assistance to farmers in efficient water use, especially as regards irrigation systems. Local or subnational organizations, networked for greater impact, can develop farm-level and cooperative strategies for both groundwater and surface-water use. Another adaptation option includes establishing or strengthening community-based water user associations (WUAs) and forest user groups (FUGs), with better coordination links to national policy frameworks for water management and health (clean water and sanitation) (USAID, 2010).

Managing Flood Risks

The first step in reducing potential flooding impacts from climate change is to map which communities are at risk (NRC, 2009). The primary risk of flooding from glacial melt per se is GLOFs, which are mostly a risk to high-elevation communities along rivers and streams, but similar phenomena can pose risks at lower elevations when debris or ice jams dam water that then bursts out. In contrast, the risk of downstream flooding may be increased by climate change, depending on a number of factors including the rate and timing of snowmelt and the magnitude of monsoonal rains. Because there are many large settlements near rivers in the lower floodplains of the Ganges/Brahmaputra and Indus basins, if climate change increases the risk of downstream flooding events, it could significantly affect hundreds of millions of people.

Once communities at risk from flooding are identified, there are various options that can be used to minimize risk, although many are very difficult to implement. New development can be limited in floodplains or other sensitive areas, or existing homes and infrastructure in floodplains at risk of flooding can be decommissioned. Vegetation, including forests, can be restored where needed to retain water and thus mitigate flooding. Governments can offer flood insurance programs, as the Federal Emergency Management Agency's National Flood Insurance Program does in the United States, both mandatory in high-risk areas and nonmandatory in low-risk areas. Alternatively, new infrastructure can be built to protect areas at risk of floods (e.g., dams, pumping stations, or storage basins). Sometimes this infrastructure is traditional "gray" infrastructure, such as levees. However, levees are often considered to be maladaptive, because they can encourage settlement in vulnerable low-elevation areas (NRC, 2012b). In other cases, so called "green" infrastructure solutions are used, where floodplains are reconnected hydrologically with rivers to allow flood waters to spread out over the entire floodplain. This reduces the flooding risk to downstream communities by reducing the height of peak flows in a river.

Flood management also includes early warning systems, which can reduce deaths and injuries, and disaster response capacity, which is highly variable in the region. Improvements in each of these areas would be adaptive to both glacial melt and hydrological change.

There is a growing sentiment within parts of the climate science community that the social effects of climate change are already more extensive than previously thought or recognized, and are mounting more quickly and more extensively than predicted. This suggests that in discussions of climate change impacts over 50-year-plus time horizons may have to be replaced with ten-year-plus time horizons, and more comprehensive approaches to hydroclimatic forecasting, natural hazards mitigation, and water management.

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Appendix A

Workshop Agenda and Participants

Himalayan Glaciers, Hydrology, Climate Change,
and Implications for Water Security

Workshop
October 19-20, 2011

House of Sweden
2900 K Street NW
Washington, DC

WEDNESDAY, OCTOBER 19, 2011

7:30 A.M.	*Breakfast Served*	
8:00 A.M.	Welcome and Purpose of Workshop	Henry Vaux *University of California, Berkeley*

Regional Climate and Meteorology
Moderators: Edward Cook, *Lamont-Doherty Earth Observatory*
William Lau, *NASA Goddard Space Flight Center*

8:30 A.M.	Observed and Projected Changes in Hydrometeorological Variables over the Indian Himalayas	Krishna Kumar *Indian Institute of Tropical Meteorology*
8:55 A.M.	Regional Meteorology and Monsoon Dynamics	Arnico Panday *University of Virginia*
9:20 A.M.	What Do We Know About Snow Darkening Effects on the Himalayan Glaciers?	Teppei Yasunari *NASA Goddard Space Flight Center*
9:45 A.M.	*Break*	
10:15 A.M.	Hydroclimate Variability and Change over the Northern Gangetic Plain and Himalayan Region: Observations, Simulations, and Projections	Sumant Nigam *University of Maryland*
10:40 A.M.	Hydro-Climatic Challenges for Pakistan: Ideational and Material Drivers	Daanish Mustafa *Kings College London*
11:05 A.M.	Group Discussion	
11:45 A.M.	*Continued Discussion over Lunch*	

Regional Hydrology, Water Supply, Use, and Management

Moderator: Peter Gleick, *Pacific Institute*

1:00 P.M.	The Glaciers of the Hindu Kush-Himalayan Region: A Summary of the Science Regarding Glacier Melt and Retreat in the Himalayan, Hindu Kush, Karakoram, Pamir, and Tien Shan Mountain Ranges	Richard Armstrong *University of Colorado*
1:25 P.M.	Glacial Lake Outburst Floods	Alton Byers *The Mountain Institute*
1:50 P.M.	The Water Towers of Asia: Can we Reconcile Water Demands for Livelihood in a Changing Climate?	Shama Perveen *Columbia University*
2:15 P.M.	Under Pressure: International Water Management Challenges in the Himalayan Region	David Michel *Stimson Center*
2:40 P.M.	Group Discussion	
3:20 P.M.	*Break*	

Regional Demography

Moderator: Deborah Balk, *City University of New York*

3:40 P.M.	Overview of Social and Family Demography in South Asia	Sajeda Amin *Population Council*
4:05 P.M.	Regional Population Trends and Environmental Issues	Malea Hoepf Young *Independent Consultant*
4:30 P.M.	Group Discussion	
5:15 P.M.	*Break*	
6:00 P.M.	*Continued Discussion over Dinner*	

THURSDAY, OCTOBER 20, 2011

7:30 A.M.	*Breakfast Served*	
8:00 A.M.	Inventorying and Monitoring the Recent Behavior of Afghanistan's Glaciers	Bruce Molnia *U.S. Geological Survey*

Regional Politics

Moderator: Marc Levy, *Center for International Earth Sciences Information Network*

8:30 A.M.	Resource and Security Links	Richard Matthew *University of California, Irvine*
8:55 A.M.	Group Discussion	
9:40 A.M.	*Break*	

Risk Factors and Vulnerabilities

Moderator: Elizabeth Malone, *Joint Global Change Research Institute*

10:00 A.M.	Panel Discussion	
	Afghanistan	Sanjay Pahuja *World Bank*
	Bangladesh	Ahsan Uddin Ahmed *Centre for Global Change*
	Bhutan	Thinley Namgyel *National Environment Commission Secretariat*

	China	Jennifer Turner *Woodrow Wilson Center*
	India	Sumit Ganguly *Indiana University, Bloomington*
	Nepal	Dipak Gyawali *Nepal Water Conservation Foundation*
	Pakistan	David Archer *JBA Consulting*
12:15 P.M.	Assignments to Working Groups	Henry Vaux *University of California, Berkeley*
12:30 P.M.	*Pick Up Lunch and Break into Working Groups*	
12:50 P.M.	Working Groups Meet	
	Working Group 1 *Climate and Meteorology*	Moderator: Drew Shindell *NASA Goddard Institute of Space Studies* Rapporteur: Balaji Rajagopalan *University of Colorado*
	Working Group 2 *Hydrology, Water Supply, Use, and Management*	Moderator: Mark Williams *University of Colorado, Boulder* Rapporteur: Bodo Bookhagen *University of California, Santa Barbara*
	Working Group 3 *Demography and Security*	Moderator: Robert McDonald *The Nature Conservancy* Rapporteur: Nathalie Williams *University of North Carolina*
	Working Group 4 *Risk Factors and Vulnerabilities*	Moderator: James Wescoat *Massachusetts Institute of Technology* Rapporteur: Henry Vaux *University of California, Berkeley*
2:30	*Break*	
2:45 P.M.	Presentations from Working Group Rapporteurs	
3:45 P.M.	Closing Remarks	Henry Vaux *University of California, Berkeley*
4:00 P.M.	*Workshop Adjourns*	

Participants

Ahsan Uddin Ahmed, *Centre for Global Change*
Sajeda Amin, *Population Council*
David Archer, *JBA Consulting*
Richard Armstrong, *University of Colorado, Boulder*
D. James Baker, *William J. Clinton Foundation*
Bodo Bookhagen, *University of California, Santa Barbara*
Alton Byers, *The Mountain Institute*
Tom Carson, *iSciences*
Ric Cicone, *iSciences*

