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Monitoring of Glaciers, Climate, and Runoff in the **Hindu Kush-Himalaya Mountains**

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Donald Alford, David Archer, Bodo Bookhagen, Wolfgang Grabs, Sarah Halvorson, Kenneth Hewitt, Walter Immerzeel, Ulrich Kamp, and Brandon Krumwiede

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Ulrich Kamp is Associate Professor at the Department of Geography, University of Montana in Missoula. He began his career at the Institute for Space Sciences at Freie Universität, Berlin, where he focused on airborne remote sensing and water quality monitoring of lakes and rivers in urban areas. In 1999, he received his PhD in Geography from Technische Universität, Berlin, with a thesis about Quaternary geomorphology and glaciations in the Pakistani Hindu Kush. He then carried out postdoctoral studies at the Department of Geography and Geology at the University of Nebraska, Omaha, in remote sensing of glaciers in the Himalaya. He then spent three years as an assistant Professor of Geography and Environmental Science at DePaul University in Chicago before joining the University of Montana in summer 2005. As a research fellow of the Alexander von Humboldt Foundation of Bonn, Germany, Kamp spent the academic year 2010–11 at the Institute for Space Sciences at Freie Universität, where he worked on monitoring of glaciers in the Altai Mountains of Mongolia. His research includes mountain geography, geomorphology, Quaternary glaciations, glacier monitoring, natural hazards, remote sensing, and environmental studies. He has carried out fieldwork in Algeria, India, Jordan, Lesotho, Mongolia, Pakistan, Peru, South Africa, and Venezuela.

Brandon Krumwiede is a GIS specialist and project assistant with the National Weather Service's National Operational Hydrologic Remote Sensing Center in Chanhassen, Minnesota. He has a master's degree in geomatics from the University of Montana, where he was a student of Ulrich Kamp. He was a technical adviser on GIS and satellite imagery for the recent World Bank study on the glaciers and streamflow of the upper Indus basin, and was responsible for the development of all SRTM models of the catchment basins as well as the shapefile for the Karakoram and western Himalayan glaciers. His MS thesis topic was: *Mapping Glacier Variations from 1990 to 2006 in the Central Mongolian Altai*. Prior to returning to school, Krumwiede was a GIS specialist with Eastview Cartographics, of Minneapolis, MN.

Abbreviations and Acronyms

ADCP	acoustic doppler current profiler
ALOS	Advanced Land Observing Satellite
AMSR-E	Advanced Microwave Scanning Radiometer for the Earth Observing System
AMSU-B	Advanced Microwave Sounding Unit
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVNIR-2	Advanced Visible and Near Infrared Radiometer type 2
CAREERI	Cold and Arid Regions Environmental and Engineering Research Institute
CDMA	code division multiple access
CIS	Commonwealth of Independent States
cm	centimeter
DEM	digital elevation model
DMSP	Defense Meteorological Satellite Program
ELA	equilibrium line altitude
ERS	European Remote Sensing
ETM+	Enhanced Thematic Mapper Plus
FAO	Food and Agriculture Organization of the United Nations
GCOS	Global Climate Observing System
GCP	ground control point
GIS	geographic information system
GLIMS	Global Land Ice Measurements from Space
GLOF	glacial lake outburst flood
GPRS	general packet radio service
GPS	global positioning system
GSDQ	gauging station data quality
HF	high frequency
HKH	Hindu Kush-Himalaya
ICIMOD	International Center for Integrated Mountain Development
IDW	inverse distance weighted
IGOS	Integrated Global Observing Strategy
IPCC	Intergovernmental Panel on Climate Change
IRS	Indian Remote Sensing
ISO	International Organization for Standardization
IT	information technology
km	kilometer
km^2	square kilometer
km^3	cubic kilometer
LiDAR	light detection and ranging
m	meter
m^2	square meter

m^3	cubic meter
MGM	morphometric glacier mapping
MIR	mid-infrared
mm	millimeter
mm (we)	millimeters water equivalent
MODIS	Moderate Resolution Imaging Spectrometer
MSS	Multispectral Scanner
NASA	National Aeronautics and Space Administration
NDSI	normalized difference snow index
NIR	near infrared
RMSE	root mean square error
SAR	synthetic aperture radar
SNHT	standard normal homogeneity test
SPOT	Système Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
SSM/I	special sensor microwave/imager
TIN	triangular irregular network
TIR	thermal infrared
TM	Thematic Mapper
TMI	TRMM microwave imager
TRMM	Tropical Rainfall Monitoring Mission
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USGS	United States Geological Survey
VNIR	near infrared
VIR	visible infrared
VIS	visible
WAPDA	Water and Power Development Authority
WMO	World Meteorological Organization

Executive Summary

Effective monitoring of the hydrometeorological environment of the Hindu Kush-Himalaya (HKH) Mountains – the collection of information defining the climate, hydrology, and glaciers of these mountains – has proven difficult because of problems of accessibility, the complex nature of the mountain environment, lack of conceptual models of the mountain hydrometeorological environment, and inadequate analysis of the existing databases from monitoring of the Indus and Ganges River basins of India, Nepal, and Pakistan.

A realistic monitoring program will need to consider the interactions of climate, glaciers, and stream flow in the Himalaya headwater catchment basins as a factor in monitoring network design. To date, a majority of the descriptions of elements of the HKH hydrometeorological monitoring regime have involved traditional "black box" statistical analyses, based on the gross aggregate mean of temperature and precipitation measured at only a few sites in each basin to forecast lowland water supply. While this approach has provided realistic data for many types of lowland water use problems, it is apparent that viewing the headwater catchment as a black box located above the altitudes at which the processes of energy and water exchange appear to be maximized will provide little guidance in monitoring instrument placement or in interpreting the data they produce. The challenge is to design a monitoring station network that is properly located, relatively accessible, and at a scale appropriate for the mountain topography, and in which all processes are defined in credible terms. This report will begin a discussion of the composition and design of a climate, glacier, and runoff monitoring network for the HKH Mountains of India, Nepal, and Pakistan.

There is no hydrometeorological monitoring "cookbook," as such, for a region as complex as the HKH Mountains. The first step in planning a monitoring effort must be a clear statement of purpose and an understanding of the general characteristics of the area to be monitored.

Monitoring Objectives

Hydrometeorological monitoring encompasses a set of activities that characterize the environment of the hydrosphere. The development of a credible hydrometeorological monitoring network must be approached as a problem in technology transfer that involves: (a) instrument selection and placement; (b) instrument maintenance; (c) data acquisition; (d) data synthesis and digitization; (e) data analysis; (f) data storage; (g) user training; and (h) data sharing. Further, it will involve development of standard operating procedures, including: (a) integrated data collection and analysis procedures; (b) funding and maintenance responsibilities; (c) personnel training; (d) procedures related to scale and modeling; and (e) ensuring accessibility of monitoring sites.

Developing a regional monitoring program in hydrometeorology faces a number of obstacles: (a) there is no history of any serious, sustained collaboration on water resources problems among countries of the HKH region; (b) there is no history of serious, continuing, independent field research in the mountains by scientists of the region; (c) although hydrometeorological databases for the HKH mountain catchment basins do exist, they are often unanalyzed and unshared; (d) the extreme topography of the mountain catchment basins of the major rivers of the region limit accessibility and scale;[1] and (e) a generally accepted set of monitoring procedures does not exist.

[1] *Accessibility* determines the effort needed to reach a particular study or monitoring site, maintain a presence there, and undertake meaningful research. This is a problem in studying the region's glaciers, which are commonly located in roadless areas at altitudes of 3,000–7,000 meters above sea level. *Scale* determines the appropriateness of data density, and of both data collection procedures and analyses.

This study was undertaken at the request of the World Bank. The purpose of the study was to assess the current status of major factors related to the development of a regional approach to the management of the water resources of the mountain headwaters of the Indus and Ganges Rivers of South Asia. These factors were identified as: (a) data availability and sharing; (b) status of the current hydrometeorological and glacier observation networks in South Asia; (c) adequacy of the existing systems to support the assessment of climate change implications; (d) modern hydrometeorological observation systems (ground and satellite based) and related information technology (IT) improvements; and (e) harmonization and exchange of hydrometeorological data among riparian states. The geographic scope of the study was the headwaters of the Ganges and Indus Rivers in the HKH Mountains in South Asia, encompassing the mountain arc from eastern Nepal to eastern Afghanistan.

From lists provided by the governments of Nepal and Pakistan, and limited information from the literature regarding Indian monitoring, a total of 493 hydrometeorological monitoring stations were identified in the defined study region, of which approximately 90 percent are located below 1,000 meters (m) above sea level. Recent studies have indicated that the primary altitudinal zones of specific runoff (millimeters per meter), total runoff volume (cubic kilometers (km^3)), ice cover area (square meters (m^2)), and glacier ablation zones are generally at altitudes of 3,000–6,000 m from eastern Nepal to the Karakoram. This altitudinal zone should be the focus of any program of enhanced monitoring in the HKH Mountains. While findings based on statistical correlations between the measured low-altitude climate and the glaciers and hydrometeorology of the higher altitudes have produced useful results, they may also be a factor in some of the more extreme concerns regarding climate change and glacier retreat.

This report consists of assessments of:
(a) the nature of the major elements of the hydrometeorological regime of the mountain headwaters of the Indus and Ganges Rivers, namely climate, glaciers, and hydrology;
(b) the primary tools available to monitor these elements and the current and potential status and applicability of these tools, primarily automatic weather stations, satellite imagery, geographic information systems (GIS), and distributed process hydrological models; and (c) recommendations for improvement of monitoring procedures and data management. The contributors to this report have undertaken field studies of aspects of the hydrometeorology, culture, and data management in the mountains of South Asia, and are generally recognized as knowledgeable authorities in their respective fields. This report is intended for anyone with an interest in monitoring in a high-mountain environment, but is primarily aimed at two principal audiences: (a) those responsible for planning the future course of hydrometeorological monitoring in the headwater basins of the HKH Mountains; and (b) those charged with implementing those plans.

Establishing a regional hydrometeorological research facility in the HKH Mountains will involve developing solutions in the areas of integrated data collection and analysis procedures, instrument selection placement, compatibility of monitoring instruments, procedures, and analyses, training of personnel, procedures related to scale and modeling, ensuring accessibility of monitoring sites, and management, analysis, and archiving of the acquired data. The major themes of this report are the monitoring of climate, glaciers, and streamflow; the appropriate use of the mountain peoples in a monitoring program; the types of satellite imagery that are available to supplement ground-based activities; and the administrative needs of a credible monitoring effort. The following are general summaries of those themes as reflected in the main text of this report.

Monitoring of Glaciers, Climate, and Runoff: Main Themes

Climate

Climate, defined here as the long-term trend of meteorological processes determining the water and energy balance at a site, varies widely in the HKH Mountains. Mean seasonal and annual temperatures may differ by as much as 20–30°C between the low-altitude climate stations now in use, mean altitudes of a majority of the mountain catchment basins, and glaciers they contain. The dominant precipitation source, rainfall in the eastern Himalaya resulting from the summer monsoon, becomes a mixture of rain and snow in the western Himalaya of Himachal Pradesh and Jammu and Kashmir, and is primarily winter snowfall in the Karakoram Range as the summer monsoon weakens from east to west along the mountain front, and is replaced by winter westerly lows in the west.

Temperature monitoring could be improved by an expanded network of climate stations at intermediate altitudes (2,000–5,000 m) in the mountain basins. Measurement of precipitation is much more problematic. For snow, the important variable is the water content of the winter snow layer. Under the best circumstances, measuring snow water equivalent depths at remote sites with existing instrumentation has proven challenging. The fundamental lesson is that the most reliable measurements require an observer at a site to actually measure the water content of each storm accumulation. Precipitation gauges or pressure pillows can only provide approximations. A few accurate measurements of snow water equivalent by trained villagers at intermediate altitudes in the mountains would provide much more reliable input to the rainfall–runoff forecast models than an expansion of the precipitation gauge network.

Only a very limited analysis has been carried out on climate data in the HKH. Acquisition and analysis of existing data should take priority over further development of the climate monitoring network.

Glaciers

There are four ways to address glacier monitoring: (a) direct field measurements and instrumentation in glacier basins; (b) indirect approaches using hydrometeorological data from outside glacier basins; (c) remote sensing; and (d) modeling. A strategic choice and integration of all four seems the best approach. Attempts to derive mass balance estimates and changes in the HKH have been based largely on temperature and precipitation data extrapolated from weather stations outside the glacier zones, or climate models, sometimes including assumptions about snowlines and equilibrium line altitudes (ELAs). Conditions known to influence mass balance in the HKH but largely lacking in direct measurements include high-elevation snowfall, avalanche and wind redistribution of that snow, avalanche-fed glaciers, all-year conditions and cycles in glacier basins, and glacier thermal regimes and movement. Going forward, this will entail regionally appropriate innovation, and not simply relying on greater knowledge and instruments from elsewhere. Even without the special conditions outlined, any agency or country for which glacier hydrology is required cannot avoid having a setup for continuous engagement with and experience on glaciers.

Two strategies that are the norm in regions with well-established monitoring may not work in the HKH: a set of "benchmark" glaciers or a glacier network. Both imply mass balance monitoring for whole glaciers. The former has succeeded mainly by choosing small, relatively simple glaciers that seem, nonetheless, representative for the region. It is doubtful this can work in the HKH. It is here that strategic engagement between field and indirect approaches is needed. Glaciers would need to be chosen for their suitability for training, ground control, historical reconstruction of glacier change, and experimental efforts.

Caution is urged with respect to more expensive, state-of-the-art instrumentation and techniques. Some are attractive for the high mountains and can overcome difficulties found in the HKH. However, the region is littered with "advanced" setups and devices that are broken or were quickly deemed inappropriate, or could not be maintained with local resources. Working with simpler and well-tried methods is often more reliable, and a better basis for training and building glacier experience.

In each country, direct observations will require one or more teams trained and permanently ready to work in glacierized areas. None of this is likely to happen or be successful without a core of personnel experienced in mountain environments, usually with mountaineering and winter skills, and enthusiastic about the work in which they are engaged. However, this will not happen without addressing important and special problems of safety, equipment, and training.

Hydrology

For the purposes of this discussion, mountain hydrology is defined as the methodologies associated with the monitoring and measurement of the water balance of the catchment basins of the HKH Mountains. Traditionally, hydrological monitoring undertaken for purposes of water resources planning or management has been based on "rainfall–runoff" or "black box" correlation modeling, in which input, as measured precipitation, is correlated with output, as measured streamflow, to provide an estimate of the timing and volume of streamflow from a basin. This type of modeling produces very useful information for engineers and water managers concerned with the lowland rivers originating in the mountain basins. This modeling approach, however, provides relatively little insight into questions concerning the relative contribution of rain, snow, or glacier melt to streamflow volumes, or the role of glacier retreat and climate change in the streamflow regimes of the major rivers of South Asia, a major topic of an ongoing debate.

Many of the stream flow data for HKH mountain basins are not readily available, either as a result of a formal policy, as is the case in India, or due to a general lack of procedures for data management, as in Nepal and Pakistan. Until this data access problem is resolved, many of the analyses of the hydrometeorology of the mountain basins will be based on extrapolation of lowland stream flow and climate records. The challenge is development of realistic extrapolation procedures for the extreme three-dimensional topography of those basins.