Richard Engel, *National Intelligence Council*
Sumit Ganguly, *Indiana University, Bloomington*
Dipak Gyawali, *Nepal Water Conservation Foundation*
Malea Hoepf, *Independent Consultant*
Krishna Kumar, *Indian Institute of Tropical Meteorology*
Richard Marston, *U.S. Department of State*
Richard Matthew, *University of California, Irvine*
Mary Melnyk, *U.S. Agency for International Development*
David Michel, *Stimson Center*
Bruce Molnia, *U.S. Geological Survey*
Daanish Mustafa, *Kings College London*
Thinley Namgyel, *National Environment Commission Secretariat*
Sumant Nigam, *University of Maryland*
Sanjay Pahuja, *World Bank*
Arnico Panday, *University of Virginia*
Shama Perveen, *Columbia University*
Balaji Rajagopalan, *University of Colorado, Boulder*
John Steinbruner, *University of Maryland*
Andrew Taber, *The Mountain Institute*
Jennifer Turner, *Woodrow Wilson Center*
Nathalie Williams, *University of North Carolina*
Teppei Yasunari, *NASA Goddard Space Flight Center*

Committee Members

Henry J. Vaux, Jr. (Chair), *University of California, Berkeley*
Deborah Balk, *Baruch College of the City University of New York*
Edward R. Cook, *Lamont-Doherty Earth Observatory*
Peter Gleick, *Pacific Institute for Studies in Development, Environment and Security*
William K.-M. Lau, *NASA Goddard Space Flight Center*
Marc Levy, *Center for International Earth Sciences Information Network*
Elizabeth L. Malone, *Pacific Northwest National Laboratory Joint Global Change Research Institute at the University of Maryland*
Robert McDonald, *The Nature Conservancy*
Drew Shindell, *NASA Goddard Institute of Space Studies*
James L. Wescoat, Jr., *Massachusetts Institute of Technology*
Mark W. Williams, *University of Colorado, Boulder*

NRC Staff

Lauren Brown
Edward Dunlea
Chris Elfring
Shelly Freeland
Laura Helsabeck
Malay Majmundar
Daniel Muth
Paul Stern

Appendix B

Summaries of Workshop Presentations

Observed and Projected Changes in Hydrometeorological Variables over the Indian Himalayas

K. Krishna Kumar, Indian Institute of Tropical Meteorology

The Indian Himalayas can be divided into different sections: western, central, and eastern; this presentation focused on comparing and contrasting these regions. There is considerable complexity involved in observing changes over the Indian Himalayas. Most of the observations on projected changes in hydrometeorological variables are from the past 10-15 years, including the APHRODITE dataset, which has great promise. Most of the western Himalayas get precipitation in the winter, whereas the central region gets the most precipitation in the monsoon season. The eastern and central regions, dominated by the monsoon, show a decline in precipitation over the past ~50 years. The west does not show a trend in precipitation. Temperature, however, shows a general warming trend, over the last three decades in particular, but the seasonal monsoon is influential. Several researchers are collecting tree-ring data in India from the past 300-400 years in an attempt to reconstruct long-term climate record. In the western Himalaya, tree-ring chronologies indicate an increase in temperatures—in agreement with the temperature trends observed over the past 40-50 years in the western region. Trained models seem to capture end-of-century climatology well, giving hope for projecting into the future. Models indicate that in the near term (2020) the foothills show negative rainfall trends. However, further in the future (2050, 2080) it appears that the precipitation will be enhanced. Models show that the temperature trends will continue monotonically in the future (+2°C in 50 years), in agreement with the results from another model from the Inter-governmental Panel on Climate Change AR4.

Regional Meteorology and Monsoon Dynamics: Patterns, Changes, and Drivers of Change

Arnico K. Panday, University of Virginia

The dominant precipitation patterns in the Himalayan region are summer monsoons (in the central and eastern half of the region), some winter rain and snow, and winter fog as a source of moisture. There are east-west variations and north-south variations, though the latter are not as great. Evidence shows that temperature is increasing more rapidly with altitude; however, there are fewer observation stations at higher elevations, leading to a potential data bias. Over the Ganges Basin, there is an increase in aerosol haze as well as an increase in fog. Snow cover has decreased, which has been particularly noted in 2010 and 2011. There is also clear evidence of glacial retreat in the area, though there are not many studies on how glacial melt affects regional precipitation. There are several drivers of change in the area: greenhouse gases, an increase in aerosols, and a sixfold increase in black carbon emissions. Main sources of aerosols are biofuels from wood cookstoves. Forest fires, urban pollution, and dust being blown from the Thar Desert to the southwest are also contributors. In the Annapurna region, there is a strong buildup of haze with heavy convection on the south side. The Kali Gandaki Valley is a very open connection to the Tibetan Plateau; this could be a major route of transport of aerosols to the plateau and the glaciers.

What Do We Know About Snow-Darkening Effects on Himalayan Glaciers?

Teppei J. Yasunari, NASA Goddard Space Flight Center

Absorbing aerosols such as dust, black carbon, and organic carbon are well-known warming factors in the atmosphere. When aerosols deposit on snow, it causes darkening of snow, causing absorption of more energy at the surface, leading to accelerated melting of snow. If this happens to Himalayan glacier surfaces, the melting may contribute to mass balance changes, though the mass balance itself is a complicated issue. There are limited observations of the effect of snow darkening on glaciers, but most of our knowledge is the result of model simulations. Ice-core measurements of black carbon show much higher concentrations in recent years (1995-present). However, since 1860, there has not been an overall trend of an increase in dust. Black carbon satellite data over the region is still limited, and most of the snow samples measuring black carbon are from the eastern side of the region (e.g., in China). These snow samples show "rings" of very clear deposition that can help track levels of black carbon and dust. The black layers correspond to the spring season (when the atmospheric concentration of black carbon is higher). Though such studies show an increasing trend, we must be careful to integrate measurements to account for seasonality. The NASA GEOS-5 model simulations show very large deposition of black carbon in the Himalayan snowpack—much larger than anywhere else in the world. Some studies suggest that this has significantly affected the albedo of the snowpack. This seems to correlate to studies that are showing increases in snow surface temperature and decreases in the snow water equivalent.

Hydroclimate Variability and Change over the Northern Gangetic Plain and Himalayan Region

Sumant Nigam, University of Maryland, College Park

Analysis of the 20th century observational record can yield insights about future variability and change in the region. Models are not yet able to cover the regional hydroclimate, but the observational record itself has a lot of information that has not been sufficiently mined. AR4 simulations show that various climate products do not agree with each other (or the observations) regarding local trends. As such, there is a widely divergent agreement on projection models. Models can only produce the very broad features of climate and cannot resolve the specifics. However, this does not mean that the climate system cannot be resolved for the natural and secular impacts. Regressions of principal large-scale climate events, such as El Niño and monsoon, over the last century can show robust trends that can be used to reconstruct variables of interest (e.g., temperature and precipitation). Surface temperature is only captured broadly, and a latitudinal increase is observed in the region. If the natural variability can be unraveled from secular change components, analysis of the 20th century observational record could yield insights about future variability and change. There are several techniques to tease out the actual physical components from larger variability. For example, one can look at trends using observations for the full 20th century and the last 60 years. The 60-year trends show decadal variability most likely coming from the El Niño-Southern Oscillation. The century-long trend analysis does not show these trends.

Hydroclimatic Challenges for Pakistan: Ideational and Material Drivers

Daanish Mustafa, King's College London

Water has multiple values in all cultures beyond its obvious use for livelihoods and economic value generation. Most modern water management systems in the world tend to be indifferent to the multiple, cultural, spiritual, aesthetic, and identity values that are nevertheless important to water users. There is considerable uncertainty regarding specific climate scenarios at the country scale; but it is certain that past climatic normals will not continue into the future. Climate change for Pakistan, as in the rest of the world, will involve decisions on water management in a context in which past trends are no longer effective guides for future action. Pakistan in particular has suffered some dramatic and unusual hazards over the past decade, ranging from a multiyear drought in western Pakistan to relatively unusual tropical depressions and cyclones hitting southern Pakistan. Floods in the main-stem Indus River in northwestern Pakistan are extremely rare; the historic 2010 floods were one such occurrence. Pakistan has the largest contiguous surface irrigation system in the world. Much of the water entering the system is withdrawn for irrigation purposes, reducing the amount of water available to flush the system. This leads to a reduction of channel capacity, which was one of the factors in the floods of 2010. Incorporation of concerns about differential vulnerability, environmental quality, and social equity will be critical to building a climate-resilient future for Pakistan. Pakistani water managers will have to incorporate local people's multiple values for water within their management paradigms and seek to realize multiple social objectives from Pakistan's water systems beyond just economic growth.

The Glaciers of the Hindu Kush-Himalayan Region: A Summary of the Science Regarding Glacial Melt and Retreat in the Himalayan, Hindu Kush, Karakoram, Pamir, and Tien Shan Mountain Ranges

Richard L. Armstrong, University of Colorado, Boulder

Many of the glaciers in the Himalayas are retreating, especially at the lower elevations in the eastern Himalayas. However, there is no spatially comprehensive or regionwide evidence to support the claim that the glaciers of the Himalayas are retreating faster than any other location in the world. Data are sparse in the region, but the most common is terminus location. The terminus is a point measurement intended to describe the glacier but it does not do an adequate job of describing the entire system. Conditions in the region contrast between the east and the west; data in the region should be compiled. In the east, the river runoff system is dominated by the monsoon. As you move to the west, glacial ice and seasonal snow play a much bigger role. In the west, both the seasonal snow cover and glacier volumes are much more stable that they are in the east. The fact that glaciers across the Himalayas may not be disappearing at as rapid a rate as had been previously thought does not in any way reduce the need for mitigation and adaptation to the response of these glacier systems to climate change in the region. In the short term, well-planned management, conservation, and efficient use of water currently available are certainly as important as any changes that may take place in the regional climate in the near future.

Glacial Lakes and Glacial Lake Outburst Floods (GLOFs) in the Hindu-Kush Himalayas

Alton C. Byers, The Mountain Institute

As glaciers have melted in the Hindu Kush-Himalayas (HKH) and Andes, hundreds of new glacial lakes have formed behind dams usually consisting of soil and loose boulders. These lakes present a risk of glacial lake outburst floods (GLOFs). GLOFs often cause large loss of life and property downstream. Glacial lakes can become dangerous because they are held at bay by fragile terminal moraines that are susceptible to collapse (earthquakes, slides, etc.). When this breaks, the result is a GLOF. When overhanging ice is present, it can fall, and water can go over the wall. In terms of mitigation possibilities for this type of event, the Andes provide a good example. Between 1940 and 1950, they had several of these sorts of floods killing 10,000 people. In response, the government started working on how to control these floods through the fortification of the terminal moraine with a drainpipe or drilling through bedrock to create a canal to lower the lake level and use the water. A workshop and field expedition were held to discuss whether these technologies might be applicable in Nepal, and researchers discovered the value of local knowledge. The team formed a Global Glacial Lake Partnership to promote and enhance collaboration and communication between scientists.

Himalayas, the Water Towers of Asia: Can We Reconcile Water Demands for Livelihood in a Changing Climate?

Shama Perveen, Columbia University

The Himalayan region contains the largest area of glaciers, permafrost, and the largest freshwater resources outside the poles. It is the source of 10 of Asia's largest rivers and more than a billion people depend on the river flows for drinking water, irrigation, hydropower, and tourism. Already the seasonality of the supply and the increasing demand are not well reconciled. If snowmelt begins early and summer is longer, this will affect subsequent downstream uses. To combat this, you can either conserve or store water. The region is losing groundwater according to GRACE data and we do not know much about recharge. Thus, the groundwater profile is incomplete. In India, there is a proposal for a "linking" project, moving "surplus" water from the Himalayan rivers to the "deficient" peninsular rivers. It was estimated that this would include 9 large dams, 24 small dams, and 12,500 canals and cost 200 billion US$. The proposal did not include a feasibility study and did not account for seasonal spikes in hydrographs. The capacity for the links has not even a 10th the capacity needed to carry peak flow. Another challenge for water resources in the region is sedimentation, where the sediment discharge is the highest in the world. There are large knowledge gaps in the Himalayas hindering educated management, including data, the well-coordinated sharing of knowledge, the remoteness of glaciers, seismic risks, and uncertainties in time and space scales, and diversity of uses/users.

Under Pressure: International Water Management Challenges in the Himalayan Region

David Michel, The Stimson Center

Water managers across the Himalayan region will confront a host of overlapping socioeconomic, environmental, and policy challenges as they strive to fulfill their societies' future water needs. In many of the great rivers that rise in the Hindu Kush Himalayan mountains—the Amu Darya, Ganges, Indus, Yellow—total withdrawals nearly equal or even surpass long-term flow balances. Water flows across borders throughout the region, and these rivers are "allocated" or distributed. With population growth in India, Nepal, Pakistan, and Afghanistan and changes in dietary patterns, the demand for food will increase. To account for this, irrigation is speculated to increase by 10 percent. Nonagricultural water use will also increase. Projected water deficits vary from country to country and basin to basin, without considering climate change, which would increase the severity of the situation. For example, there are limited options for adaptability on the Indus. Major infrastructure projects in the Himalayas are commencing to increase water storage; many of them occur in interesting political areas. Water wars are an extreme outcome. Water can also lead to cooperative efforts. However, pressures may be greater than have been accounted for in the past. Many treaties do not have mechanisms to account for water instability and they do not include key players (such as China or Afghanistan).

Demographic Trends, Social Trends, and Possible Futures

Sajeda Amin, Population Council

People have always moved in response to climate. This is not a new phenomenon. Internal migration tends to be to urban areas, although refugees also migrate internationally (e.g., to London, Japan, Saudi Arabia, and India). The climate conversation is dominated by discussions of low-elevation coastal zones, and in this area of the world, there is very little conversation about migration and the associated human rights. Fertility trends in South Asia are declining generally across the board and are stabilizing. However, Pakistan is "lagging" behind in this respect. Infant mortality is also declining (highest rate in Bangladesh). The percent of population in urban areas is growing steadily. Pakistan has the lowest level of female labor, and there is not much movement in female labor force participation. Education levels have improved dramatically, and gender participation has nearly reached parity. There has also been a shift from agriculture to the service sector within the labor force, hence urban migration. Urban growth in Bangladesh is largely in environmentally vulnerable areas.

Regional Population Trends and Environmental Issues

Malea Hoepf, Independent Consultant

The countries fed by the Himalayan glaciers have a broad range of demographic histories and futures. All of the countries have experienced dramatic fertility declines over the last half century, the result of various social and policy changes, ranging from China's "One Child Policy," to Bangladesh's approach that paired government support with improved services and social marketing, to Pakistan's less successful policies that leave it with one of the highest fertility rates in Asia. These countries also have different population-environment interactions, sometimes pairing traditional developed-country concerns, such as growing carbon emissions and developing-country challenges of feeding large population with food grown from degraded land and diminishing water supplies. The challenges in these countries to handle demographic change and address environmental degradation have important implications for adapting to a changing environment, reducing the risk of conflict, and alleviating poverty for their people in the decades to come.

Inventorying and Monitoring the Recent Behavior of Afghanistan's Glaciers

Bruce Molnia, U.S. Geological Survey

The U.S. Geological Survey's nationwide investigation of the water resources of Afghanistan has components focused on characterizing the relationship between glaciers and Afghanistan's water resources, determining the recent behavior of the country's glaciers, and understanding the response of Afghanistan's glaciers to changing climate. GIS analysis, a supervised classification, and a remote sensing assessment are being conducted to determine the number, location, size, area, aspect, and many other parameters of Afghanistan's glaciers. At low elevations, many glaciers have already disappeared. The mid-range altitudes show the effects of complex behaviors in glaciers: debris coverage, transient water, stagnation. High-elevation glaciers are not significantly affected at this time. In the Karakorum Range, the dynamics are different and 65 percent of the glaciers are advancing. In northeast Afghanistan, water delivery is affected by glacial runoff. There is a large mobile water component that may be increasing with increasing temperatures, which gives potential for flooding. The amount of glacial melt compared with snowfall and rain in the area is still being determined. In this area, snow is significant, but it is hard to quantify.

Environment-Security Links

Richard Matthew, University of California, Irvine

It is very difficult to model how changes in the environment affect political stability. There is agreement that the environment is a security issue, and the prevailing opinion is that climate change will lead to more resource conflicts. There is much uncertainty, however, and resource scarcity could lead to more cooperation rather than conflict. It can also spark ingenuity. Certain countries are particularly vulnerable to climate change. In this region, population is growing, resources are becoming scarce, and many of the states are high on the Failed State Index, a measure of how readily a government can provide services. Thus, though climate change will undoubtedly affect this region, it is difficult to say whether it is the issue that will push these systems over a threshold, or be a small player in an otherwise stressed system. Nonetheless, the implications are large and varied (terrorism, development factors, water scarcity, agricultural failure, etc.). In many South Asian countries, problems are exacerbated by climate change, but many problems are associated with misused resources and ignoring of environmental regulations; poor strategies and decisions can create vulnerabilities that climate change may magnify.