In the eastern Himalaya, runoff is produced primarily by rainfall associated with the summer southeast monsoon. In the Karakoram, in the extreme western portion of the mountain chain, stream flow results primarily from the summer melt of the previous winter snowpack, with the addition of a glacier melt component. A comparison of mean basin-specific runoff (in millimeters) with mean basin altitude (in m) shows a curvilinear trend of runoff depth with altitude, with specific values reaching a maximum at intermediate altitudes, and minima at the altitude extremes. This suggests that any expansion of the hydrometric monitoring network should be focused on the zone between 3,000 and 5,000 m above sea level, with a particular emphasis on the hydrology of the glacier and periglacial environments.

While the annual hydrographs of runoff from the eastern and western portions of the HKH are very similar, with maximum values occurring during the summer months, it is apparent that the underlying hydrometeorological processes are quite different between the two.

Indigenous Monitoring

In terms of existing glacier-related research activities, there is an absence of explicit involvement and participation of mountain communities in monitoring and assessing change. Proposals to scientifically monitor glaciers, weather, and environmental changes in ways that directly involve people living in upper basin catchments have not been advanced in the region.

Indigenous glacier monitoring goals in terms of selected impact indicators should be related to the needs of the scientific community, glacier hazard risk reduction, vulnerabilities and capacities of mountain communities, awareness and knowledge of the public, evidence-based adaptation planning, and prioritization of community objectives. Intermediate outcome indicators could be targeted for achievement in the next three to five years and could include the following: (a) training and participation of local villagers as research assistants and technicians; (b) increased scientific knowledge among the mountain-based population; (c) implementation of new curricula in glaciology, mapping, data analysis, hydrology, and hazards planning at regional institutes of higher education; and (d) creative and innovative solutions to reduce risks and hazards.

Satellite Imagery and GIS

Satellite imagery is becoming increasingly available for use in studies of elements of the water and energy characteristics of high-mountain basins, such as glacier and snow cover extent. A basic problem involves the need to ensure that the scale of the imagery is compatible with the scale of the variable being studied. Imagery scale is defined by the size of pixels (a physical point in an image, the smallest controllable element of a picture represented in the image). Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images with a pixel size of 15 m are considered here as mesoscale, or intermediate scale, and are appropriate for measurements at the scale of individual glaciers or mountain basins. Moderate Resolution Imaging Spectrometer (MODIS), Tropical Rainfall Monitoring Mission (TRMM), and Advanced Very High Resolution Radiometer (AVHRR) images have a pixel size of about 250 m, and are defined here as macroscale imagery, which is more appropriate for measuring the extent of the glacier or snow cover over much larger areas such as an entire mountain range.

Mesoscale Imagery

Until the early 1970s, aerial photography was the primary remote sensing technology in glacier mapping and monitoring. Although this technology has many advantages, it also has many restrictions, for example, in the extent of ground coverage, its availability for many study areas such as the HKH region, and high costs of aircraft and flight campaigns. This led to the introduction of satellite imagery analysis in studies of the cryosphere. Since the early 1970s, medium-resolution (10–90 m) optical satellite data have become available, particularly with the launch of sensors such as Landsat Multispectral Scanner (MSS), Landsat Thematic Mapper (TM), Système pour l'Observation de la Terre (SPOT), Indian Remote Sensing (IRS) including Cartosat and Resourcesat, Landsat 7 ETM+, ASTER, and Advanced Land Observing Satellite (ALOS). Today, large-scale (less than 10 m) imagery suitable for detailed glacier studies at basin scale is available from, for example, IKONOS, Quickbird, and GeoEye-1. However, the narrow swath, long revisit cycles, and high costs limit its use for systematic glacier monitoring of larger regions such as the HKH. CORONA data from 1960 to 1972 were declassified in 1995 but are only available for some glacierized areas within the HKH region.

Some of the potential datasets that can be obtained through satellite imagery, digital elevation models (DEMs), and GIS include elevation values, glacier hypsometry, basin hypsometry, glacier longitudinal profiles, glacier ELAs, slope, surface curvature, aspect, and surface roughness. Through the use of satellite imagery, DEMs, and GIS-derived datasets in combination with empirical measurements, it will be possible to develop a better understanding of the HKH environment.

Macroscale Imagery

MODIS

MODIS instruments of the National Aeronautics and Space Administration (NASA) capture data in 36 spectral bands ranging in wavelength from 0.4 to 14.4 micrometers and at varying spatial resolutions. They are designed to provide measurements of large-scale global dynamics, including changes in Earth's cloud cover and radiation budget, and processes occurring in the oceans, on land, and in the lower atmosphere. NASA software extracts time series datasets with given resolution and time averaging from specific sensed wavelengths. Records are available from early 2000 to the present. A major problem encountered in the use of MODIS imagery in mountain terrain is the lack of correspondence between the spatial scale of the MODIS image and the scale at which processes of water and energy exchange vary over the surface of the mountain basin.

TRMM

TRMM high-resolution observations provide indirect data on rainfall through a correlation between rainfall depth and lightning frequency. The TRMM specific observations are merged with additional passive microwave observations from several other satellite-borne instruments (such as special sensor microwave/imager (SSM/I), Defense Meteorological Satellite Program (DMSP), Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E), and Advanced Microwave Sounding Unit (AMSU-B)) as well as the near-continuous low-resolution infrared and thermal imagery from geostationary weather satellites.

TRMM may provide reliable quantitative estimates of summer monsoon convective rainfall, but the application to orographically enhanced winter snowfall from westerly systems may prove more problematic. Comparisons with available local long-record observations of precipitation and river discharge data in the upper Indus suggest that TRMM estimates provide a quantitative index of monthly precipitation rather than a measure of absolute magnitude. In this, they are similar to the local long-record meteorological observations, which also do not directly represent catchmentwide precipitation but do correlate well as indicators of mass inputs for seasonal snowmelt-driven catchments.

AVHRR

AVHRR is a radiation detection imager that can be used for determining cloud cover, surface temperature, and snow cover extent. Although with more limited spectral resolution, this long record offers the potential to: (a) greatly increase the overlap of the spatial data products with local observations, thus refining quantification of relationships between them; and (b) extend the range of observations by MODIS to better capture present spatiotemporal climate variability.

DEMs and Geomorphometry

DEMs are digital representations of the Earth's surface. In glacier monitoring, they are required for image orthorectification and radiometric calibration, debris-covered glacier mapping, surface energy balance studies, glacier ice volume loss and mass balance estimates, glacier hypsometry, and ELA estimation. DEMs are generated from digitized topographic maps, satellite stereo-imagery (for example, ASTER, IRS, SPOT), and data derived from radar interferometry (for example, Shuttle Radar Topography Mission (SRTM), TerraSAR-X) and laser altimetry (for example, light detection and ranging (LiDAR)). Digital terrain modeling is a complex process involving acquisition of source data, interpolation techniques, and surface modeling; in addition, there is the need for quality control, including accuracy assessment (overall planimetric and vertical accuracy), data management, interpretation, and application. Accurate glacier assessment using topographic information is frequently an issue of DEM quality. Great care is required to ensure that the data selected for an application are appropriate, processing is carried out with a high level of expertise, and errors in any derived data are accurately reported, so that real geophysical patterns and features can be differentiated from image and processing artifacts.

Geomorphometry is defined as the science of quantitative land surface analysis and draws from mathematics, computer science, and geosciences. The field of geomorphometry has two modes of study: the study of individual or specific landforms and features (for example, glaciers), and study of the general land surface or region (for example, the Himalaya). Glacier mapping usually includes the geomorphometric analysis of the glacier surface, and most software packages include relevant tools. However, as much as geomorphometric parameters help in identifying, describing, and classifying glaciers, their quality depends on the accuracy of the input DEM.

Requirements for Instituting a Monitoring Program

Carrying out monitoring programs in high-mountain areas, and especially in the HKH region, have been challenged by the rough environment, insufficient funding of continued, long-term observation programs, weak institutions, and difficulty of dispatching government officials on a regular basis to high-mountain regions on missions that often last several weeks. Also, under current civil service rules in all three countries, there are no special provisions for extra allowances that would make it attractive to staff to work under harsh conditions.

Depending on local conditions, logistic arrangements are made by the executing entity or with the assistance of a well-established trekking agency as partner. Finding human resources (such as porters) for logistic support has recently become difficult and more expensive because, at least for the conditions in Nepal, large numbers of younger people are migrating out of the country for better job opportunities. In general, field visits and station maintenance need to be undertaken using local facilities and possibilities. For cost-effectiveness and sustainability of the installed infrastructure, it is not advisable to leave all observations, maintenance, and station surveillance to office staff back in the city but, to the largest extent possible, delegate such functions to locally available staff, who may take great pride in doing these works if their services are adequately recognized and acknowledged. For example, after the end of a project, helicopters for station supply are not a realistic and sustainable option for a government organization or any other locally operating entity. It is essential for the monitoring programs to have local, well-trained technical personnel to reduce travel and mission costs and time lags in reaching a station after a problem has occurred. This is technically feasible through adequate capacity-building programs that enable local personnel to perform essential technical functions based on well-defined, station-specific standard operating procedures.

As a lesson of past projects, an agreed data policy needs to be developed covering the different data streams that the project will establish. Such data will have a multitude of origins, mostly however from national sources (such as national hydrometeorological networks).

1. Introduction

Hydrometeorological monitoring, as discussed here, describes the activities required to characterize the properties and processes of the hydrosphere as it exists in the three-dimensional mesoscale environment of the high-mountain catchment basins of the Hindu Kush-Himalaya (HKH) Mountains. Credible monitoring involves: (a) functional institutions; (b) operational instruments; (c) trained, motivated individuals; (d) scientific procedures; and (e) dedicated funding. Establishing a regional hydrometeorological research facility in the HKH Mountains will involve developing solutions in the areas of integrated data collection and analysis procedures, instrument selection and placement, compatibility of monitoring instruments and procedures, training of personnel, procedures related to scale and modeling, ensuring accessibility of monitoring sites, and management, analysis, and archiving of the acquired data, all in the context of processes within the mountain basins, not in the adjacent lowlands.

Mountain hydrometeorology is defined by a set of complex, three-dimensional, biophysical environments, produced by interactions among terrain, geology, and meteorology. The homogeneity seen from the distant lowlands becomes a complex mosaic of environments within the headwater basins. Altitude determines the properties of an atmospheric column extending upwards from a point within the mountains. These atmospheric properties determine the potential water and energy budgets at a point, or within a basin, in the mountains. Relief – slope aspect and angle – defines local topography. These terrain properties, in turn, create the three-dimensional spatial mosaic of water and energy budgets that characterize mountain catchment basins – the mountain topoclimatology. Controls on this zonation (together with the questions concerning these controls), installation and maintenance of instruments, balance between "ground-truth" and remote sensing, storage and digitization, and analysis and sharing must be defined before the nature of the monitoring network can be specified with any confidence.

Much of the literature describing the hydrology and glaciology of the Himalaya is in the form of "snapshots" from single or discontinuous visits to particular locations or is based on the extrapolation of lowland, gross aggregate databases. There are few continuous records other than low-altitude streamflow and climate data for the hydrometeorological or glaciological environments of these mountains, and still fewer models that would permit the synthesis and analysis of these data, many of which are not readily available. Of necessity, much of the literature is speculative and based on relationships developed from other mountain regions in Asia, Europe, and North America. An excellent exception is Bruijneel and Bremer 1989, which provides a general overview of the hydrology of the mountain basins of the Ganges River, based on analyses of studies of those basins.

A realistic monitoring program involving climate, glaciers, and streamflow in the Himalaya headwater catchment basins will be needed to tie the three elements together as a factor in network design. To date, a majority of the descriptions of elements of the HKH hydrometeorological regime have involved traditional "black box" statistical analyses based on the use of gross aggregate means of mountain processes of water and energy exchange. While this approach has provided realistic input into many types of lowland water use problems, it is apparent that a view of the headwater catchment as a black box, located above the altitudes at which the processes of energy and water exchange appear to be maximized, will provide little guidance in monitoring instrument placement, or in the interpretation of the data produced by those instruments. The challenge is to design a monitoring station network that is properly located, relatively accessible, and in which all processes are defined in credible terms. This report is intended to begin a discussion of the realistic composition and design of a climate, glacier, and runoff monitoring network for the HKH Mountains of India, Nepal, and Pakistan.

1.1 History

Traditionally, the study of mountain climates, glaciers, and hydrology has been the province of small groups of scientists working with limited funding, in relative obscurity, within the context of conceptual and theoretical frameworks provided largely by studies from the adjacent lowlands. This has led to the development of two separate approaches to the study of what might be termed "mountain science": (a) development of concepts and models of the mountain environment based on gross aggregate means of a range of elements, as measured in the adjacent lowlands, or at a few low-altitude sites within the mountain basins, or at a few, limited sites within selected basins; and (b) a fragmented collection of studies, scattered throughout the scientific literature, describing primarily results of site-specific climate, glacier mass balance, and water budget studies within the mountains. A majority of these latter studies are from the European Alps and the mountain ranges of North America. This has resulted in a specialized literature that traditionally has been of immediate interest to a relative handful of individuals, and that may or may not have relevance to the hydrometeorological environments of the Himalaya.

This situation has changed dramatically in the past decade as mountain glaciers have become an icon of climate change and anthropogenic global warming. The result was a sudden interest in glaciers at all levels, from sensational stories in the media to the now-discredited statement that the glaciers of the Himalaya would be gone by 2035 (IPCC 2007, chapter 10.6). It is now recognized that these initial statements and resulting alarms were made possible by the lack of hard data on which to base credible assessments of the role of climate change in the growth and shrinkage of glaciers, in addition to a general lack of familiarity, among both technical and nontechnical publics, with mountain environments in general and specifically the very high mountains of Asia, and analyses of existing databases by only a handful of concerned, qualified scientists. The global climate is changing and the global ice cover is shrinking, but the societal impacts of this change on the hydrometeorological environments of the Himalaya, particularly on the timing and volume of the flow of the major rivers with headwaters in those mountains, remain uncertain.

All the major rivers of the region have headwaters in the HKH mountain ranges. The fundamental challenge is to assess the quantitative importance of glaciers in determining the annual volume and timing of rivers with headwaters in mountains containing glaciers. Recent studies have suggested that this importance may vary widely in the HKH Mountains. The primary problems stem from the facts that (a) climate change is a complex process, most probably involving both water and energy input and output, and does not respond solely to temperature fluctuations; and (b) the mountain climate is a result of a complex interaction between the mountain topography and the surrounding atmosphere (or lack of it), involving a three-dimensional mosaic of topoclimates, defined primarily by local variations of altitude, aspect, and slope.

Perhaps more importantly, a reliable analysis of HKH mountain hydrometeorology is becoming increasingly relevant in the context of the economic (and population) growth being experienced by the countries of South Asia. At the same time, procedures for undertaking monitoring or research within the high-altitude mountain basins of the HKH have evolved slowly, primarily on an ad hoc basis for each project, with limited formal documentation in the technical literature.