Strategic Options for Addressing Climate Change and Water Security Risks in Afghanistan

Sanjay Pahuja, World Bank

In Afghanistan, rapid growth in the Kabul area means demand growth for household and hydropower and industrial water uses. Hydropower development is only 5 to 10 percent of its potential, but years of conflict have left the power grids severely damaged. The growth of the mining industry is raising demand for water. Only 4 to 5 percent of agricultural land is irrigated, although the majority of Afghans depend upon agriculture. Even modest improvements in regional water management and infrastructure can lead to expansions in both energy and food production. International agreements exist for five river basins, but changing conditions will likely test them. Ongoing political and military conflict hinders improvement, but many water management projects (most of them large scale) are under consideration by international aid donors. Insufficient water for allocation, inadequate financing, and limited human resources have resulted in stagnation in preparation and implementation. A systemwide perspective is critically needed, to include both large-scale and small-scale efforts, but Afghanistan, as a "least developed country" has little capacity to take this perspective.

Bangladesh: Climate Risk and Vulnerabilities

Ahsan Uddin Ahmed, Centre for Global Change

Bangladesh has special water-related vulnerabilities, including a high population density in an area vulnerable to flooding and sea level rise, a dependence on upstream countries for water supply, and important regional water quality challenges arising from local groundwater contaminated by natural and human contaminants. Social conditions are improving, including education (e.g., increasing female enrollment in primary and secondary schools, and increasing literacy among farmers), skills enhancement, and an economy growing at about 6 percent annually. Food security is an issue for the growing population, although progress has been made in developing agricultural products to defy climate variability and change.

Bhutan: Climate Risk and Vulnerabilities

Thinley Namgyel, National Environment Commission, Bhutan

Bhutan has plenty of water at the national level but experiences local and seasonal shortages. Hydropower accounts for 21 percent of its GDP and almost 100 percent of its electricity; Bhutan's goal is to install 10,000 MW by 2020 against the 1,480 MW in 2011. This ambitious target is unlikely to be met because of controversy over large-scale hydro development, financial constraints, and uncertainties about future hydrological conditions. Seasonal differences result in winter shortages, and competition for water from small water sources often leads to conflicts between communities during the irrigation season. Because of its upstream location, Bhutan is especially vulnerable to climate changes that increase seasonal flood risks, including flash floods during the monsoon season, with damage to infrastructure, property, and lives. Bhutan also faces risks associated with glacial lake outburst floods, with 25 of its 1,674 glacial lakes at risk for floods. Bhutan has limited resources to deal with these issues; it is designated as a "least developed country," small, landlocked, in debt, and with only a nascent private sector. Parliamentary democracy was introduced in Bhutan only in 2008.

China: Climate Risk and Vulnerabilities

Jennifer Turner, Woodrow Wilson Center

China's water-related issues have the potential to undermine its growth. Seventy percent of its energy comes from coal mines located largely in the north, and coal uses 20 percent of the country's water. China sees its priorities as developing new supply rather than improving water management. This includes major efforts to move water from the southern watersheds to the north and developing and diverting waters from upstream basins without regard for downstream impacts. China may be building a significant number of new large dams in the coming years, but some existing dams are already underutilized because of diminished water supply. China has not been a central participant in regional water commissions or planning activities, preferring to pursue water development without consultation with other affected nations. Other challenges include territorial conflicts over shared watersheds such as the Sichuan Glacier dispute with India.

Border Dispute in the Himalayan Region

Sumit Ganguly, Indiana University, Bloomington

The Sino-Indian border along the Himalayas remains one of the most militarized areas of the world. The militarization of this region stems from an unresolved border dispute that has its origins in British colonial border policies from the 19th century. Despite multiple bilateral negotiations on the border dispute, little progress has been made toward its resolution. In recent years, China has expanded the scope of its claims along portions of the Sino-Indian border. Not surprisingly, this has contributed to greater troop concentrations resulting in greater environmental stresses to the area. Finally, the dispute may take on even greater salience as China plans to divert water and construct hydroelectric stations in Tibet.

Toad's Eye Perspective: The Missing Element in Climate Change Debates

Dipak Gyawali, Nepal Academy of Science and Technology and Water Conservation Foundation

Nepal's 10-year Maoist insurrection ended in 2007, but its effects linger in the inability of the government to write a constitution and in its weak capacity to enact or implement policies and programs. Like Afghanistan and Bhutan, it is designated as a "least developed country." There are planned large-scale dams, but small-scale, community-centered water management would be preferable to top-down planned projects and might provide greater flexibility in the face of climate change. The country has an active mountain-climbing and tourism industry (although agriculture dominates the economy), with glaciers being a strong attraction in the high-mountain landscapes.

Pakistan: Climate Risk and Vulnerabilities

David Archer, JBA Consulting

The viability of Pakistan's economy depends on the state of the Indus River. Apart from the narrow ribbon of green along the Himalayan range, Pakistan is largely desert and semidesert. As a predominantly agricultural economy it depends on the Indus River for irrigation of both food and cash crops. In a normal year, about 75 percent of the river inflow is diverted, and in a drought year only a trickle of freshwater reaches the Indian Ocean. The Indus Basin Irrigation System irrigates 80 percent of Pakistan's approximately 22 million hectares of farmland. Hence changes in flow in the Indus River arising from climate change or other causes, or in the balance between water supply and demand (mainly for irrigation) send a ripple effect through the entire Pakistan economy and have implications for food security, poverty and prosperity, and ultimately for personal and state security.

Appendix C

Glacier Measurement Methods

GLACIOLOGICAL MASS BALANCE MEASUREMENT

In the glaciological method, a network of stakes and pits are placed on the glacier surface and used to measure the change in surface level while taking into account snow/firn/ice density. Comparing measurements between two fixed dates yields an annual mass balance, while comparing measurements at the end of the ablation and accumulation seasons yields a seasonal mass balance (Racoviteanu et al., 2008). The mass balance for the glacier is then estimated by multiplying the changes in mass balance at each sampling point with the area that point represents, and summing the product over the entire glacier. This method provides detailed information on the mass balance spatial variation and is considered more accurate than other methods (Kaser et al., 2003).

The glaciological method may achieve the greatest accuracy and provides the investigator insight for the field conditions, it is based on repeated field measurements, which have to be carried out under sometimes rather challenging conditions. These challenges include logistical constraints in remote areas, inclement weather conditions including cold temperatures and high winds, crevasses, avalanches and icefalls, and rockfall from surrounding terrain. The rate of data acquisition is slow and the process expensive (Kaser et al., 2003). Thus, only a few dozen such records in the world exist that cover significant periods of time (i.e., decades; WGMS, 2008; Zemp et al., 2009), and there are currently no such long-term records for the HKH region (Kaser et al., 2006).

GEODETIC MASS BALANCE MEASUREMENT

The geodetic method measures elevation changes of the glacial surface over time from various digital elevation models (DEMs) constructed over the entire glacial surface (Racoviteanu et al., 2008). This method can be applied using topographic maps, DEMs obtained by aircraft and satellite imagery, and by airborne laser scanning (Kaser et al., 2003). The accuracy of this method depends on (1) the interpolation method used to derive a DEM, (2) errors introduced by any change in spatial resolution, (3) biases inherent in the remote sensing—derived DEMs, and (4) density assumptions (Racoviteanu et al., 2008). Errors in the original DEMs propagate with each calculation and may introduce large errors in the end result. Because of these issues, it is recommended that the geodetic method only be used for mass balance measurements on decadal or longer timescales (Kaser et al., 2003; Racoviteanu et al., 2008).

HYDROLOGICAL MASS BALANCE MEASUREMENT

The hydrological mass balance can also be used to estimate the glacial mass balance. The hydrological method uses a water-balance approach to compute glacial mass balance. The estimated net precipitation in the basin is subtracted from the net runoff to compute the water storage within the basin, which is then interpreted as due to changes in glacial mass balance (Braithwaite, 2002). Although this approach is considered to provide only a crude approximation and is not generally recommended (Barry, 2006), it was used for many years for the basin of the Grosse Aletsch in Switzerland (PSFG, 1967, 1973). The hydrological approach is difficult to use in the HKH area because of limited precipitation and discharge measurements. However, the approach does hold promise as more basins become instrumented with automatic weather stations and automated measurements of discharge height, as demonstrated for the Langtang Basin in Nepal by the recent International Centre for Integrated Mountain Development (ICIMOD) field class on glacial mass balance measurements.

REMOTE SENSING MEASUREMENTS

Remote sensing measurements are based on information gained by aerial sensing technologies installed on aircraft and satellites. Scientists are increasingly able to measure glacier properties over larger areas and longer time spans because of the increased availability of imagery from remote sensing platforms. Remote sensing yields information about glacier properties including glacier area, length, surface elevation, surface flow fields, accumulation/ablation rates, albedo, equilibrium line altitude (ELA), accumulation area ratio, and the mass balance gradient. The ELA, accumulation area ratio, and mass balance gradient respond to annual changes in temperature, precipitation, and humidity and are therefore important for mass balance monitoring. Changes in glacier area and terminus positions over timescales of several decades, which are relatively easy to determine from remote sensing imagery, have been used as indicators of a glacier's response to climate forcing (Barry, 2006).

Remote sensing uses sensors that detect solar energy reflected by Earth's features as well as the emission of the Earth's own thermal energy (Figure C.1). Wavelength ranges (or bands) of interest to remote sensing of glaciers generally include visible light (VIS ranging from about 0.45 to 0.75 µm), near-infrared (NIR ranging from 0.75 to 1.4 µm), short-wavelength infrared (SWIR ranging from 1.4 to 3 µm), and thermal infrared (TIR ranging from about 8 to 15 µm). Sensors record the brightness temperature within a defined band that depends on the characteristics of the specific sensor, as illustrated for two different sensors in Figure C.1. For example, Band 2 of Landsat[1] 7 records the brightness temperature from 0.53 to 0.61 µm, often mapped as the blue band.

Snow and ice are characterized by (1) high reflectivity in the visible wavelengths, (2) medium reflectivity in the near-infrared, (3) low reflectivity and high emissivity in the thermal infrared, and (4) low absorption and high scattering in the microwave (Racoviteanu et al., 2008). Increasing amounts of black carbon quickly reduce the albedo of snow and ice.

The spatial resolution of a remote sensing image is critical to obtaining glacial properties in mountainous terrain, such as the ELA. A pixel size of 500 m on a side (e.g., MODIS)[2] means that, in general, the remote sensing information can only detect changes that occur in lengths greater than 500 m.

Newer sensors can acquire data at medium spatial resolutions (5 to 90 m in multispectral mode), with larger swath widths (185 km for Landsat and 60 km for ASTER)[3] and short revisit times (16 days for ASTER). These capabilities allow regular glacier mapping over extensive areas. The thermal band of Landsat Enhanced Thermal Mapper Plus (EMT+)[4] (10.4 to 12.5 µm, at 60-m pixel size) and the multispectral thermal bands of ASTER (8.125 to 11.65 µm, at 90 m pixel size) could potentially distinguish debris cover on glaciers. The ASTER, SPOT5,[5] IRS-1C,[6] and CORONA KH-4, KH-4A and KH-4B[7] can acquire stereoscopic images, which in turn provide elevation data that can be used for geodetic mass balance estimates (Racoviteanu et al.,

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[1] Landsat is a series of Earth-observing satellite missions jointly managed by the National Aeronautics and Space Administration and the U.S. Geological Survey. More information about the program is available at http://landsat.gsfc.nasa.gov/.

[2] The Moderate Resolution Imaging Spectroradiometer is an instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. More information about the instrument is available at *http://modis.gsfc.nasa.gov/*.

[3] The Advanced Spaceborne Thermal Emission and Reflection Radiometer is an instrument aboard the Terra (EOS AM) satellite. More information about the instrument is available at *http://asterweb.jpl.nasa.gov/*.

[4] More information about this instrument is available at *http://landsat.gsfc.nasa.gov/about/etm+.html*.

[5] A fifth-generation Earth observation satellite launched in 2002, the series of SPOT satellites were initiated by the French space agency and are run by Spot Image base in Toulouse, France.

[6] India's second generation remote sensing satellite.

[7] A series of U.S. reconnaissance satellites launched between 1959 and 1972.

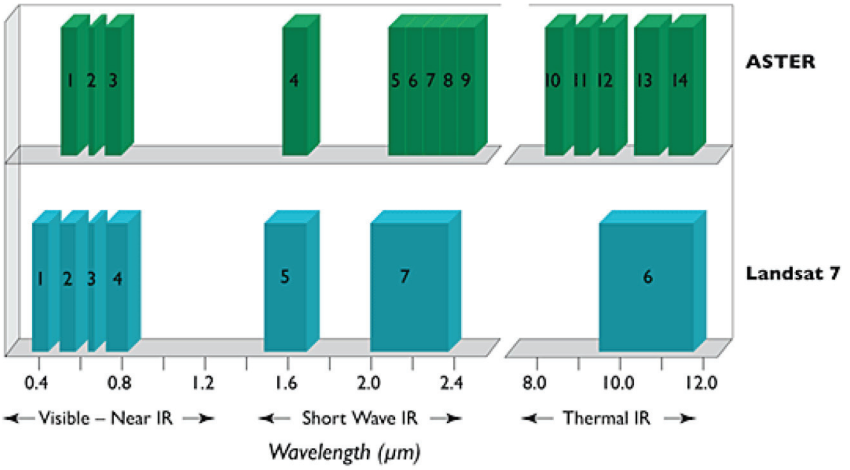

FIGURE C.1 Wavelength regions and bandwidths for two remote sensing satellites, Landsat 7 and ASTER. SOURCE: NASA Goddard Space Flight Center and U.S. Geological Survey.

2008). Thus, newer sensors with pixel sizes on the order of 3 to 30 m provide more accurate representations (and changes over time) of such parameters as glacial area, location of the glacier terminus, and location of the ELA.

Snow and ice are distinct from surrounding terrain in clear weather. Thick cloud cover can complicate such distinction. However, measurements of the 1.6 to 1.7 μm wavelengths (wavelength band 4 of ASTER) can overcome this issue. At these wavelengths, clouds are reflective but snow and ice are absorbing (Racoviteanu et al., 2008). Techniques including single-band ratios and the normalized difference snow index (NDSI) use the high brightness values of snow and ice in the visible wavelengths to distinguish them from darker rock, soil, or vegetation (Racoviteanu et al., 2008).[8] The single-band ratio and NDSI techniques are also fast and robust, making them relatively easy to automate over extensive areas. Challenges to automatic mapping of glaciers using band ratios include (1) the presence of proglacial and supraglacial lakes, (2) the presence of fresh snow on surfaces other than a glacier, and (3) debris cover on glaciers (Racoviteanu et al., 2008). Lakes are misidentified as glacial ice because liquid water and ice have similar bulk optical properties in the visible and near-infrared wavelength. Glaciers always have snow above the ELA. However, surrounding bedrock, moraines, tundra, and other surfaces may also have snow. These snow-covered surfaces can easily be misclassified as part of a glacier. Care must be taken to discriminate snow on surrounding areas from snow on glaciers. Often multiple years of imagery are needed to do so.

Debris cover is one of the greatest challenges in remote sensing of glaciers. In the visible and near-infrared wavelengths, debris cover has optical properties very similar to the surrounding moraines. Automated methods of analyzing spectral information are ineffective in mapping ice covered by debris. However, manual digitization is time-consuming and subject to human error. Thus, debris on glaciers may result in underrepresenting glacial area and overcalculating rates of glacial retreat.

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[8] NDSI is calculated as (VIS – SWIR)/(VIS + SWIR), where VIS is band 1 of ASTER (0.52-0.6 μm) at 15 m and SWIR is band 4 of ASTER (1.6-1.7 μm) at 30 m.

Appendix D

Disaster Agencies and Databases

A greater understanding of the occurrence and impacts of natural disasters in the region and the capabilities of response in the region can be gained from a variety of sources. These include national and international databases; regional international intergovernmental and international nongovernmental organizations (INGO) and programs; and national disaster agencies.