1.2 The Problem

Recent concerns about climate change and retreating glaciers and their effects on river flows, specifically in the Himalaya, have illustrated how little the scientific and water management communities know about the role the mountain headwaters play in the annual flow of the major river systems of Asia. The water available from these rivers determines the supply use problems the region's countries now face and has caused concerns over the future availability of water resources for all uses in the countries of South and Central Asia. The solution must include an understanding of how important the Himalayan glaciers are as a source of the major rivers of the region by defining the role of glaciers as a component of the hydrological cycle of the mountain basins. The countries of South Asia face a number of challenges in developing a credible hydrometeorological monitoring program. They are as follows:

- Countries of the HKH region have no history of any earnest and sustained collaboration on water resources problems;
- A history of independent field research in the mountains among scientists of the region is lacking;
- Databases related to these problems exist in each of the HKH countries, but are generally unorganized, unanalyzed, and, most importantly, unshared;
- The extreme topography of the mountain catchment basins of the major rivers of the region complicates all attempts to study the problem. The extremity of the topography is characterized by the factors of accessibility and scale. (Accessibility determines the effort needed to reach a particular study or monitoring site, maintain a presence there, and undertake meaningful research. This is a problem in studying the region's glaciers, which are commonly located in roadless areas at altitudes of 3,000–7,000 meter (m) above sea level. Scale determines the appropriateness of data density, and of both data collection procedures and analyses.); and
- There is currently no generally accepted set of "best practices" for conducting monitoring or research of the mesoscale hydrometeorology of large mountain ranges such as the HKH.

Given current concerns related to glaciers, climate, and rivers, a monitoring program might establish the following objectives: (a) to either measure directly or develop credible estimation techniques for the annual cycle of mass gain and loss of the mountain glaciers; (b) to develop analytical methodologies to link mass balance fluctuations of these glaciers to the regional and global climate cycles; and (c) to link these fluctuations to variations in the timing and volume of the rivers flowing from the mountain catchments.

1.3 Scale and Location

While satellite-derived data are becoming increasingly important in the study of the hydrometeorology of the mountains of Asia, it is essential to use imagery with a resolution compatible with that of the glaciers, snowfields, and catchment basins of these mountains to produce realistic results defining the interrelations and interactions of properties and processes in the mountain basins. Development of procedures for testing and ensuring the accuracy, reliability, and reproducibility of the various types of satellite imagery now in use, or proposed, should be a priority.

In recent years, macroscale satellite imagery and global-scale climate models have been the primary tools of climatologists studying the effect of climate change on mountain climates, glaciers, and streamflow. This has necessitated the introduction of procedures for generating regional components of climates – at the macroscale of the global circulation model, with grid spacing of up to 50 kilometer (km) or a pixel resolution of 500 m – that can then be tested statistically against monthly or annual values of runoff volume. This is basically a continuation of the traditional approach to studies of mountain hydrology, involving a lumped parameter, or "black box," approach. In considering scale as a factor in hydrological studies, it has been argued that:

> [L]evels of scale at which a meaningful conceptualization of physical processes is possible are not arbitrary and their range is not continuous. Formulations appropriate at a given level usually are not applicable at the immediately adjoining levels. This is seen as one of the important reasons for the slow progress of hydrological science on basin scale (Klemes 1983).

In general, the processes controlling water and energy exchange in mountain basins are operating at the mesoscale or intermediate-scale level, controlled by topographic elements of slope, aspect, and altitude. Glaciers originate in favored mountain basins, or "cirques," where accumulation, as snow, is maximized by wind drifting or avalanching of snow, and ablation, or melt, is minimized by shielding from radiation by terrain or the low temperatures associated with high altitudes. These mesoscale aspects controlling glacier growth and shrinkage are not captured by either macroscale satellite imagery or global-scale climate models. These local mesoscale topographic influences will produce local variations in factors such as the equilibrium line altitude (ELA) or the ablation gradient among the glaciers in the basin. These differences in the scale of the glaciers, and of the macroscale tools currently used for most glacier monitoring in the HKH Mountains, make it virtually impossible to reach a consensus view of the relationship between climate change, glaciers, and streamflow, as it will vary from basin to basin.

The primary locations of an empirical study of the glacier hydrology of a mountain basin in the HKH Mountains are those of the hydrometric stations and of the glaciers that are separated horizontally by tens of kilometers and vertically by thousands of meters. At the terminus of the glacier, most streamflow is a result of glacier melt. As distance downstream increases, the glacier contribution will be diluted by other sources of input, such as snowmelt or rainfall. Seen in this context, it is easier to understand why recent statements that some fixed percentage of the volume of flow of a given river is the result of glacier melt may contain substantial error. In order to test the hypothesis that the current glacier retreat that is occurring in the eastern Himalaya is a result of climate change, it will be necessary to demonstrate a correlation between the two that will in addition explain the current advance of the glaciers of the Karakoram Range, in the western HKH region.

One of the implicit arguments for the use of macroscale satellite imagery and global climate models has been a lack of suitable topographic maps for much of the HKH region. Development of digital elevation models (DEMs) based on geographic information system (GIS) principles for any portion of the HKH Mountains is now a relatively straightforward matter, and can be a part of hydrological or glaciological modeling or monitoring in mountain basins. It has been recognized for some time that knowledge of local conditions of topography and meteorology is necessary to understand the basin-scale hydrology of mountains:

> [M]ountain hydrology modeling makes painfully obvious … the importance of areal mapping of hydrological and other geophysical variables and the inadequacy of the traditional point measurements which are the legacy of the century old technology (Klemes 1990).

1.4 Objectives and Procedures

The primary objective of a monitoring program is to develop general procedures for undertaking assessment and monitoring of the components of the water and energy budgets of the mountain catchments of the Himalaya. The two basic assumptions of the approach discussed in this report are:

- While any improvement in the existing monitoring network of climatological and hydrometric stations would be a positive step, the most useful and informative results will be obtained from stations established in some defined relationship with the existing station locations, and justified in the context of existing analyses and models of the three-dimensional Himalayan environmental matrix; and
- All data collected by this program must be available to international scientific and technical communities.

The value of any particular number and location of instruments in a monitoring network, the mix of ground-based instruments, and the regional data collected from satellite imagery can only be determined from the extent to which the data obtained provide answers to major questions related to the system being monitored. Examples of relationships in the hydrometeorology of the HKH Mountains that could be better defined are:

- East–west variation in stream flow components;
- Recent glacier retreat and temperature increases;
- Seasonal sources of monthly streamflow;
- Significance of area–altitude distribution of surface area in Nepal and the upper Indus basin; and
- Regional variations in glacier melt as a component of streamflow.

The objectives of a climatological and hydrological monitoring network are as follows:

- Provide sufficient information to determine areal averages of moisture and energy inputs and outputs and storages (water and energy balances) at a range of space scales and time intervals;
- Provide a sufficient duration of record to assess trends and periodicities in climatic variables relating to moisture and energy. Data on trends may be required over different time intervals, including annual, seasonal, monthly, and extremes. The shorter the time interval, notably for extremes, the more the demand on the network and monitoring requirement;
- Provide data on which day-to-day resource management decisions may be based;
- Provide sufficient climatic information to assess trends and year-by-year changes in glacier mass balance, depending on moisture and precipitation inputs and energy and melt outputs; and
- Provide sufficient information to assess year-by-year and decadal variations and trends in the comparative contribution to streamflow from glaciers, seasonal snowmelt, and liquid precipitation.

The density of the network required to satisfy these needs depends on the accuracy with which individual measurements can be made (a particular problem with snow measurement), the spatial variability of the variable (how spatially correlated it is within the region), whether the variations are systematic (for example, through lapse rates of temperature), and the time interval over which the balance is required (for example, a denser network for flood forecasting than for glacial mass balance studies or water resources management).

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2. Climate Monitoring

Climate and climate change have always played a central role in the culture and economy of the Indian subcontinent. The great early Indus civilization of the third millennium BCE, with centers at Harappa and Mohenjo-Daro, collapsed towards 1800 BCE and its cities were abandoned, almost certainly as the result of climate change (Wood 2007). In the Mughal era, the Emperor Akbar's magnificent palace and capital at Fatehpur Sikri was abandoned, probably as a result of an unanticipated shortage of water. In the 19th century, the British Raj used information on rainfall and its impact on agricultural productivity as a basis for taxation. Climate measurement, therefore, became a part of administrative duty, and rainfall records exist from the middle of the 19th century. The India Meteorological Department was founded in 1875, and, in 1891, the system of climate monitoring and reporting was formalized. Measurements include temperature and precipitation – principally used for climate change analysis – and wind speed, humidity, cloud cover, sunshine, and, more recently, radiation, all of which are now considered important variables for understanding climate change.

The climate of the mountain fringe was considered important when hill stations were developed for administrators as mountain retreats from the summer heat of the plains. The headquarters of the India Meteorological Department was based at such a station, Shimla. Himalayan climate had been an early subject of scientific study in its own right (Hill 1881) and as a basis for forecasting the monsoon (Blanford 1884). The Himalaya is believed to play a significant role in building the land–ocean thermal contrast that helps drive South Asian summer monsoon rainfall (Douville and Royer 1996).

In the last 20 years, the retreat of glaciers in the central Himalaya has generated heated debate on the role of anthropogenically driven climate change. Uncertainty has arisen primarily owing to the inadequacy of climate, glacier, and streamflow data, due to the difficulty of ground-based measurements at high elevations where climate has most impact on glacier mass balance, snowmelt, and streamflow. In addition, political sensitivity over shared water resources has restricted the dissemination of climate data by national agencies.

In the following text, network design is discussed in relation to high-altitude environments, how such networks have been typically used in previous analysis, and the relationship between topography and climatic variables. The use of historical climate data and the necessity of assessing the homogeneity of such data for climate change studies are discussed. Measurement methodologies are considered in relation to the extreme environment. Finally, recommendations are made with respect to monitoring, instrumentation, and analysis.

2.1 Monitoring Objectives

The objectives of a climatological and hydrological monitoring network include the following:

- Information to determine areal averages of moisture and energy inputs and outputs and storages (water and energy balances) at a range of space scales and time intervals;
- Sufficient duration of record to assess trends and periodicities in climatic variables relating to moisture and energy. Trends may be required over different time intervals, including annual,

seasonal, monthly, and extremes (5th and 95th percentiles). The shorter the time interval, notably for extremes, the more demanding the network and monitoring requirement;
- Climatic information to assess trends and year-by-year changes in glacier mass balance, depending on moisture and precipitation inputs and energy and melt outputs; and
- Information to assess year-by-year and decadal variations and trends in the comparative contribution to streamflow from glaciers, seasonal snowmelt, and liquid precipitation.

The density of the network required to satisfy these needs depends on the accuracy with which individual measurements can be made (a particular problem with snow measurement), the spatial variability of the variable (how spatially correlated it is within the region), whether the variations are systematic (for example, through lapse rates of temperature), and the time interval over which the balance is required (for example, a denser network for flood forecasting than for glacial mass balance studies or water resources management).

Starting from the simplest theoretical variable that is uniform throughout a region, only a single point measurement would be necessary to define the spatial average of the variable. As a second stage, a variable that has a defined and unique systematic relationship over a range of geographic physical features such as altitude could still require only a single measurement. The use of a single station to define certain aspects of the hydrology of large Himalayan catchments is not as outrageous as it may seem at first. In some meteorological settings, the measurements of a single station may be sufficient to characterize the system. However, a large network of stations is still required to establish such relationships.

With increasing spatial variability, the number of point measurements required increases for a given spatial accuracy (thus a greater density for convective than for frontal precipitation). Space scale is also important in the required density; at small scale, local factors such as orientation, slope, soils, geology, and glacier cover assume greater importance than in large basins where local factors are averaged. In other contexts and environments, Bleasdale (1965) has suggested that the density of gauges to define monthly estimates of average areal rainfall varies by a factor of 25 for catchments between 25 and 7,500 square kilometers (km^2).

2.2 Previous Network Design Recommendations

Previous consideration in the literature is concentrated on the design of precipitation networks. The discussion below focuses on precipitation but is relevant to network design for other variables. The World Meteorological Organization (WMO) (2010) gives a general guide to the density of precipitation stations required for different physiographic units, as abbreviated in Table 2.1.

In general, the more variable the areal distribution of precipitation, as in convective storms or in mountainous areas, the more gauges are needed to give an adequate sample. Thus, because of the perceived variability of mountain precipitation, the recommended density is more than double that required in other regions. However, actual densities are much lower than those recommended. For Nepal, with 281 rainfall stations on an area of 147,000 km^2, the density is 523 km^2 per gauge, while for the upper Indus and Jhelum in Pakistan, with an area approaching 200,000 km^2, the density is about 5,000 km^2 per gauge. Of course, in both cases, the gauges are concentrated at lower elevations, with limited representation at those levels where most precipitation occurs and where most flow is generated from melting of snow and glaciers. In the Himalayan region, existing methods for network design and the creation of gridded climatic

Table 2.1
Recommended Minimum Density of Precipitation Stations

Physiographic unit	Minimum density (km²/gauge)	
	Nonrecording (daily)	Recording
Coastal	900	9,000
Mountainous	250	2,500
Interior plains	575	5,750
Hilly/undulating	575	5,750
Small islands	25	250
Urban areas		10–20
Polar/arid	10,000	100,000

Source: WMO 2010.

databases are seriously limited. The ground-based climate network currently in place to validate models and interpolation methods is sparse and unrepresentative. The study in this report was designed to specify where and how such limitations can be overcome. While some global datasets are important inputs to regional climate models, none of the globally gridded data are sufficient to capture key elements of meteorological variables in the Himalaya. For example, data of the Climate Research Unit, the ERA model of the European Centre for Medium-Range Weather Forecasts, or the Modern-Era Retrospective Analysis for Research and Applications of the National Aeronautics and Space Administration (NASA) do not capture the distinct orographic rainfall bands that have been identified with higher-resolution data, for example, from the TRMM or from Asian Precipitation–Highly Resolved Observational Data Integration towards Evaluation of Water Resources.

2.3 Use of Climate Networks

Despite the limitations discussed, there is clear evidence that the existing climate network in the Himalaya can provide some useful guidance on trends in climatic variables that are relevant not only to the point of measurement but also over a wide area and in elevation zones in which measurements are limited or entirely absent. This conclusion is based on an analysis of the spatial correlation of the climate variables of precipitation and temperature in the upper Indus basin in Pakistan (Archer 2004; Archer and Fowler 2004; Fowler and Archer 2006) and on links to runoff (Archer 2003; Archer and Fowler 2008).

2.3.1 Temperature

Thus, for example, with respect to temperature from April to June, station seasonal temperatures are significantly correlated across the entire region, stretching 340 km east to west and 200 km north to south. At opposite ends of the upper Indus basin, Chitral (1,499 m) and Srinagar (1,587 m), which have major mountain barriers in between, have a correlation coefficient of 0.82. It seems reasonable to suggest that the correlation applies also to higher elevations; limited data for Kunjerab (4,730 m) and Shandur (3,750 m) appear to support this suggestion. The correlation analysis has been repeated for other seasons. The winter period, October–December, shows lower correlation coefficients and may be influenced to a greater extent by local temperature inversion effects at valley stations. The station at Astore (2,394 m) has the most consistent correlation with other stations for both the October–December and April–June periods.

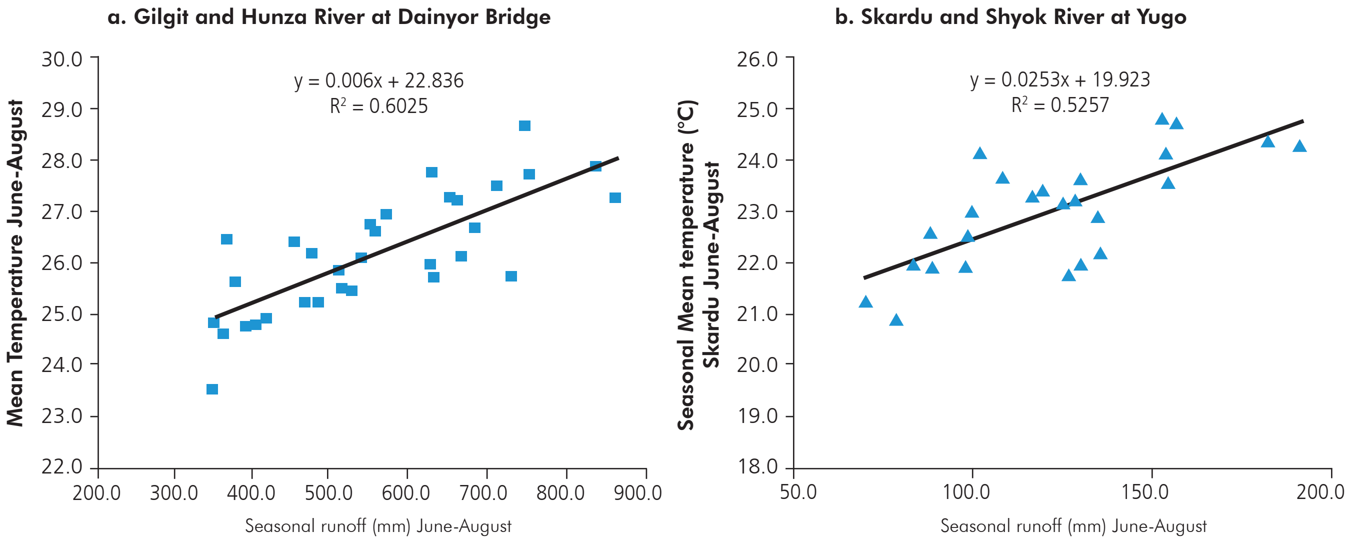
What further evidence is there that variations in low-elevation valley temperatures are representative of variations at high elevations? The evidence lies not just in correlation with high-level measurements of temperature (which are limited) but also in correlation with runoff from catchments where the flow originates from melt of high-level permanent snowfields and glaciers (Archer 2003; Fowler and Archer 2006). Figure 2.1 shows the relationship between temperature at valley stations at Gilgit and Skardu and seasonal runoff for the Hunza and Shyok catchments, both with mean catchment elevations over 4,400 m.

2.3.2 Precipitation

A problem similar to the correlation problem with temperature emerges with respect to the extent to which precipitation measured at valley floor level (where annual precipitation is generally less than 200 millimeter (mm)) is representative of variations and trends at higher altitudes (where precipitation may reach 1,500 mm) (Wake 1987). Again, the evidence lies in correlation between precipitation measured at valley level and the runoff from catchments where the flow originates from snow accumulated during the previous winter season. Figure 2.2 shows the relationship between winter precipitation at Astore and seasonal runoff for the Astore at Doyien (mean catchment elevation 3,921 m) and the Jhelum at Kohala (mean catchment elevation 2,629 m) stations.

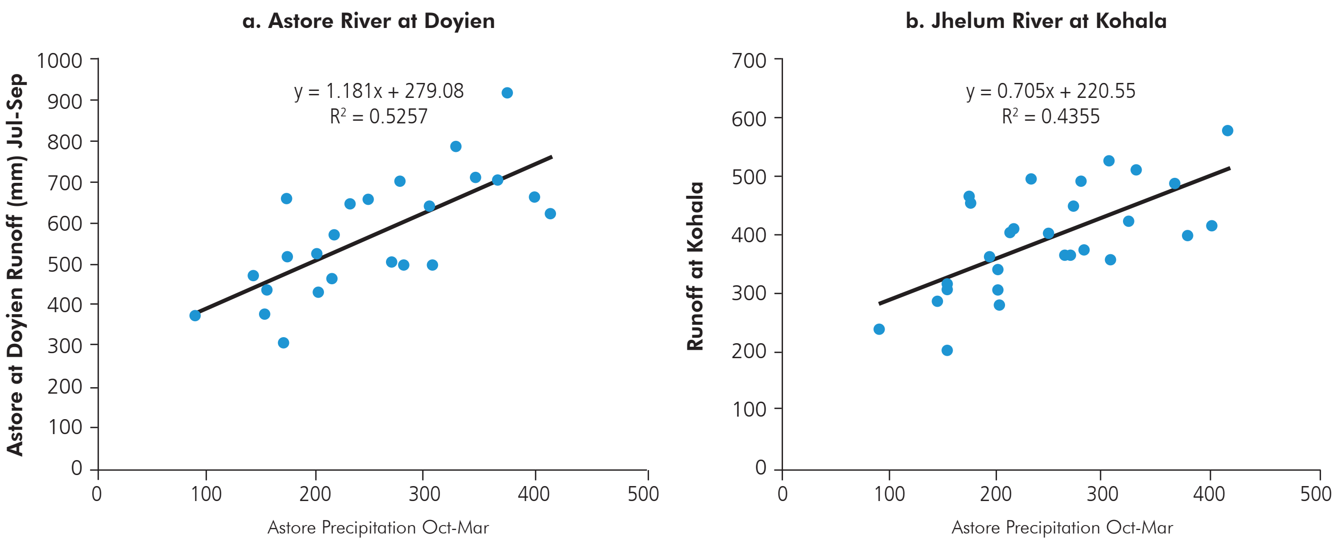
The use of low-level precipitation as an index of precipitation at higher elevations does not in itself provide knowledge of the actual precipitation at higher elevations. Such information is essential, for example, in assessing year-to-year changes in glacier mass balance. Some guidance on the progress and retreat of snow cover is provided by remote sensing observations of snow-covered area from the NASA Moderate Resolution Imaging

Figure 2.1
Seasonal Temperature and Runoff, June–August, at Two Locations in Pakistan



Source: Fowler and Archer 2006.

Figure 2.2
Preceding Seasonal Precipitation (October–March) at Astore and Runoff (July–September) at Two Locations



Source: Archer and Fowler 2005; Archer and Fowler 2008.

Spectrometer (MODIS) instrument. However, actual measurements of precipitation are quite inadequate (or not made available) above 2,500 m and virtually absent over 5,000 m in the northwestern Himalaya. In Nepal, in the Khumbu valley, a high-elevation network of six automatic weather stations has been installed over the past 10 years, which measure total precipitation as well as other standard meteorological variables.[2] They range in elevation from 2,660 to 5,050 m above sea level near the Pyramid Laboratory-Observatory. However, the total number of such high-level stations is still inadequate.

2.4 Environmental Features Affecting Variations in Climate and Glacier Mass Balance

Lapse rates of temperature with altitude are a fundamental physical aspect of climate. Basista, Bell, and Meentemeyer (1994) developed statistical relationships between mean annual precipitation and topographic variables including elevation, slope, orientation, and exposure. Such analysis is not new. Before the computer era, graphical methods were used to demonstrate that rainfall in the Rocky Mountains in the United States of America was influenced by elevation, slope, rise, orientation, and exposure, which together accounted for 85 percent of variation. Establishment of such relationships using either ground-based or remotely-sensed data may provide key links to a realistic assessment of areal averages of variables in rugged mountain topography. Existing evidence is given here mainly with respect to precipitation and temperature in the HKH. Other components of energy exchange are considered briefly below.

2.4.1 Precipitation

The general perception is that orography provides the necessary uplift for moisture-laden currents striking against a mountain range, resulting in copious rainfall, mainly on the windward side and

[2] EVK2CNR website: http://www.evk2cnr.org/cms/en/home.html.

increasing with altitude. However, in high-mountain areas, orographic uplift and convergence is balanced with increasing altitude by the decreasing capacity of the atmosphere to hold moisture at lower temperatures and the smaller remaining depth of the air column. Thus, beyond a certain point, precipitation will decrease with altitude. In the HKH, an early study by Hill (1881) suggested that rainfall in the northwestern Himalaya increases with elevation up to about 1,200 m and decreases thereafter. Dhar and Rakhecha (1981) found that maximum rainfall occurred in the foothills of the Nepal Himalaya at an elevation of 2,000–2,400 m.

In the Indus and Jhelum basins, the highest totals are at the comparatively low-level southern foothill stations, which receive significant totals in both summer and winter. The main influence is the sheltering effect of mountain barriers. Thus, there is a sharp northward decrease in the monsoon rainfall originating from the southeast in the Hindu Kush from July to September, falling to as low as 5 percent of the annual total at Chitral.

Limited evidence from the Karakoram suggests a quite different relationship between precipitation and altitude than in the southern ranges of the Himalaya. First, the valley floors at 1,000 to 1,500 m are arid, with annual totals generally less than 200 mm. Studies by Jacobsen (1997) in the Yasin valley, a tributary of the Gilgit River, showed increasing precipitation up to 4,400 m (636 mm). Cramer (1997) similarly found rainfall up to 720 mm in the Bagrot valley at 4,120 m. Evidence at higher elevations comes from the analysis of firn ice. Shi and Wang (1980) concluded that precipitation above 5,000 m on the Batura Glacier could exceed 2,000 mm, while Wake (1989) suggested typical annual accumulation rates of 1,500 to 2,000 mm at 5,500 m in the central Karakoram. In addition, hydrological studies of the runoff rates from Karakoram glaciers show annual rates of over 1,000 mm, which again implies (if the glaciers are even approximately in balance) that significantly higher precipitation occurs at higher altitudes. Nevertheless, the evidence base is still very weak, based on very limited time series or locations, and it requires strengthening.

A primary reason for the contrast between the Karakoram and Himalaya is probably that the Karakoram is affected to a much greater extent by the winter and spring westerlies, which are high-level meteorological systems compared to the low- to middle-level monsoons. The Karakoram appears to share the increasing precipitation with altitude regime with the Greater Himalaya (Singh, Ramashastri, and Kumar 1995), where the monsoon contributes only 35 percent of the annual precipitation total.

2.4.2 Temperature

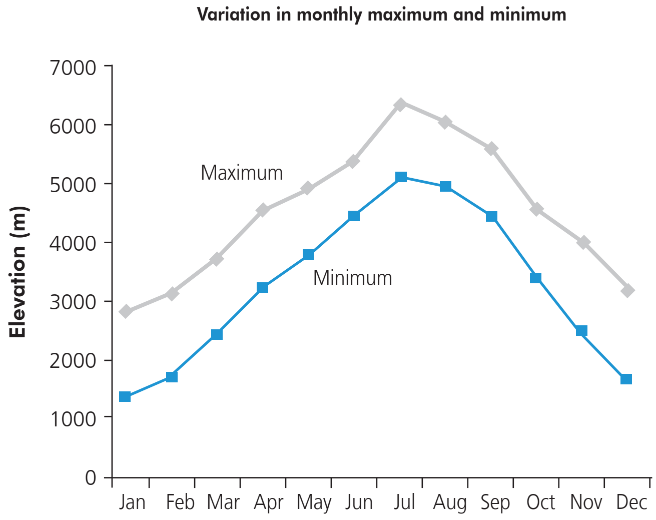
Since few measurements of temperature are made at high altitudes, extrapolation must be made from measurements at lower elevations using lapse rates of temperature. The accuracy of such extrapolation is critical for determining the extent, magnitude, and duration of the melt of snow and glaciers over a range of elevations. Environmental lapse rates refer to the actual change of temperature with altitude for a stationary atmosphere (that is, the temperature gradient); they depend on the saturation of the air mass and can vary from day to day and season to season. Where measurements are made at ground-based stations, additional variability arises from ground cover, including snow and ice, and the potential for temperature inversions at valley stations.

Linear regression of seasonal temperatures with station altitude in the upper Indus (Archer 2004) gave marginally higher lapse rates during the spring and summer (0.75°C per 100 m) and lower during fall (0.65°C per 100 m). Similar monthly analysis of lapse rates for maximum and minimum temperatures enabled freezing levels to

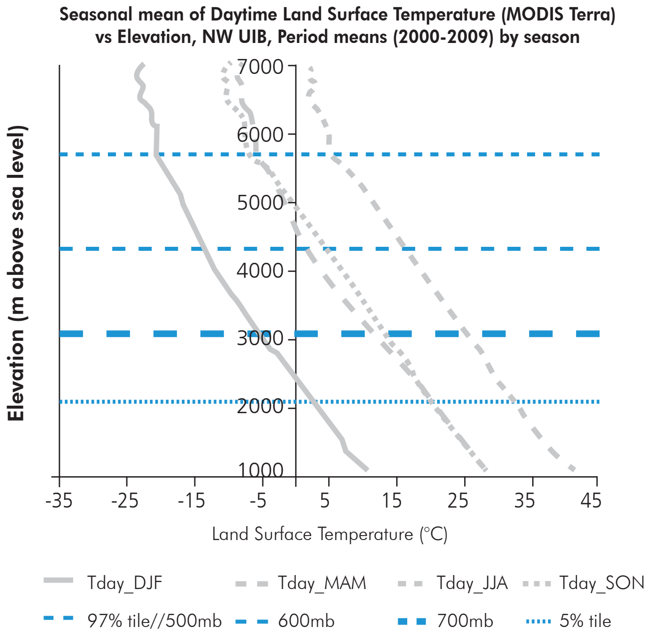
Figure 2.3

Estimates of Monthly Freezing Level and Seasonal Mean Daytime Land Surface Temperature Lapse Rates for Upper Indus Basin

a. Elevation of freezing level for monthly maximum and minimum temperatures based on station data, 1994–2000



b. Daytime land surface temperature versus altitude by season, 2000–09, based on MODIS remote sensing data



Source: Archer 2004; Forsythe et al. 2010.

be calculated for each month, as shown in Figure 2.3.a. From a hydrological point of view, the upper zone at elevations above the 0°C isotherm for maximum temperature is one of continuous frost, where precipitation falls as snow and where there is virtually no contribution to river runoff. However, it provides nourishment to lower zones through snow avalanche and glacier flow. The middle zone is one with frequent freeze–thaw cycles, where precipitation may fall as rain or snow, melt of lying snow occurs during daylight hours, and refreezing occurs at night. In the lower zone with continuous above-freezing temperatures, precipitation is expected to fall as rain and melt is continuous, though enhanced during daylight hours.

Satellite-based MODIS land surface temperature data provide an opportunity to evaluate continuous changes in temperature and lapse rate through the full elevation range of a catchment area, as shown in Figure 2.3.b (Forsythe et al. 2010). Note that the MODIS land surface temperature data are based on "clear sky conditions," and do not incorporate data from overcast periods; and they are based on separate passes at approximately 11:00 (daytime, as shown in Figure 2.3.b) and 23:00 (nighttime, not shown). Examination of the daytime land surface temperature lapse rate seems to indicate differentiated behavior depending on the snow cover or melt state. For example, the summer (June–August) and fall (September–November) seasons – corresponding to melting and snow-free conditions – demonstrate largely identical vertical patterns, a key feature of which appears to be a relatively constant value (approximately 7°C per 1,000 m) below 4,500 m above sea level. In contrast, the winter (December–February) and spring (March–May) seasons – corresponding to freezing and snow-covered conditions – have a steadily reducing lapse rate with increasing altitude.