INTERNATIONAL DISASTER DATABASES

There have been increasing efforts to compile international datasets on natural disasters worldwide, five of which are examined here (cf. the review of hazards in South Asia by Gupta and Muralikrishna, 2010). These datasets differ in coverage and data quality; they have different filters, strengths, and limitations (see reviews by Beckman, 2009; Gall et al., 2009). Although these databases have some overlap, each offers different information and insights into disasters that have risen to an international level of recognition. Damage and loss estimation is particularly uneven. The ECLAC (2003) methodology is sometimes used for assessing damage and needs in major disasters, but it is not consistently applied for database development.[1]

Currently all databases need to be searched and compared independently. They include different types of hazards, and in some cases different definitions of hydroclimatic hazards (Table D.1). They present nationally aggregated data, and it is therefore important to compare them with national databases. The Center for Research on the Epidemiology of Disasters (CRED) has reported on efforts to "harmonize" national databases in Asia (Below et al., 2010). One international database, for example, the DesInventar Global Assessment Report (GAR), hosts a national disaster database that is discussed under national programs.

Centre for Research on the Epidemiology of Disasters EM-DAT Database (CRED EM-DAT)

The Centre for Research on the Epidemiology of Disasters (CRED) at Louvain, Belgium, compiles the most comprehensive public-access database worldwide, the EM-DAT international disaster database.[2] It has coverage from 1900 to the present for ten major categories of hazards (Table D.1). It also provides individual Country Profiles.[3]

Global Identifier Number (GLIDE)

The Asian Disaster Reduction Center in Kobe, Japan, has developed a uniform numbering system for disaster data management. Each disaster that meets a set of criteria is issued a global identifier number (GLIDE) and catalogued using this number.[4] GLIDE

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[1] There are other INGOs that have natural hazards programs, for example, the United Nations Development Programme's GRIP (*www.gripweb.org*). An important effort for detailed forensic case study analysis is under development (Burton, 2010; IRDR, 2011).

[2] See *www.emdat.be.*

[3] Cf. country profiles on UNISDR's Prevention Web: *www.preventionweb.net.*

[4] See *www.glidenumber.net.*

TABLE D.1 Types of Natural Hazards Recorded by International Dataset

CRED EM-DAT	Dartmouth Flood Observatory Database	GAR	GLIDE
Drought	Dam release + heavy rain	Drought	Drought
Earthquake (seismic activity)	Dam/Levy, break or release	Cold wave	Cold wave
Epidemic	Monsoon rain	Avalanche	Earthquake
Extreme temperature	Torrential rain	Earthquake	Epidemic
Flood	Tropical cyclone	Fire	Extreme temperature
Insect infestation	Tropical storm	Flood	Flash flood
Mass movement Dry	Rain and snowmelt	Forest fire	Flood
Mass movement Wet	Snowmelt	Frost	Heat wave
Storm	Tidal surge	Hailstorm	Landslide
Wildfire		Heat wave	Mudslide
		Landslide	Severe local storm
		Liquefaction	SLIDE (use LS/ AV/MS instead)
		Rains	Snow avalanche
		Snowstorm	Tornadoes
		Storm	Tropical cyclone
		Strong wind	Tsunami
		Thunderstorm	Volcano
			wave/surge(use TS/SS instead)

numbers are used by disaster-related organizations worldwide (example.g., CRED). A strength of the GLIDE system is that it differentiates among many types of hazards (Table D.1). One weakness is that it does not provide consistent comments on damages or separate losses of life, livelihoods, and property into separate data fields. The GLIDE data do not indicate increasing disaster frequency over the past decade; however, they do support other observations about the relative high frequency of flood and storm events.

Munich RE NATHAN Database

The Munich RE NATHAN Database is a proprietary database used for insurance, investment and strategic planning purposes.[5] Its historical archive includes 28,000 datasets with increasingly comprehensive coverage after 1980. Its annual map of losses in 2010 indicates that a large proportion of hazards in South Asia have been meteorological or hydrological events. Although some NATHAN data are publically accessible, some detailed NATHAN data are not publically available and were therefore not used extensively in this report.

ReliefWeb

The U.N. Office for Coordination of Humanitarian Affairs maintains a comprehensive portal for humanitarian concerns worldwide called ReliefWeb.[6] As of August 19, 2011, Afghanistan had the largest number of "Updates" in the region. Most of Afghanistan's entries are conflict related, for which it ranks first worldwide with 27,231 Updates, followed by Sudan and the Democratic Republic of Congo. Pakistan also has a high number of updates for both natural disasters and complex emergencies. In 2010, ReliefWeb reported the following number of humanitarian entries for the countries in the study area: Afghanistan, 27,674; Bangladesh, 4,838; Bhutan, 159; India, 10,201; Nepal, 6,089; and Pakistan, 17,120.

Dartmouth Flood Observatory Database and Flood Remote Sensing Databases

The Dartmouth Flood Observatory Database,[7] now hosted at the University of Colorado, Boulder, has compiled and mapped major flood events worldwide since 1985. Other agency websites provide detailed remotely sensed flood imagery, for example, the Global Flood Detection System,[8] the National Oceanic and Atmospheric Administration's Operational Significant Event Imagery,[9] the National Aeronautics and Space Administration's Tropical Rainfall Measuring Mission or TRMM,[10] the CREST site,[11] and others. As these

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[5] See *www.munichre.com/touch/*.

[6] See *www.relief.int*.

[7] See *floodobservatory.colorado.edu*.

[8] See *www.gdacs.org/flooddetection*.

[9] See *www.osei.noaa.gov/*.

[10] See *trmm.gsfc.nasa.gov/*.

[11] See *oas.gsfc.nasa.gov/CREST/global/*.

data and technologies expand, it will be important to make comparable investments in integrative field research on the human dimensions of flood hazards (Guha-Sapir et al., 2011).

REGIONAL INTERGOVERNMENTAL ORGANIZATIONS AND INTERNATIONAL NONGOVERNMENTAL ORGANIZATIONS

Regional intergovernmental organizations and international nongovernmental organizations that focus on natural hazards and disaster reduction in the South Asia region offer different perspectives on, and approaches to, natural hazards. Although not intended as an exhaustive list, the following provides a summary of organizations of note along with information about their focus:

- *Asian Disaster Preparedness Center (ADPC)*.[12] This regional organization in Bangkok serves most countries in South Asia except, it appears, Afghanistan and Bhutan. The center offers professional training and a clearinghouse of information in association with the Asian Institute of Technology in Bangkok.
- *Asian Disaster Reduction and Response Network.*[13] The Asian Disaster Reduction and Response Network (ADRRN) out of Kuala Lumpur, Malaysia, is a consortium of 34 NGOs dedicated to humanitarian assistance in the Asia-Pacific region, organized to support regional networking and information sharing.
- *Asian Ministerial Conference on Disaster Risk Reduction*. This organization convenes biennial meetings of government ministers in disaster agencies. The most recent meeting took place in Seoul, Korea, in 2010. It focused on disaster risk reduction through climate change adaptation,[14] and it was followed by a biennial conference in Colombo, Sri Lanka.[15]
- *Duryog Nivaran*.[16] This regional nongovernmental organization based in Colombo, Sri Lanka, is devoted to decentralized disaster risk reduction, which bears comparison with ADPC's community-based approach to disaster risk reduction.
- *Integrated Water and Hazard Management Programmes*.[17] The International Centre for Integrated Mountain Development (ICIMOD) is a regional knowledge development and learning center based in Kathmandu, Nepal. The center supports three major projects on mountain hydroclimate hazards in the Himalayan region:
  - Disaster Preparedness in the Himalayas Program is the broadest initiative in the field.
  - The new INDUS Project for Capacity Building for Improved Monitoring of Snow, Ice and Water Resources brings together scientists from Indus Basin countries for joint discussions and possible collaboration.
  - The HKH-HYCOS Project established a Regional Flood Information System in the Hindu Kush-Himalayan area.
- *SAARC—Disaster Knowledge Network.*[18] SAARC is the main regional intergovernmental organization (IGO) for South Asia. It has added disaster reduction to its shared concerns, creating a regional center in New Delhi that networks members and agencies in each country. It has created a knowledge clearinghouse that includes country profiles with links to policies, institutions, and resources.
- *U.N. ESCAP.*[19] The U.N. Economic and Social Commission for Asia and the Pacific (ESCAP) in Bangkok has a Committee on Disaster Risk Reduction that was established in 2009 and is serviced by a Committee on Information and Communications Technology.