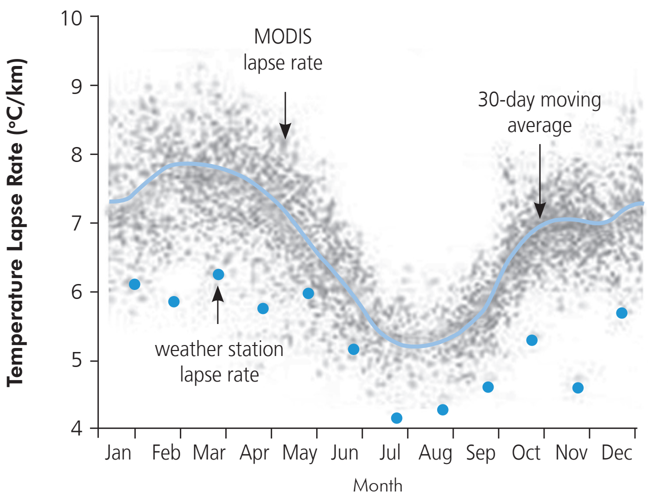
A quite different picture of lapse rate variation emerges from studies in the Sutlej basin (Figure 2.4) (Wulf, Bookhagen, and Scherler, in review). Both MODIS and ground-based data from the Sutlej valley suggest that the lapse rate is at a minimum during the summer. Wulf, Bookhagen, and Scherler suggest that this is because the upper Sutlej basin on the plateau of southwestern Tibet heats up much more during the summer, thus lowering the lapse rate. The Sutlej also has a much stronger monsoon influence than the upper Indus.

These analyses suggest that patterns of lapse rate vary not only with altitude and with season but also in quite different ways in different reaches of the HKH. Verification of lapse rates with ground-based data will be an essential component of successful modeling of the melt runoff process, both for the upper Indus and for catchments elsewhere in the Himalaya.

2.4.3 Energy Balance Variables

Air temperature is an imperfect indicator of the heat budget at the snow and ice surface, especially where melt is primarily due to radiant heat under cloud-free conditions. It has been investigated rigorously simply because it is the only variable with long and continuous records. In practice, temperature has been found in many applications to perform as well in modeling streamflow as using the full set of variables for the energy budget (Bergström et al. 1992; WMO 1986). However, application of the full energy budget may prove necessary to solve some of the difficult problems of the HKH. Some of these questions are as follows: How is energy partitioned between melt and evaporation or sublimation? What is the source of the increasing trend in diurnal temperature range experienced across the Himalaya (and shared with other parts of the Indian subcontinent) but contrasting with decreasing diurnal temperature range elsewhere in the world? In addition, radiation variables may be more readily adjusted than temperature for aspect, slope, and exposure where distributed modeling is based on a digital elevation model.

Figure 2.4
Annual Variation of the Temperature Lapse Rate for the Sutlej River Valley



Source: Modified after Wulf, Bookhagen, and Scherler, in review, WRR.
Note: The weather station location is a point measurement, while the MODIS data include all measurements within the Sutlej River basin.

Some climate stations, for example the high-level automatic weather station in northern Pakistan, now include a full range of solar radiation, wind, and humidity measurements, which should be thoroughly investigated for spatial variations when they are made available.

2.5 Monitoring and Analysis Needs

The summary of previous analysis across the HKH, and particularly in the upper Indus basin, indicates that some of the stated objectives can be plausibly satisfied with existing data in some parts of the region. In all cases, the release of more up-to-date data and data collected but withheld would provide a more secure basis for such analysis. This is particularly true in the case of meeting the needs of water resources management using monthly and seasonal data in the upper Indus basin, where the main source of moisture for summer melt originates from winter and spring precipitation and where climate variables are well correlated spatially. Analysis could be carried out with data currently available to establish whether such relationships apply in the eastern and central Himalaya, where the principal source of precipitation, both for direct runoff and for accumulation as snow, is the summer monsoon. Flow and flood forecasting need estimated catchment data at a short time interval, preferably a day or less. While previous analyses indicate that temperature and precipitation are well correlated spatially and altitudinally on a seasonal basis, it is not clear whether these relationships break down at shorter time intervals. This could be investigated with current data, but results would be more reliable if high-elevation data, currently withheld, could be made available.

The more difficult problems arise in satisfying the objectives associated with climatic controls (both energy and moisture) on glacier mass balance and trends. Glacier mass balance depends both on precipitation inputs and on energy outputs; trends could result from secular changes in either moisture or energy. Given the above analysis, it is possible that the combination of temperature data measured at lower elevations and remotely sensed data could be used on a monthly or seasonal basis to make first estimates of conditions at the elevations (3,500–5,500 m) where the greatest contribution of melt to runoff occurs. Direct measurements both of temperature and other energy balance variables at these elevations will be needed to validate or improve on these estimates.

The greatest problem arises in the assessment of precipitation in the headwaters of glaciated catchments. The analysis for the Indus River suggests that precipitation measured at valley level can be used as an index of runoff from catchments fed by melt of seasonal snowfall. However, this is merely an index; it does not indicate the actual precipitation received at different elevations. There is no physical basis for an extrapolation such as that provided by temperature lapse rates. Remote sensing provides information on snow-covered area but little reliability in assessing snow water equivalent. The relationship between high- and low-level precipitation is likely to vary from year to year and from region to region. There seems to be little alternative but to attempt to make the measurements, mainly of precipitation falling as snow, at the elevations where glaciers are being fed.

Snow measurement offers the most serious challenges of all climatic variables in obtaining reliable estimates, either as falling snow or as snow on the ground, even in accessible environments with good power and communication services. More serious difficulties arise in attempting to make automatic measurements in remote environments with limited power sources. The following is an assessment of whether and how these difficulties can be overcome.

2.5.1 Using Existing Climatological Data

A principal objective in climate monitoring is to assess trends and periodicities in climatic variables – or more generally, nonstationary or nonhomogeneous aspects of a climatic record – either existing or eventually acquired. Such assessment requires a long record period and will be long delayed if it is to depend on future monitoring. Therefore, the best use must be made of existing records and an attempt should be made to ascribe causes of trends or periodicities observed. It is of particular interest to determine whether observed changes are the result of: (a) widespread climatic phenomena such as the growth in greenhouse gases or the influence of oceanic–atmospheric processes such as the El Niño Southern Oscillation and the Pacific Decadal Oscillation; or (b) the result of observational changes or local land use influences. The second group of factors is unlikely to have any significant effect on trends in glacier mass balance. Awareness of these sources of nonhomogeneity or nonstationarity is important, not only for the analysis of existing data but also for the design, location, and management of an improved network.

The climatological network is long established on the Indian subcontinent, with some records of precipitation and temperature extending back to the mid-19th century. For example, there is a precipitation record for Leh in Ladakh from 1868 and temperature from 1882. Prior to 1890, there were large differences in the methods of measuring rain (time and type of rain gauge). The colonial government of India established a uniform system for rainfall measurement in 1890 covering areas now in Bangladesh, India, and Pakistan.

Rainfall listings in annual yearbooks are for the Indian subcontinent and cover principal stations in what are now Bangladesh, India, and Pakistan. Among the information provided for each year is a comparison with the average monthly rainfall from the previous record. The average monthly rainfall and the number of rainy days in each month were calculated for all stations with at least five years of rainfall data but, in the majority of cases, the averages in 1891 extended back over 20–30 years and were listed in columns entitled "normal data." Presumably all these data are still held at the India Meteorological Department as paper files, probably now digitized back to 1900 or to the beginning of records around 1860.

The United Kingdom Meteorological Office holds copies of India Meteorological Department rainfall reports dating from 1891 to 1947. Lists of rainfall stations by province for areas covering locations now in Pakistan and neighboring areas of India were extracted for three snapshot years – 1891, 1920, and 1946. For Jammu and Kashmir, nine stations are listed for 1891, 40 in 1920, and 46 in 1946. The earliest records included Gilgit, Leh, Srinagar, and Skardu. Punjab, initially a much larger province, had 196 stations in 1891 and for a province reduced in size in 1946 had 206 stations, several of which were on the mountain fringe.

The India Meteorological Department and Pakistan Meteorological Department took over responsibility for the networks after independence, though with a break of several years at some mountain stations. As far as can be ascertained, they continued the instrumentation and practices previously adopted with well-trained observers and periodic inspections. It is assumed that inspection reports and changes in location and instrumentation practice were held in a central office.

Separate networks were established by hydropower and irrigation agencies to serve their own specific purposes. It cannot be assumed that these records were maintained to a similar high standard.

Other daily climate variables, including temperature for the pre-independence period for the whole Indian subcontinent, were published by the India Meteorological Department in books, each covering a six-month period with one page for each day of record. It is assumed copies of these reports are held by the India Meteorological Department in Pune. An incomplete set is held at the Pakistan Meteorological Department in Lahore. Given that a number of papers have been published in which temperature data back to 1901 are analyzed (for example, Kumar, Kumar, and Pant 1994), it can be assumed that monthly maximum and minimum temperatures must have been held at many locations for over 100 years.

2.5.2 Assessing Stationarity and Homogeneity of Records

A homogeneous climate time series is defined as one where variations are caused only by variations in weather and climate (Conrad and Pollak 1950). As Peterson et al. (1998, p. 1493) note:

> [M]ost decade- to century-scale time series of atmospheric data have been adversely impacted by inhomogeneities caused by, for example, changes in instrumentation, station moves, changes in the local environment such

as urbanization, or the introduction of different observing practices like a new formula for calculating mean daily temperature or different observation times. If these inhomogeneities are not accounted for properly, the results of climate analyses using these data can be erroneous.

Data from the HKH are equally subject to the possibilities of these nonclimate-related changes, as the examples below demonstrate.

Observational and Entry Errors

Even the best records contain some observational or entry errors, perhaps arising from illegible handwritten records. For example, a misplaced decimal point can affect the extreme statistics of an entire record. Problems are multiplied where observers are poorly educated or trained, especially at remote sites where the prime purpose of the organization is not meteorology. Thus the author has observed on the Indian subcontinent more than one hill station where the observer ignored the minus sign in low temperatures! Such errors are often easily identified (minimum temperature greater than maximum), but others are more difficult, for example, those arising from a faulty thermometer.

Changes of Instrument or Measurement Practice

Kumar, Kumar, and Pant (1994) note that the instrument housing for thermometers in India changed in 1926, when thatched sheds were replaced by Stevenson screens. Presumably this affected all early records. Since the radiation properties of the housing might have changed, it was reported that the India Meteorological Department took overlapping observations to estimate the bias. The earlier records were then adjusted. Further details of these adjustments are noted in Kumar and Hingane 1988, mainly for the effects of urban heat islands on temperature. Automatic weather stations (and possibly other stations) now use thermistors instead of liquid-in-glass thermometers for maximum and minimum temperatures. Quayle et al. (1991) used station metadata in the United States to show significant changes, especially in maximum temperature, since thermistors can respond more quickly to rapid fluctuations in temperature.

Inspection of the precipitation records for Gilgit and Skardu shows that for the period 1928–47, daily rainfall totals in the archive were entered to the nearest 0.1 inch (2.5 mm), then to 0.01 inches during 1893–1927 and after 1947. In a study of Gilgit rainfall, Cramer (1997) found that, although there were 95 rain days in the year, 39 days had less than 0.2 mm and a further 21 days had less than 1.0 mm of rainfall, and together these contributed just over 10 percent of the annual total. Thus during 1928–47 rainfalls of less than half 2.5 mm would have been rounded down to zero. The recording method is, therefore, a source of heterogeneity in the precipitation record. It is believed that the total annual rainfall will be underestimated, perhaps by as much as 10 percent.

Changes in Station Location

Many principal climate stations are now located at airports. Clearly they cannot have been at the same site through their entire 100-year record period. Metadata in the form of station records, where available, should be checked for the impact of such site changes.

Changes in Station Environment

Station location changes can cause sharp discontinuities, while change in the environment around the station can cause gradual biases in the data. Factors may be very local or arise from more widespread phenomena and include:

- Growth of vegetation or nearby new buildings affecting exposure of the station;
- Effects of new irrigation in the vicinity of the

station (affecting temperature as well as humidity and evaporation);
- Effects of the urban heat island with growing urbanization; and
- The growing influence of the Asian "brown cloud."

While mountain stations are less vulnerable to some of these sources of bias, they are not entirely immune. For example, Kathmandu and Srinagar may well be affected by their own urban heat island, while all stations on the southern foothills are affected to some extent by the Asian brown cloud.

2.6 Identification of and Adjustment for Bias

A whole branch of statistical science has grown up around the identification of inhomogeneities in time series data. Many of the techniques now in use have been developed over the last 20 years in order to ensure that estimates of the effects of greenhouse gases on global temperature are not misrepresented. The statistical procedures are described briefly below, based mainly on review papers: Peterson et al. 1998 for monthly or annual resolution series, and Wijngaard, Klein Tank, and Können 2003 for daily series.

Generally, a combination of statistical methods and methods relying on metadata information is considered to be most effective to track down inhomogeneities. Where metadata are not available (as has so far been the case on the Indian subcontinent) statistical methods alone can be applied but with lower confidence.

2.6.1 Statistical Methods

To isolate the effects of station discontinuities from regional climate change, many techniques use data from nearby stations as an indicator of the regional climate. A long-established method for detecting discontinuities in records is double-mass analysis. A double-mass curve analysis plots the cumulative sum of the candidate station against the cumulative sum of a nearby station. Most double-mass plots are roughly linear, so a sudden change to a new slope indicates a discontinuity. A problem with the method is that it is impossible to determine whether the indicated discontinuity occurred at the candidate or nearby station. To correct for this problem, Rhoades and Salinger (1993) used plots of parallel cumulative sums at several nearby stations at the same time.

The use of data from several neighboring stations to develop a reference series is integral to many methods (Potter 1981; Alexandersson 1986). However, in some cases, where changes to instrumentation and other elements have all been made at the same time (such as the change in instrument shelters in 1926), neighboring station data cannot provide insights into those inhomogeneities.

Methods are also available for detecting inhomogeneities in single stations (Zurbenko et al. 1996; Rhoades and Salinger 1993; Potter 1981). Alexandersson (1986) developed the standard normal homogeneity test for a single break in a time series. A technique based on multiple linear regression was developed by Vincent (1998) to identify steps and trends in temperature series. The technique systematically divides the tested series into homogeneous segments. Adjustments are applied to bring each segment into agreement with the most recent homogeneous part of the series Wijngaard, Klein Tank, and Können (2003) applied a sequence of four tests to individual sites. The four test methods selected to test the homogeneity in the time series are the standard normal homogeneity test (SNHT) (Alexandersson 1986); the Buishand range test (Buishand 1982); the Pettitt test (Pettitt 1979); and the Von Neumann ratio test (Von Neumann 1941). The first three tests are capable of locating the year where a break is likely, and are referred to as location-specific tests. Wijngaard, Klein Tank, and Können (2003) also found that although discontinuities were difficult to detect in annual means of temperature, the diurnal temperature range proved a more robust means of detecting changes due to station or instrument relocations, changing observing practices and measuring techniques. Archer (2001) also found that diurnal temperature range could be used to detect a step change in the temperature record for Gilgit. Peterson et al. (1998) provides a description of the detection and homogenization techniques that have been used in both country-specific and global datasets.

2.6.2 Investigation of Regional Consistency

Apart from these objective tests, an appreciation may be gained of the reliability of trend assessments by a preliminary investigation of the consistency of records across a region, researching the following questions: Are seasonal totals (rainfall) and averages (temperature) highly correlated? Are the observed seasonal trends consistent between neighboring stations and across regions? Are there stations that are poorly correlated and have inconsistent trends? Such an analysis can be particularly useful for temperature that is spatially conservative and can be seasonally correlated over a wide region.