NATIONAL DISASTER AGENCIES AND DATABASES

Nations in the HKH region have disaster agencies and databases that take a variety of forms and include different types of information, as discussed here. This is not intended as an exhaustive list; rather, it is included to provide additional context when considering the response of the region to natural and hydroclimatic hazards.

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[12] See *www.adpc.net/2011/*.

[13] See *www.adrrn.net/*.

[14] See *www.amcdrrkorea.org/*

[15] See *www.adrc.asia/acdr/2011_index.html*.

[16] See *www.duryognivaran.org/*.

[17] See *www.icimod.org/?q=209*.

[18] See *saarc-sadkn.org/countries/india/default.aspx*

[19] See *www.unescap.org/*.

- *Afghanistan* has a cabinet-level Department of Fighting Disasters and a Department of Red Cross (i.e., 2 of its 11 government departments). It also has a National Disaster Management Authority).[20] Afghanistan has limited data on hydroclimate disasters, its stream gauging only being resumed in the early 2000s after a two-decade lapse due to armed conflict and civil strife (Mack et al., 2010; World Bank, 2010a). International organizations still report and respond to natural hazards, though most international appeals and programs address Afghanistan's pervasive "complex emergencies" that include civil strife.
- *Bangladesh's* Ministry of Food and Disaster Management contains a Disaster Management and Relief Division. Its Comprehensive Disaster Management Programme (CDMP) strives to link disaster risk reduction with climate change and development planning (Government of the People's Republic of Bangladesh, 2010a,b, 2011). A website search of these agencies and programs indicated no specific references to snow, ice, or glacial hazards, as compared with their emphasis on river and coastal flooding and sea level rise. For example, Bangladesh has an online list of 41 past disasters (floods and/or erosion, or cyclones) from 1986 to 2009[21] and it maintains a "Disaster Incidence Database" with a GIS interface categorizing floods, cold waves, and droughts.[22] The country's main disaster maps characterize the northern areas as affected by mountain flood hazards along the main river channels with drought hazards off channel. Below et al. (2010) reported that one national database had only 71 records and that 62 percent of them lacked damage data. By comparison, the international CRED EM-DAT dataset for Bangladesh has 477 records of which only 3.3 percent lack damage data. However, closer inspection of the Government of Bangladesh's online list of 41 past disasters revealed that it contains more detailed damage data than CRED EM-DAT.
- *Bhutan* has a Department of Disaster Management under the Ministry of Home and Cultural Affairs.[23] Its website emphasizes training programs, community-based disaster risk management, GLOFs (including lowering impounded water levels),[24] and school safety. It also includes a disaster management framework, earthquake recovery, regional climate risk reduction, and annual plans.
- *India's* National Disaster Management Authority was established in 2005 after the catastrophic Gujarat and Kashmir earthquakes.[25] Disaster management is becoming mainstreamed across national policies and programs. A major section of the Government of India Planning Commission's current 5-Year Plan for national development is devoted to the subject (Government of India, 2006a, 2008). India's National Institute of Disaster Management[26] established in 1995 as part of the International Decade for Natural Disaster Reduction (IDNDR) has aligned itself with the Indian Statistical Institute in Kolkata for advanced quantitative analysis of disaster risk and response. It publishes its own journal and publication series and convenes workshops, etc.

The subject of hydroclimatic hazards in the Himalayas is addressed in large measure through additional agencies, for example, the Ministry of Environment and Forests. Although India does not currently appear to have a national publically accessible online disaster database, the Ministry of Housing and Urban Poverty Alleviation's Building Materials and Technology Promotion Council has produced a detailed *Vulnerability Atlas of India* with detailed district as well as aggregate data (Government of India, 2006b). Disaster management is on the concurrent list of the Constitution of India that gives joint authority to national and state governments. State governments are addressed below, but none of the states on the left bank of the Ganges River Basin affected by HKH flooding appear to have detailed disaster databases.[27] As mentioned elsewhere in this report, security restrictions on access to streamflow data from India's international basins constrain scientific analysis of hydroclimate risk reduction from the local to state, national, and international levels.

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[20] See *www.andma.gov.af/.*

[21] See *www.dmb.gov.bd/pastdisaster.html.*

[22] See *http://www.dmic.org.bd/didb/didb.php.*

[23] See *www.ddm.gov.bt/.*

[24] See *www.ddm.gov.bt/?page_id=130.*

[25] See *ndma.gov.in/ndma/index.htm.*

[26] See *nidm.gov.in/default.asp.*

[27] The states of Orissa and Tamil Nadu, which are particularly affected by cyclones and tsunamis, have detailed disaster loss datasets online at *www.desinventar.org.*

In other respects, India's research capacity is the highest in the region. Kapur (2009) has compiled and analyzed 4,004 natural hazards research publications, limiting the search to hydroclimatic and geophysical disasters, and excluding related human crises (e.g., famines) and technological hazards (e.g., environmental pollution spills). India's advanced remote sensing programs and meteorological research centers also give it a vital role in the region as a whole.

- *Nepal's* Ministry of Energy has a Department of Water-Induced Disaster Prevention.[28] Additionally, its Ministry of Environment has a Department of Hydrology and Meteorology.[29] Although not on its national website, Nepal maintains a "Disaster Information/Inventory Management System (DIMS) (Below et al., 2010). The Nepal data are publically available on the GAR Database—National Disaster Inventory for Nepal.[30] This database has approximately 16,879 records whereas CRED EM-DAT includes only 144 for Nepal and is a case in which the national database is superior to the international one.
- *Pakistan* is undergoing a process of administrative devolution under the 18th Amendment to its Constitution, enacted in 2010, which shifts many agencies on its concurrent list of joint federal-provincial authority to an exclusively provincial level of control. Important hazards-related exceptions include the Pakistan Meteorological Department under the Ministry of Defense, a Federal Flood Commission under the Ministry of Water and Power, a Pakistan Centre for Research on Water Resources under the Ministry of Science and Technology, and the semiautonomous Water and Power Development Authority—each of which has responsibility for different aspects of hydroclimate hazards management. Devolution of the Ministry of Environment raised questions about how climate change policies and programs would unfold at the national level (Aftab, 2011; Ghumman, 2012), but the federal cabinet adopted a national climate change policy and established a Ministry of Climate Change in 2012. At the same time, the Ministries of Agriculture and Livestock were devolved, and irrigation has already been administered at the provincial level. The role of the National Disaster Management Authority,[31] established in 2006, relative to provincial disaster management agencies will likewise be important—as hydroclimate hazards cross all of the provincial boundaries in Pakistan.

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[28] See *http://www.dwidp.gov.np*.

[29] See *www.dhm.gov.np*.

[30] See *gar-isdr.desinventar.net/DesInventar/profiletab.jsp?countrycode=np11*.

[31] *ndma.gov.pk/*.

Appendix E

Acronyms and Abbreviations

ADPC	Asian Disaster Preparedness Center
AOT	aerosol optical thickness
BC	black carbon
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CRED	Centre for Research on the Epidemiology of Disasters
DEMs	digital elevation models
DTM	digital terrain model
EF	environmental flow
EHP	elevated heat pump
ELA	equilibrium line altitude
EPS	expressed population signal
FAO	Food and Agriculture Organization
FUGs	forest user groups
GAR	Global Assessment Report on Disaster Risk Reduction
GHG	greenhouse gas
GLIDE	GLobal IDEntifier
GLOF	glacial lake outburst flood
GRACE	Gravity Recovery and Climate Experiment
GRanD	Global Reservoir and Dam
GRUMP	Global Rural Urban Mapping Project
HKH	Hindu Kush-Himalayan
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
LIA	Little Ice Age
LLOF	landslide lake outburst flood
masl	meters above sea level
MODIS	Moderate Resolution Imaging Spectroradiometer
MSU	Microwave Sounding Unit
NATHAN	Natural Hazards Assessment Network
NDSI	Normalized Difference Snow Index
NGO	nongovernmental organization
NRC	National Research Council
OCHA	Office for the Coordination of Humanitarian Affairs
OMI	ozone measuring instrument
POP	persistent organic pollutant
SAARC	South Asian Association for Regional Cooperation
SST	sea surface temperature
TP	Tibetan Plateau
WGMS	World Glacier Monitoring Service
WUAs	water user associations

Appendix F

Institutional Oversight

Institutional oversight for this project was provided by the following.