Indian mountain temperature records show strong seasonal consistency in the direction of trend between 1950 and 1991, which, surprisingly, during the spring and summer months is a downward trend but is predominantly upward in winter months, more in line with expectation (Shrivastava 2011). The summer result is at least curious, given the widespread observation of retreating glaciers and the belief that it is caused by global warming initiated by an increase in greenhouse gases. A similar analysis applied to the same stations with respect to rainfall trend shows consistently falling summer precipitation but consistently rising spring precipitation. If these records were found to be unbiased and also representative of higher elevations, then retreating glaciers might be more readily explained by changes in precipitation rather than temperature.

2.7 Monitoring Network Components

Climatological information is lacking principally for elevations greater than 2,500 m above sea level, but particularly at levels above the equilibrium line of glaciers, where ground-based measurements are extremely limited. Satellite-based data can fill some of the gaps at higher elevations but some variables (notably the water equivalent of precipitation falling as snow) remain largely outside the current scope of satellite remote sensing capabilities. Therefore ground-based information is still essential both for its own sake and as a means of verifying satellite-based measurements. However, the extreme environment places severe constraints on instrumentation, power demands, and communication of data, as well as on installation and management of such networks. Manually maintained climate stations may be possible in some locations up to the altitudes of the highest villages (about 3,000 m) but, above that altitude, automatic weather stations will almost invariably be required. The absence of continuous routine manual measurements places further limitations on the reliability and completeness of data. Since measurements are required in relation to glacier mass balance, the siting of stations on glaciers of variable mobility creates further difficulties in measurement.

2.7.1 Automatic Weather Stations

Many thousands of automatic weather stations, manufactured and supplied by companies, are in use around the world. Companies generally provide a standard complete weather station that includes a mast from which to attach the sensors. For standard meteorological stations, sensors include temperature and relative humidity, solar energy flux, possibly soil temperature, an anemometer and wind vane, and a tipping bucket or weighing rain gauge. Additional sensors can be attached that measure barometric pressure, additional measures of solar radiation or sunshine duration, soil moisture content, and evaporation (measured by pressure transmitter in an evaporation pan).

Standard stations come with associated data loggers and software. Logger memory can be uprated if many sensors are attached or if the logger memory is downloaded infrequently (remote sites).

Power requirements are generally low for a standard station and may be supplied by standard AA battery cells. However, there are options for operation via power mains (with adaptor), rechargeable lead-acid batteries with or without solar panels for recharging. This description is primarily for stations operating in a temperate environment. Where weather is extreme, it may be preferable to custom-build an automatic weather station, selecting the most robust sensors for the site. Power may have to be uprated with solar panels or a wind turbine, for example, to heat a rain gauge to prevent bridging of snow, to ventilate the temperature screen, or for communications. Some new technologies for snowfall measurement may have such power demands that their installation may still be impractical without a power main. The automatic weather station at Kunjerab in the Hunza basin at 4,733 m above sea level is shown in Figure 2.5.

2.7.2 Communications

Options are generally available for local download using a portable personal computer or a hand-held data capture device, or for remote download by landline telephone, GSM mobile phone link, satellite link, or meteor burst technology. Reijmer (2011, p. 13) summarizes typical communications used from remote mountain sites as follows:

Figure 2.5
Kunjerab Automatic Weather Station at 4,733 m above Sea Level in Hunza Tributary of the Upper Indus in Pakistan

Source: Photo by D. Archer.

Different communication techniques are used, particularly the Argos and Iridium satellite systems, but also Inmarsat satellite system, GSM, radio communication and Bluetooth. All have advantages and disadvantages related to power demands, costs involved, distance over which they can be communicated, amount of data that can be transferred, one- or two-way communication possibilities. For example, the Argos system is very reliable but is expensive and limited in the amount of data to be transferred, and only data retrieval is possible. Iridium, Inmarsat, and the GSM system have two-way communication possibilities but are more power demanding, with the latter two having limited communication ranges. Radio communication is only used for short line of sight distances. In general new measuring systems are mostly using the Iridium satellite system.

Meteor burst communication has been used effectively for the automatic weather station operated in northern Pakistan by the Water and Power Development Authority (WAPDA) and Pakistan Meteorological Department.

2.7.3 Measurement of Snow

Since precipitation contributing to glacier mass balance or forming the seasonal winter snowpack falls as snow, the accurate measurement of snow is an essential component of glacier and catchment water balances. However, measuring snow has greater problems than measuring liquid precipitation. Snow is hard to catch, it is readily redistributed on the ground, it melts differentially, and its presence restricts access to measurement points. For hydrological and glaciological purposes, the most important information required is the volume of snow as water equivalent – the depth of water that would result from melting. Both measurement of snow as it falls and measurement on the ground are fraught with difficulties that are further compounded where automatic measurement on remote sites is required.

Falling Snow

For the measurement of snowfall, the standard practice in many countries and with respect to automatic weather station sensors is to use a conventional rain gauge where amounts and rates of fall are determined by a tipping bucket or a weighing mechanism. Such conventional gauges suffer seriously from the effects of wind eddies created by the gauge itself and by nearby obstructions, including interception of drifting or blowing snow, bridging of the gauge orifice, or occasionally complete burial (Archer 1998). Wilson (1954) demonstrated the effect of wind speed on gauge catch and showed, for example, that with a wind speed of 11 m per second the deficiency is around 60 percent. For regular manual measurement in countries with regular high snowfall, special shields are fitted to gauges to minimize the effects of turbulent eddies, including the flexible Alter shield in the United States, the Tretyakov shield in the Russian Federation, and the Nipher shield in Canada. Even with these modifications, investigations show that measured snowfall is generally deficient (Goodison and McKay 1978). New sensors offer the possibility of more reliable measurement of snowfall, for example, the Campbell Scientific PWS 100 system, which uses an optical system and a laser-based light to accurately measure the velocity and size of precipitation. The use of two separate detectors and laser Doppler anemometry techniques allows the device to distinguish falling snow from blowing snow by assessing only the downward component. Precipitation rate and accumulation values can be calculated automatically. Similarly, the OTT Parsivel is a laser-based disdrometer for comprehensive measurement of all types of precipitation using the shadowing effects they cause when they pass through a laser band. A signal processor uses the raw data to calculate the type of precipitation as well as the amount and intensity of the precipitation. Both these instruments have a high energy demand and have so far been applied mainly where mains power is available. Further developments and testing may prove a valuable addition to measurements in extreme environments.

Snow on the Ground

The difficulties in accurately measuring falling snow and the subsequent differential redistribution and melting of the snowpack have focused attention on the measurement of snow on the ground. Snow depth measurements do not in themselves provide a useful hydrological measure, owing to the wide range of snow density, unless density can be separately assessed.

Where manual measurements are possible, the standard practice is to measure snow water equivalent using a snow core sampler at a repeated series of points along a snow course. Averaging of multiple points enables account to be taken of variability due to vegetation, drifting, and obstructions. Few such measurements have been made in the HKH, but De Scally (1994) used a limited set of such measurements (now discontinued) on the Kunhar River tributary of the Jhelum River and obtained high correlation coefficients between annual maximum snowpack water storage and annual runoff. There seems to be potential for more widespread use of such manual measurements at levels up to 3,000 m above sea level. Such measurements are likely to prove more useful in catchments fed by winter snowfall than in Himalayan catchments fed mainly by monsoon precipitation that falls as rain to a much higher elevation.

The snow core sampler has the advantages of mobility and low cost but has the disadvantage that it cannot be adapted for remote and automatic readings. For this purpose, a number of devices have been developed. Ultrasonic distance-measuring sensors placed over the snowpack are widely used as part of an automatic weather station assembly for continuous recording of snow depth at a point, but it requires independent measurement of snow density to convert depth to water equivalent.

Snow pressure pillows provide such information by detecting the pressure of snow on an antifreeze-filled pillow. Differences in sequential measurements indicate rates of snow water equivalent accumulation and ablation. Again, such measurements are not without problems: the possibility of accumulation of material other than snow, development of ice lenses that form bridges over the pillow, and the effects of differences in pillow albedo and roughness from surrounding vegetation in shallow packs may produce unrepresentative measurements. In addition, these are only single point samples of water equivalent and may not be representative of the surrounding area.

A unique approach was taken by Wake (1989), who used glaciochemical methods to distinguish annual accumulations in firn ice; he suggested typical annual accumulation rates of 1,500–2,000 mm at 5,500 m elevation. Few such wide plateau reaches exist at elevations above the ELA, but where they do exist, they should be exploited to assess annual precipitation accumulations and to compare with totals derived by other methods.

2.8 Recommendations

Good climate data provide the basis for analysis relating to climate change and water resources management and are essential for policy making, design, and operation of water resources systems. The following recommendations summarize and are derived from the previous discussion. The first set of recommendations relates primarily to historical climate records whose acquisition and use has been limited. However, such data need careful scrutiny to ensure their reliability and homogeneity.

2.8.1 Data and Metadata Acquisition and Validation Recommendations

- Acquisition and analysis of existing climate data should take priority over further development of the monitoring network;
- Attempts should be made to extend the readily available climate data (from about 1960–95) to include early pre-independence records from the mid-19th century. Hard copy records and perhaps digitized records are available at government meteorological departments, and some records are held at the United Kingdom Meteorological Office. Also, local sources, such as monasteries, should be asked for climate records;
- The data should also be updated to the present, especially as a basis for validating satellite monitoring records, some of which may cover only the last decade. Of particular importance are records from high-altitude automatic weather stations, some of which now have records in excess of 15 years;
- It is assumed that inspection reports, and hence station histories, were made for every station.

These should be requested and made available as a basis for checking the homogeneity of records. Some sources of metadata contain large amounts of irrelevant information, making extracting what is useful or relevant time consuming and tedious. Digitization of metadata should be considered, as it could ultimately offer researchers access to station history information without the expensive burden of performing a station-by-station search through paper archives;
- A preliminary appraisal of the data might include cross-correlation of seasonal totals, averages, standard deviations, and assessment of trends in the raw data. This will provide a basis for identifying anomalous, though not necessarily incorrect, records;
- A program of homogeneity testing should then follow, using agreed-upon and consistent tests. Where bias correction has occurred in the past, an attempt should be made to identify both raw and corrected data;
- Trend analysis of the adjusted data should then proceed;
- If correction is necessary, the corrected data can be applied to catchment and glacier modeling;
- Existing methods for the creation of gridded climatic databases are severely limited in the Himalayan region by the sparse, unrepresentative, ground-based climate network with which to validate models and interpolation methods. Such databases should be used with care; and
- Whilst numerous targeted climate research projects have been carried out in the HKH, there is a need for continuing routine analysis, especially relating to water resources, which requires coordination with hydrological databases often managed by different agencies.

2.8.2 Climate Analysis Recommendations

- In summary, the previous analyses across the HKH, and particularly in the upper Indus basin, indicate that some of the stated objectives can be plausibly satisfied with existing data in some parts of the region. In all cases, the release of more up-to-date data and data collected but withheld would provide a more secure basis for such analysis. This is particularly true in the case of meeting the needs of water resources management using monthly and seasonal data in the upper Indus basin, where the main source of moisture for summer melt originates from winter and spring precipitation and where climate variables are well correlated spatially;
- Analysis could be carried out with data currently available to establish whether such relationships apply in the eastern and central Himalaya, where the principal source of precipitation, both for direct runoff and for accumulation as snow, is the summer monsoon;
- Flow and flood forecasting need estimated catchment data at a short time interval, preferably a day or less. While previous analysis indicates that temperature and precipitation are well correlated spatially and altitudinally on a seasonal basis, it is not clear whether these relationships break down at shorter time intervals. This could be investigated with current data, but more reliably if data from high elevations, currently withheld, could be made available;
- For energy inputs to high-level snow and glaciers, it is possible that the combination of temperature data measured at lower elevations and remotely sensed data could be used on a monthly or seasonal basis to make first estimates of conditions at the elevations 3,500 to 5,500 m, where the greatest contribution of melt to runoff occurs. Direct measurements of temperature and other energy balance variables at these elevations will be needed to validate or improve on these estimates; and
- The greatest problem arises in the assessment of precipitation contributing to glacier mass balance in the headwaters of glaciated catchments. Monitoring and instrumentation for this purpose are noted below.

2.8.3 Monitoring and Instrumentation Recommendations

- Owing to the extreme conditions, automatic monitoring stations will provide the main source of continuous climate data at elevations above 3,000 m above sea level, and often at lower levels also;
- Where there are permanent villages at high altitudes, local personnel should be trained to run manual weather stations, check automatic weather stations, and carry out snow surveys, among other tasks;
- The operation and comparison of sensors for a wide range of climatic variables should be reviewed with respect to operation in extreme conditions. In its 2011 workshop, the International Arctic Science Committee made recommendations on the use of automatic measuring systems on glaciers;
- Standard bucket type precipitation gauges seriously and variably underestimate snowfall; their results should be used with caution in glacier mass balance studies;
- At suitable sites, snow survey courses should be established as a means of validating automatic measures of snow water equivalent;
- New sensors for measuring falling snow (and other precipitation) using the shadowing effects caused by precipitation when it passes through a laser band offer the potential for more accurate measurement both at manned and automatic sites. The operation and power demands should be reviewed to determine whether they could be adopted for use in the HKH; and
- Snow profiling at suitable sites above the ELA should be carried out to determine historical annual (and seasonal) snowfall.

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3. Glacier Mass Balance Monitoring

Monitoring glacier hydrology presents a unique set of challenges compared to other phases of water and energy balance, especially under the conditions in the HKH region. Glacier monitoring usually has three main objectives: to determine mass balance; to track fluctuations in ice extent; and to identify hazards. This chapter describes what is needed to monitor mass balance in relation to water supplies from snow and ice and their sustainability in the face of climate change and increasing demand.

The challenges of the HKH environments and diversity of societal conditions are well known. Not only are the mountains the highest, steepest, most rugged, and extensive on Earth, but there is also enormous variability of conditions and types of ice mass and differences in glacier responses to global climate change across the region. In addition, planners must keep in mind the diversity of societies and cultures in the mountains, development priorities and security issues in the countries concerned, and institutional arrangements.

This chapter describes the following phenomena that play distinctive roles in glacier mass balance in the HKH:

- High-elevation snowfall and its quantities, gradients, and variability in glacier source zones, as well as the differing climatic and seasonal regimes;
- Redistribution of snow by avalanche and wind;
- Avalanche-fed glaciers, predominant in the HKH but virtually unexamined and unresearched;
- Debris covers in ablation zones, including the extent and relative roles of different thicknesses, especially in the rather neglected areas of thin and scattered, ablation-enhancing materials, which take up more of ablation zones, are larger sources of water yields, and are climatically more sensitive than heavy mantles;
- All-year conditions and cycles in glacier basins, notably the largely neglected winter and "shoulder" seasons; and
- Glacier movement and thermal regimes, especially in relation to the predominance of sliding motion and evidence of chronic flow instabilities that are most sensitive to conditions controlling thermal, meltwater, and drainage variability.

These realities raise important challenges for monitoring. Some data on these factors exist for a few glaciers, but there are no systematic observations across the region. Obviously, neglect is partly due to the difficulties of observing many of these phenomena. Globally, monitoring for mass balance and glacier hydrology has deliberately avoided glaciers with these characteristics. Their importance is rarely recognized in approaches imported from other regions. This chapter describes how these aspects of glaciers intervene to generate distinctly different spatial and temporal patterns in the region, creating severe problems for widely used notions such as the snowline, ELA, and accumulation–area ratio.

The chapter concludes with a provisional list of suggestions concerning direct monitoring, including setups for training and experience of personnel, and research to address important issues. The neglected conditions seem mainly to require observing systems that work with and help test and support indirect and remotely sensed approaches. Actual monitoring networks for the glaciers themselves may not be a feasible goal, but much can be done to improve and integrate direct glacier observations into broader systems, and any successful program will need field competence and observations. This raises special questions of equipment and instrumentation, personnel, training, and safety, as noted by Young and Hewitt (1993):

The greatest value scientifically would be derived from a concentration on continued measurement of ablation in the ablation areas of the glaciers. It is here that very high specific yields are combined with relative ease of access. Within these zones the strategy should be to further refine balance gradients and how those gradients change under different meteorological conditions. This should be effected on areas of bare, relatively smooth ice at all elevations up to the equilibrium line.

3.1 Monitoring Approaches

Approaches to glacier monitoring may be broadly defined as follows:

- Direct measurement of ice mass variables and environmental controls in glacier basins, which requires field programs and instrumentation on and beside the ice;
- Indirect measurement, usually based on climatic conditions and water discharge measured outside glacier basins themselves. Standard weather stations and river gauging stations are the main basis for longer-term analyses, as well as possibly snow surveys. The quality of the results depends upon assumptions, correlations, and calibration with respect to what is happening at the glaciers;
- Remote monitoring using terrestrial, airborne, and satellite-based sensors that can determine glacier and off-ice parameters. Ground-truthing is a critical concern; and
- Models of glacier systems that provide data on relations and outputs derived from numerical or analog and related variables. Most have been developed for well-established cases and tested for them in terms of the first three types of measurements. A basic issue, again, is how well model results address critical conditions and correlate with direct measurements in the HKH.

Each of these approaches has its advantages and problems. In most places today, where water supply, glacier change, or hazards are concerned, some combination of the four approaches is in use.

The same is likely to apply in the strategies that may be recommended for the HKH and countries concerned, although the focus here is on issues for direct monitoring. It seems fair to say that best practices – the core concepts and standards for glacier monitoring – have been developed mainly through direct approaches or tested in relation to them. These have their problems everywhere, notably relating to logistics, cost, instrumentation, and safety. In the high mountains, constraints on access to many parts of the glaciers, instrumentation, and safety are especially severe.

Mass balance is the main and preferred approach to glacier hydrology. It looks at the relations of inputs or nourishment and losses for the whole glacier. With mountain glaciers, the usual concerns are with snowfall accumulation on the upper basin and surface ablation in the lower. The HKH raises unusual problems in this respect. In determining fluctuations, ideally the whole glacier should be considered, including its thickness and area–altitude distribution. In practice, this has rarely been done in the HKH. Nearly all studies relate to terminus fluctuations. Reliance on these to track glacier changes is unusually problematic in the region.

In the HKH, physical constraints along with economic pressures and institutional priorities have led to a preference for alternatives to direct measurement. Most estimates for the region to date use indirect and remotely sensed data and model assumptions. With a few exceptions, described below, inputs are usually inferred, not measured, and attributed strictly to "precipitation." Also, with a few important exceptions, direct observations of outputs are confined to termini: sometimes lower ablation zone areas, more often from streamflow data measured below the glaciers themselves. Nearly all direct observations available are for glaciers close to transmountain highways, on trails to highly valued mountaineering areas such as Mount Everest or K2, or on pilgrimage routes. This raises problems of representativeness and even concentrated human influences on glacier ablation, such as black carbon from fuel burning.

There is an emerging awareness, however, that checking assumptions and results against what happens on the ground is essential, given the recent reports, exaggerated or misread, of "disappearing glaciers" and imminent water crises. While not entirely unwarranted, much commentary has been based on poor or absent evidence and on poorly constrained assumptions (Raina 2009; Cogley 2011; Scherler, Bookhagen, and Strecker 2011). Glaciers with characteristics that prevail in the HKH have been systematically avoided and excluded. Conversely, programs are lacking in the HKH not only because of economic and cultural conditions, or even the extreme terrain, but also because the glaciers and environments of interest present serious challenges for conventional approaches. Security issues have also been a major impediment. An approach is needed that, while recognizing existing best practices, is informed by the conditions in the HKH and, where necessary, open to other methods. Before looking specifically at this parameter, the geography of HKH glacierized areas and programs already investigating glaciers will be described.

3.2 High Asian Context

The broader geographic setting is variously referred to as the Greater Himalaya region, the Tibetan plateau and adjoining regions (Tandong 2007), or more recently the "Third Pole" (Qiu 2008). As well as the main Himalaya, Karakoram, and Hindu Kush, the region includes the Pamir, Kunlun, Tien Shan, and east Tibetan ranges and the Tibetan plateau. The Greater Himalaya region supports over a dozen major concentrations of glaciers at high elevations. The total perennial snow and ice cover is thought to exceed 100,000 km^2.

The region that is the focus of this study, the HKH, is the arc of high mountains rimming the southern margins of the Tibetan plateau. They are the source of the headwaters of the three river basins of primary interest – the Indus, Ganges, and Tsangpo-Brahmaputra. The high mountains form a belt, rarely more than 200 km wide, that stretches nearly 3,000 km from west to east, or almost 35° of longitude. The glaciers of Nepal, Bhutan, and Sikkim are 6°–7° further south than those in Karakoram and Hindu Kush; 660–770 km further into the tropics, as well as being much further east. A predominantly southeast to northwest trend introduces considerable climatic and ecological diversity but the strongest gradients tend to be across the grain of the mountains – north to south or, in the western part, northeast to southwest.

Some estimates put the number of glaciers in the HKH region at around 50,000 (Williams and Ferrigno 2010). The Karakoram, feeding the Indus and Yarkand Rivers, has the most extensive cover, with over 16,000 km^2 of perennial snow and ice. The second largest is in and around the Nyainqentanglha Range in southeastern Tibet, draining mainly to the Tsangpo-Brahmaputra River.

Most of the ice cover consists of valley glaciers. Some small ice caps occur on peaks rising from the Tibetan plateau, and countless hanging, slope, and cirque glaciers on the lesser ranges. The larger valley glaciers comprise a major share of the ice volumes, however. In the Karakoram, the largest 15 glaciers comprise about half the total cover; the largest 50, almost three quarters. They include a majority of the largest glaciers in the region and the largest outside high latitudes (Hewitt 2011). The size of glaciers, their proportions in ice masses of different sizes, and their distributions should be considered when assessing their usefulness for monitoring. To date, this consideration of distribution has not happened, although the various inventories available may help in determining monitoring networks and procedures.

The near total neglect of the smallest glaciers in most of the region raises some questions about how to proceed. First, although individually small, in several of the ranges of interest they represent considerable amounts of snow and ice in total, as much as 6,000 km^2 in the upper Indus basin and even more in the upper Tsangpo-Brahmaputra.

They add up to much more snow and ice than in some better-known and more intensively studied areas such as the European Alps or New Zealand Alps. Second, if seemingly minor in countrywide overviews and regional water supplies, smaller glaciers are more critical for the populations living in the mountains and for ecosystems. Small ice masses on lesser ranges and interfluves, along with seasonal snowmelt in their basins, tend to offer a more manageable local water supply, for example, in small-scale hydropower developments. They can also be more sensitive to climate variations. Third, these are glaciers closer in size to those used worldwide as reference or benchmark glaciers to track mass balance and climate-related glacier change.

A major problem for monitoring is that the small ice masses are strongly influenced by local terrain and by topoclimatic and other conditions. Ruggedness and the glacier altitude relative to the regional snow line mean that many are largely or wholly fed by avalanches or affected by wind redistribution of snow. Such conditions have been scrupulously avoided when selecting benchmark glaciers, raising problems for any plans to establish them in the HKH; whether small glaciers can ever be representative of their region is in doubt. The larger glaciers are more important in regional hydrology and may provide a better basis for assessing regional conditions. They do present other large logistic and safety problems, as covered in the next section.

3.3 National and Transboundary Issues

Most of the waters from glaciers of the HKH originate within the boundaries of one country but flow into and across one or more others. The larger populations and extent of dependence on waters originating from glaciers occur in the surrounding lowlands, not necessarily in the same country as the glacier headwaters. This applies to the three major rivers of interest: the Indus, Ganges, and Tsangpo-Brahmaputra. For each, the catchment areas in which the glaciers are found straddle several countries and the rivers draining the catchments cross several countries. The Indus glaciers and meltwaters originate within the boundaries of four countries and drain to the lowlands of three. Glaciers of the Ganges basin are found in three countries and the tributaries drain through four. The Tsangpo-Brahmaputra glaciers are found in four countries and drain through five.

The largest quantities and relative shares of glacier meltwater involve the main stems of the Indus and Tsangpo-Brahmaputra. It is noteworthy that both mainly derive from trans-Himalayan glacier systems. Most glaciers draining to the Indus do so through the northwestern Himalayan or Nanga Parbat syntaxis, and most draining to the Tsangpo-Brahmaputra do so through the eastern Himalayan or Namche Barwa syntaxis – some of the most geologically active, steep, and high-relief terrain on Earth, which is also being closely scrutinized for planned hydroelectric projects.

For the Indus, the main glacier area and mass is in the Karakoram Mountains, most of it controlled by Pakistan but disputed and claimed by India. Other significant glacier areas are under Indian control, mainly in the eastern Karakoram, Ladakh, and Zanskar ranges, many of which are territories disputed by Pakistan. China controls a small area of the Aksai Chin region, with some glaciers, notably the great Rimo system, also disputed by India. Finally, most of the Hindu Kush and Hindu Raj glaciers drain to the Kabul River through Afghanistan but originate in the far northwest of Pakistan. The river returns to Pakistan through the densely populated and strategically located Peshawar basin.

The Tsangpo-Brahmaputra glaciers are largely in territory controlled by China in the southern and eastern Tibetan ranges, notably the Nyainqentanglha Mountains. Smaller but important glacier areas occur in Bhutan and Sikkim. India also has some Himalayan tracts and minor glaciers within the Tsangpo-Brahmaputra, but its situation is otherwise similar to Bangladesh in receiving the glacier waters from other countries.

The glacierized areas of the Ganges basin are comparably large in total, but more scattered by mountain range, countries, and several major tributaries. The waters from them are dwarfed by runoff from heavy rainfall in the foothills and plains. Nevertheless, on certain tributaries, they are critical for water and power developments in the mountainous headwaters. They assume special importance in years of weak or failed monsoons, at times of flood risk, and for groundwater recharge in the vast fans where the rivers leave the mountains.

From a monitoring perspective, these observations raise two distinct issues: transboundary sharing of water and information. Also at issue is how far strictly glacial conditions are of interest when the water supply from them is attenuated and modified in the key lowland areas. In the past, awareness of what is needed to effectively monitor the glaciers has been lacking and has received limited interest and funding compared to other priorities.

Each country faces different challenges, options, and likely solutions with regard to glacier monitoring. The objective givens of glacial hydrology and geography require sharing and cooperation where major components of water supply involve transboundary flows. It is difficult to plan for effective monitoring for larger water resources concerns and to track climate change without information sharing between countries in the region. However, such sharing also offers a potential source of secrecy and conflict.

From a broad perspective too, glaciers and aspects of their hydrology are of most immediate and greatest concern for people living in the HKH areas within each country. They may have very different interests and needs to those in downstream countries, and may have broader national and international concerns.

3.4 Glacier Inventories and Reference Materials

Several attempts have been made to assemble comprehensive inventories identifying the extent and locations of glaciers in the region. It is important to recognize that there are some limitations to the organization of regional inventories in terms of glacier conditions. The inventories seem to include perennial snow and ice areas rather than strictly glacier cover. The areas inventoried combine permanent snow and glaciers above climatic snowlines or firn limits, as well as active glacier ice below them.

A recent revision of the Karakoram inventory based on higher-resolution satellite imagery suggests that the figures consistently and considerably overestimate the actual glacier areas. Active glacier ice comprises less than 50 percent of perennial snow and ice (Hewitt 2005, 2011). Mayer et al. (2006) came to a similar conclusion for Baltoro Glacier. The inventories have nothing to say about the huge avalanche- and wind-driven redistribution of snowfall in off-ice areas and to the glaciers, which probably involve two thirds or more of all the snow that ends up as glacier ice.

No inventory appears to have taken into account the considerable amounts of dead ice in areas of glacier retreat since the Little Ice Age, as well as in thousands of active rock glaciers. These two accumulations could amount to some thousands of km^2 of near-surface ice in the HKH. Although they are minor sources of water outside the mountains because of slow ablation rates, locally they are important for water resources within the mountains, and in relation to climate change, ecosystem stresses, and cryosphere hazards.

In addition to glacier inventories, other inventories have been made of glacial lakes, outburst floods, and permafrost. These help provide a perspective on the region and in considering priorities and options for monitoring. However, the criteria used may not be appropriate for mass balance concerns, water yields, and responses to climate change, or as guides to monitoring. The inventories provide necessary and useful statistics for national and cryosphere background, but may also create an impression of comprehensive and coordinated knowledge of what lies behind the distributions and forms so classified, when this hardly exists.

Glacier investigations in the region, especially the more intensive and scientific ones, have been done mainly by expeditions, which go back almost two centuries. They can be the best or only sources of observations on the glaciers when reconstructing recent glacier change or compiling inventories of events for risk assessment (Mason 1954; Dainelli 1959; Bhambri and Bolch 2009). Institutions assuming responsibility in this field will need access to comprehensive bibliographic resources to track down data and results from past research. Nevertheless, the sources suffer from patchiness in space and time, as well as a range of different national languages and scientific traditions (Hewitt 2007a). Reconstructing conditions from the older literature and datasets certainly can be of value, but is complicated by how dramatically glacier science changed and advanced after the 1950s. A compilation of key references on the glaciers, possibly inventories of the best available topographic maps of glaciers, and satellite coverage – detailed in the recent United States Geological Survey (USGS) Satellite Image Atlas of Glaciers of the World – would provide a useful research source (Williams and Ferrigno 2010). Sources cited in this chapter focus on studies dealing with direct measurements and assessments of mass balance.

3.5 Past and Present Monitoring Efforts in the Region

Monitoring efforts comprising glacier mass balance and hydrological studies have taken place in the HKH since at least the 1970s. Recent efforts are described here by country for India, Nepal, and Pakistan, as well as China which has headwaters for glacier-fed HKH rivers.

3.5.1 India

Since 1978, the Geological Survey of India has carried out glacier mass balance and hydrological studies for the Indian Himalayan states of Arunachal Pradesh, Himachal Pradesh, Jammu and Kashmir, Sikkim, and Uttarakhand (Kaul 1999). An inventory of 5,243 glaciers was compiled with a total area of 37,959 km^2 (Raina and Srivastava 2008). The data were based on Survey of India topographic maps, aerial photographs, and satellite images, but there has been very limited field verification. The highest concentration of glaciers was found in Jammu and Kashmir, the lowest in Arunachal Pradesh.

Bhambri and Bolch (2009) provide a critical assessment of glacier mapping in the Indian Himalaya; they used available topographic sheets to reconstruct glacier fluctuations. Raina (2009) provides a critical assessment of the state of knowledge of Indian glaciers. He summarizes the observational base and identifies where there was a field measurement component to check estimates. While his research supports the conclusion of generally declining glacier covers and volumes, it challenges the popular view of “rapidly disappearing glaciers.”