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Appendix G

Biographical Sketches of Committee Members

Henry J. Vaux, Jr. *(Chair)* is professor emeritus of resource economics at the University of California in both Berkley and Riverside. He is also associate vice president emeritus of the University of California system. He previously served as director of California's Center for Water Resources. His principal research interests are the economics of water use, irrigated agriculture, and water marketing. Prior to joining the University of California, he worked at the Office of Management and Budget and served on the staff of the National Water Commission. Dr. Vaux has served on numerous NRC committees and was the chair of the Water Science and Technology Board of the NRC from 1994 to 2001. He is a national associate of the National Academies. Dr. Vaux received an A.B. from the University of California, Davis in biological sciences, an M.A. in natural resources administration, and an M.S. and Ph.D. in economics from the University of Michigan.

Deborah Balk is professor at the City University of New York (CUNY)'s Baruch School of Public Affairs and the CUNY Graduate Center in the Sociology and Economics Programs and associate director of the CUNY Institute for Demographic Research. Her expertise lies in spatial demography and the integration of earth and social science data and methods to address interdisciplinary policy questions. Her current research focus is on urbanization, population, poverty, and environmental interactions, in particular, climate change. Prior to joining CUNY in 2006, she was a research scientist at the Center for International Earth Science Information Network at Columbia University. There she was also lead project scientist for the NASA-funded Socioeconomic Data and Applications Center where she worked on large-scale data integration of geographic, survey, and administrative data. She received her Ph.D. in demography from the University of California, Berkeley, and her master's degree in public policy, and A.B in international relations, from the University of Michigan, Ann Arbor. She has recently completed service as a member of the International Union for the Scientific Study of Population Working Group on Urbanisation and two National Research Council panels. She has coauthored numerous papers on population and climate change, including a recent one on city population forecasts and water scarcity.

Edward R. Cook is a Ewing Research Professor at Lamont-Doherty Earth Observatory of Columbia University. He cofounded the Tree-Ring Laboratory in 1975, which is dedicated to expanding the use and application of tree-ring research around the world to improve our understanding of past climate and environmental history. His current research concentrates on the use of tree-ring data networks to study regional climate, global climate teleconnections, and anthropogenic impacts on forest growth. Dr. Cook received his Ph.D. in watershed management from the University of Arizona.

William K.-M. Lau is the deputy director for atmospheres, in the Earth Science Division at NASA Goddard Space Flight Center. He received his Ph.D. in atmospheric sciences at the University of Washington in Seattle in 1977. Dr. Lau is an adjunct professor in the Department of Atmospheric and Oceanic Sciences at the University of Maryland, adjunct professor of mathematics at the Hong Kong University of Science and Technology, and honorary professor in the School of Climate and Energy at the City University of Hong Kong. His research work spans more than three decades covering a wide range of topics in climate dynamics, tropical and monsoon meteorology, ocean-atmosphere interaction, aerosol-water cycle interaction, climate variability, and climate change. He has received many awards for his research and scientific leadership, including, among others, the American Meteorological Society Meisinger Award for Young Scientists (1988), the NASA John Lindsay Award (1987), the Goddard Exceptional Achievement Medal (1991), and the William Nordberg Award in Earth Science (1999). He is a Goddard Senior Fellow, a fellow of the American Meteorological Society, and a fellow of the American Geophysical Union.

Marc Levy is deputy director of the Center for International Earth Science Information Network, a unit of Columbia University's Earth Institute. He is also an adjunct professor in Columbia's School of International and Public Affairs. He is a political scientist specializing in the human dimensions of global environmental change. His research focuses on climate-security linkages, emerging infectious disease modeling, anthropogenic drivers of global change, sustainability indicators, and vulnerability mapping. He is also leading a project in Haiti to reduce vulnerability to disaster risks by integrating ecology and economic development goals on a watershed scale. He has served on a number of international assessments, and is currently a lead author on the Intergovernmental Panel for Climate Change Fifth Assessment Report's chapter on human security.

Elizabeth L. Malone is a senior research scientist at the Joint Global Change Research Institute. Her interests focus on policy-relevant sociological research in global change issues, developing studies that integrate disparate worldviews, data sources, and scientific approaches. Dr. Malone was an author and review editor for the most recent assessment of the Intergovernmental Panel on Climate Change, both in impacts, adaptation, and vulnerability; and mitigation. In recent years she has, with colleagues, developed structured methods for analyzing country, sector, and local vulnerabilities to climate change. Dr. Malone coordinated and developed the science portion of the National Intelligence Assessment on Climate Change and coordinated the development of regional reports on scientific knowledge about climate change. She was the technical lead for a report on glacier melt in the greater Himalayan area, including downstream vulnerabilities and potential interventions for the U.S. Agency for International Development. She received her Ph.D. in sociology from the University of Maryland in 2004.

Robert McDonald is a vanguard scientist for The Nature Conservancy. Dr. McDonald works for the Conservancy's Analysis Unit on issues related to energy, agriculture, and ecosystem services. Dr. McDonald has recently led a National Center for Ecological Analysis and Synthesis Working Group on how global urban growth and climate change will affect urban water availability and air quality. He also researches the effect of U.S. energy policy on natural habitat and water use. Prior to joining the Conservancy, he was a Smith Conservation Biology Fellow at Harvard University, studying the impact that global urban growth will have on biodiversity and conservation. Dr. McDonald has also taught landscape ecology at Harvard's Graduate School of Design, helping architects and planners incorporate ecological principles into their projects. He earned his Ph.D. in ecology from Duke University.

Drew Shindell is a senior scientist at the NASA Goddard Institute for Space Studies. Dr. Shindell researches climate change, with a focus on atmospheric chemistry. An expert on modeling the impact of emission changes, Dr. Shindell's work has investigated how the atmospheric chemical system has important effects on humans through pollutants such as smog or particulates, through acid rain, and through stratospheric ozone change, and how climate can be altered by greenhouse gases, solar variability, volcanic eruptions, aerosols, and ozone, and what effects changes in climate and air quality may have on society. Dr. Shindell serves as a coordinating lead author for the Intergovernmental Panel on Climate Change's Fifth Assessment Report on global climate change. He earned his Ph.D. at Stony Brook University.

Lonnie G. Thompson (NAS) is a professor at the Ohio State University's School of Earth Sciences and senior research scientist at the Byrd Polar Research Center. His research focuses on searching glacial ice for clues to global warming, and he uses new technologies in the emerging science of paleoclimatology. Dr. Thompson made his first expedition to glaciers in December 1973 to Antarctica and he has been on more than 50 glaciological research expeditions since then. Dr. Thompson pioneered studies of Quaternary climate change recorded in low-latitude alpine icecaps. His work on ice cores led to a fundamental shift in thinking about the importance of the tropics in global climate change. He was elected to the advisory board of the International Glaciological Society in 1999. Dr. Thompson was elected a fellow of the American Geophysical Union in 2001, was named a 2002 Distinguished University Professor from the Ohio State University, and elected to the National Academy of Sciences in 2005. He received the National Medal of Science in 2007.

James L. Wescoat, Jr., is an Aga Khan Professor at the Massachusetts Institute of Technology. His research concentrates on water systems in South Asia and the United States from the site to river basin scales. He has served on the Water Science and Technology Board, including Committees for the Review of Lake Ontario-St. Lawrence Studies; Downstream: Adaptive Management of Glen Canyon Dam and the Colorado River; and A New Era for Irrigation. He has contributed to studies of climate, water, and food security in the Indus Basin; and to historical research on waterworks of the Mughal period in India and Pakistan. In 2003, he coauthored *Water for Life: Water Management and Environmental Policy* with geographer Gilbert F. White. Dr. Wescoat received his Ph.D. in geography from the University of Chicago.

Mark W. Williams is a professor of geography and fellow of the Institute of Arctic and Alpine Research at the University of Colorado, Boulder. Dr. Williams' research interest is the processes that determine the hydrology, hydrochemistry, and biogeochemistry of high-elevation basins, including the storage and release of solutes from the snowpack, biogeochemical modifications of snowpack runoff, nutrient cycling, surface-groundwater interactions, and hydrological pathways and residence time. Current projects include the Rocky Mountains, Andes, European Alps, Central Asian areas of Kazakhstan and Kirghizia, western China including Tibet, and the Himalayas. Dr. Williams was elected a fellow of the American Geophysical Union in 2012 and is a former Fulbright Research Scholar. He received his Ph.D. in biological sciences with an emphasis in ecology and hydrology from the University of California, Santa Barbara in 1991.