Raina provides a table of “net mass balance” results in millions of cubic meters (m^3) for seven glaciers and for various years. However, he then points out that:

> Hardly any information is available regarding winter precipitation/accumulation. Even during summer months, though meteorological stations had been established at each and every glacier under observation, no data about snow precipitation were available. Lack of these data has been a major constraint in evaluating a specific factor that leads to fluctuation in glacier regimen (Raina 2009, p. 17).

Apparently some surveys were undertaken to rectify the lack of snow data, and satellite imagery is now being used to demarcate snow cover. Nevertheless, he identified a critical problem, which is one reason why different strategies are needed for the HKH.

3.5.2 China

China itself is outside the terms of reference for this study, but is important because of active and growing investigations of glaciers in High Asia as well as in all three of the basins of interest, some of which have headwaters in Chinese-controlled territory.

Chinese scientists and institutions have conducted many field-based investigations in the past two or three decades. A detailed glacier inventory was published in 2000 in 22 separate documents, based on World Glacier Inventory guidelines. It identified almost 46,300 glaciers with a total area of 59,406 km^2 (Chao-hai et al. 2000). The Institute of Tibetan Plateau Research and the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI) of the Chinese Academy of Sciences compiled a glacier inventory (Shih et al. 2010). In 2009, CAREERI published a map to a scale of 1:2,000,000 of the glaciers and lakes of the Tibetan plateau and adjoining regions (Tandong 2007). CAREERI is reported to be in the process of compiling a second, updated and improved national inventory.

A major initiative is under way under the title "Third Pole," focusing on climate change and its impacts on snow, glaciers, and permafrost. Leadership, significant participation, and funding come from China. Glacier investigations throughout the Greater Himalaya region are being actively pursued, including transects and other approaches within the three basins of interest here. This may initiate or assist in national and transboundary monitoring systems and information sharing.

3.5.3 Nepal

Between 1999 and 2004, the International Center for Integrated Mountain Development (ICIMOD) and its partner institutes prepared an inventory of glaciers in selected parts of the HKH region. The inventory was based on the 1:50,000 scale topographic maps published by the Survey of India in the 1970s, or Landsat satellite images from 2000 for areas for which no topographic maps were available. The study identified more than 15,000 glaciers with a total area of some 33,000 km^2 (Ives, Shrestha, and Mool 2010).

ICIMOD is conducting a Cryosphere Monitoring Program with funding from Norway.[3] This is a five-year program that includes a mass balance study of two glaciers, Rika Samba and Yala. Both catchments will be equipped with permanent weather and hydrometric stations, with plans to measure each glacier once every year. Short-term intensive field missions are planned to collect relevant glaciohydrological data, including ablation on debris-mantled ice, with the aim to determine spatial and vertical variations in precipitation. The program intends to build the capacity of ICIMOD's Nepalese partners in glaciology and glaciohydrology. It includes a master's level course that has already started in Kathmandu University, intended to enroll five students every year for five years. Most of this is yet to be carried out; it would be important to know what will be measured, the elevation ranges to be covered, instrumentation (how the considerable problems of winter weather and maintenance will be managed), and integration with indirect and remote approaches.

A French team from the Institut de Recherche pour le Développement, Grenoble, has been monitoring Mera Glacier for last two years, conducting measurements to estimate mass balance. In 2011, they also started monitoring a debris-covered glacier – Changri Nup – in the Khumbu area of Mount

[3] Arun Shestra, personal correspondence, November 2011.

Everest. Details of the work are not known, nor is it known whether these glaciers will be representative of larger mass balance and water resources estimation.

3.5.4 Pakistan

There has been a surge of interest in the upper Indus glaciers in recent years, mainly in relation to threats of "disappearing glaciers" and water resources demands. Various centers, cells, institutes, and government departments have begun using remote sensing, GIS, and satellite imagery. They are mainly concerned with mapping of snow and ice and cataloging the glaciers. Several institutions have taken initiatives to develop field programs and initiate or expand instrumentation near glaciers in the upper Indus basin. Most of this is at an early stage of development.

The Hydrology Research Division of WAPDA is unusual in that it has glacier and snow and ice hydrology investigations going back to the early 1980s, and even some snow survey activity in the 1970s. WAPDA is current engaged in the following activities:[4]

- Keeping the facilities provided under the Pakistan Snow and Ice Hydrology Project within acceptable limits and generating seasonal and 10-day flow forecasts for the Indus at Tarbela River, Jhelum River at Mangla, and Kabul River at Nowshera;
- Analyzing the data collected from the upper Indus basin high-altitude network to understand the climatic behavior of the hydrological active zone through use of the unit hydrographs;
- In collaboration with ICIMOD, training an engineer in modeling for the Hunza basin by using the topographic kinematic approximation and integration (TOPKAPI) model; and
- Most importantly, establishing a center within WAPDA to monitor upper Indus basin glaciers for water resources management in relation to climate change, for which a proposal was prepared for the federal government and an approach made to the World Bank for funding.

In addition, the Pakistan Snow and Ice Hydrology Project includes a program to monitor the Pasu Glacier, Hunza, in collaboration with the Pakistan Meteorological Department. An automatic river level station has been installed at the outlet of the glacier, and the use of tracer technology to measure discharge from the glacier is being investigated. The Pakistan Meteorological Department has installed an automatic weather station near the terminus of the glacier and plans to install another at a higher elevation.

3.6 Current State of Direct Glacier Monitoring

A number of efforts have been made to begin or extend and upgrade glacier observations in the HKH region, which, although promising, are at a very early stage of development. Critical questions need to be addressed regarding whether what is already known offers a sound basis on which to determine the best way forward.

Almost all data currently gathered and estimates for mass balance depend mainly or wholly on indirect data or extrapolation from terminus changes and snowline estimates (Ren et al. 2006; Raina 2009). Some major efforts are under way to exploit improved quality and frequency of satellite imagery to assess total ice mass changes (Bolch, Pieczonka, and Ben 2011; Scherler, Bookhagen, and Strecker 2011; Gardelle, Berthier, and Arnaud 2012; Benn et al. 2012; Kayashta and Harrison 2008).

Only a handful of individual research projects have been conducted on one or two glaciers for which mass balance estimates do not depend entirely on indirect, remote, and modeling resources (Fujita et al. 2006; Smiraglia et al. 2008). A very few

[4] Daniyal Hashmi, personal correspondence, 2012.

automatic weather stations are located near and along the same glaciers. In general, however, the sort of ground control that has been essential to check and calibrate remote sensing elsewhere is lacking in the HKH. Prior to satellite coverage, most of the HKH glacierized area lacked any modern observation capabilities.

Various studies have pieced together dispersed reports from visitors to the glaciers for a century or more, mainly to track terminus positions (Mason 1930; Bhambri and Bolch 2009; Shroder and Bishop 2010). Inventories of terminus fluctuations have been used to provide regional overviews for recent decades (Raina 2009). Longer-term regional assessments of glacier hydrology and glacier change are largely based on indirect and model approaches (Kayashta and Harrison 2008; Bhambri et al. 2011). As yet there are no provisions for regular assessments or updates, forecasts, and information sharing.

In a few places in the HKH and for barely a handful of glaciers, the full range of critical variables has been measured, as described in the next section. Rarely are they at all sufficient to produce plausible mass balance estimates or to track the sources of glacier fluctuations. Few of the best datasets on the glaciers extend beyond a few weeks of summer and only rarely for more than one or two successive years. The few instrument stations in glacier basins are in off-ice locations, and none has as much as a decade of continuous measurements.

More specifically, there are no reference or benchmark glaciers in the HKH (Fountain et al. 1997; Bolch 2011). Such glaciers are the bedrock of global mass balance and climate change monitoring. In all cases, they are derived from programs of direct measurements of main mass balance variables over many years and, for the global set, over several decades (UNESCO 1998; Haeberli 2011). Such glaciers are generally expected to be representative of the region concerned, although the fact that most are quite small ice masses makes this doubtful.

In its two major databases for mass balance and for fluctuations, the World Glacier Monitoring Service has no HKH glaciers (WGMS 2009). In his pioneering study of global changes, Oerlemans (2001) cited one glacier from the region, Minapin in the Karakoram, but it is predominantly avalanche nourished and has only intermittent observations which suggest it is a surge type glacier. Like the nearby Pasu Glacier, the main attraction of the Minapin for use as a source of observations is its road accessibility. However, it is questionable whether established global categories and assumptions for benchmark glaciers are appropriate or useful in the HKH for reasons addressed in the next section.

Useful observations of Karakoram glaciers go back at least 150 years, much longer than for the western United States or Canada, for instance. Observations in the region for the International Glacier Commission started to be compiled more than a century ago (Mason 1930; Korzhenevsky 1930; Raina 2009). Activities to determine mass balance and glacier hydrology in the Karakoram, for example, were resumed by major expeditions within a decade after the Second World War (Untersteiner 1957; Wiche 1959; Schneider 1969; Batura Glacier Investigation Group 1979). However, the work never progressed to fully fledged or continuous monitoring.

Second, as noted, more is now being done in and by organizations in the countries concerned than at any time in the past. India and Pakistan, for example, have established hydrological and meteorological networks that, in terms of the length of record, forecasting capabilities, and quality of personnel, should be the envy of most countries. Historically, however, very little of this involved or seemed to need monitoring of the high-mountain areas or glaciers. The focus has been on rainfall–runoff studies and river and groundwater hydrology in the foothills and lowlands. The field is benefitting from the increasing numbers of professionals with an essential requirement for this work – interest and experience in mountains and with snow and ice.

3.6.1 Elements of Mass Balance in the HKH

Mass balance is an accounting approach, ultimately about volumes or water equivalent amounts, and ratios between processes that add mass to a glacier and those that remove it. Measurements are made or calculated for an annual cycle or "budget year." Among others, Paterson (1994) gives a detailed account of terms, relevant phenomena, and equations.

Although new techniques and directions continue to be developed, a fairly well-defined conventional picture has emerged from mass balance studies worldwide, providing a basis for most actual monitoring and for indirect approaches and assumptions. The focus has been on the balance between snowfall and accumulation in the upper glacier area, and ablation and glacier ice melting from the surface on the lower part (Haeberli 2011). Mass may be added or subtracted in other ways, but existing studies of mountain glaciers largely concern these two. They lead to a spatial division of glaciers into accumulation zones, where there is an annual net addition of snowfall, and an ablation zone, with net losses. In valley glaciers an ELA separates the two, where inputs are exactly balanced by losses. Typically, the ELA is found to occur at or very close to the firn limit on the glacier where the seasonal snow is completely removed, exposing glacier ice. "Firn" is snow that survives on the glacier through the end of the budget year. The firn limit at the end of the ablation season is commonly seen as part of the climatic snowline – the highest retreat of seasonal snow cover in the mountain area. Physically, ice movement from the accumulation to the ablation zone maintains balance. Glacier movement volumes and throughput are expected, therefore, to increase towards the ELA and decrease below it down to the terminus. This is observed in most glaciers with well-established mass balance monitoring. It can be seen how, if firn limits snowlines, and ELAs are closely related, they offer a very convenient way to estimate mass balance. Deriving it from direct measurements is a much more laborious task.

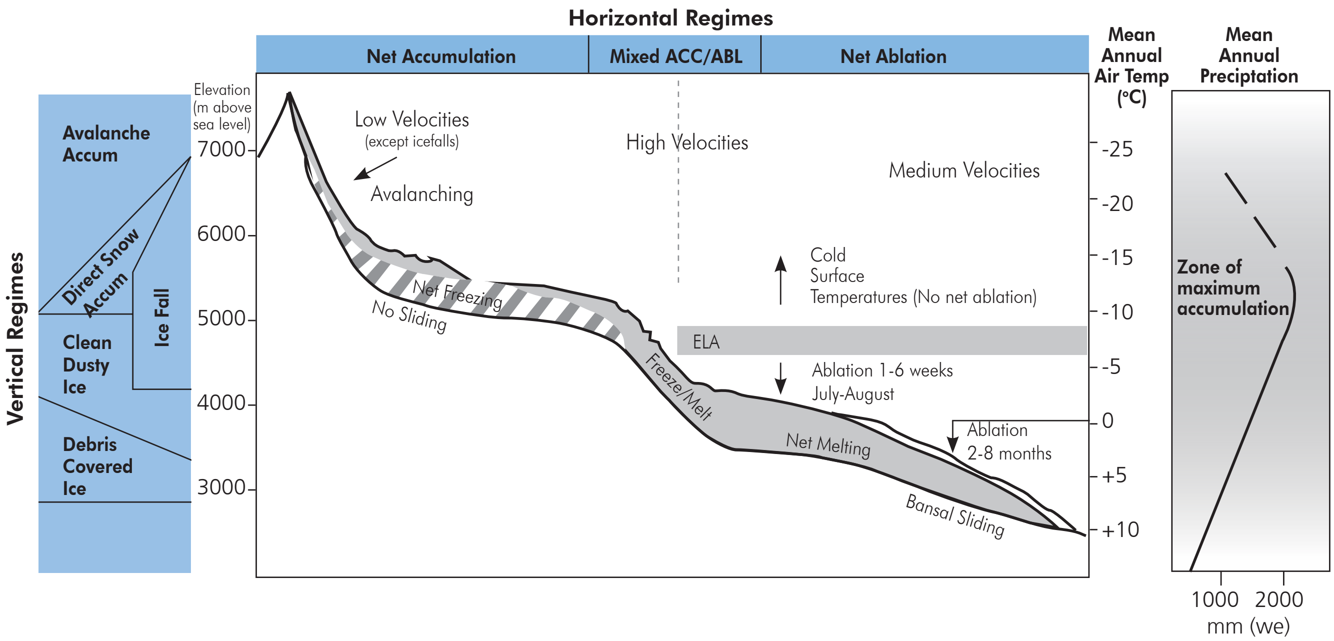
These relations are also the basis for expecting that any advance of the glacier terminus will reflect an increase in the net balance. Above the terminus, there will be thickening with positive balance or thinning with negative, and somewhat faster or slower rates of movement, respectively. In such cases, the main complication is a certain lag time, according to the size and morphology of the glacier, as adjustments pass through the whole. If the lag times can be determined, terminus changes ought to be useful in tracking changes in annual budgets.

The conventional procedure needs to be clearly understood. It arose out of direct glacier measurements, primarily in the European Alps and the mountains of western North America, that has become the basis for the general analysis of the advance or retreat of the glacier terminus. Moreover, mass balance estimates for the HKH have used or assumed the conventional terms: that is, nearly all studies and estimates for the HKH use the concepts developed in the Alps or North America (Harper and Humphrey 2003; Raina 2009). When models or concepts are imported from other regions, the limitations need to be clearly understood.

Figure 3.1 shows the main zonal, vertical, and mass balance regimes of valley glaciers, based on Karakoram examples. While interrelated, the different area–altitude conditions respond to climate and climate change in distinctive ways. They vary from glacier to glacier and regionally, and all are factors that monitoring projects must address. It will be seen that the conventional approach, focused on snowfall accumulation and surface ablation zone losses, and assuming consistent relations between them, greatly oversimplifies the high Himalayan picture.

This sketch (Figure 3.1) of a Karakoram glacier illustrates many of the features of glaciers in the circum-Tibetan Mountains of Asia. These glaciers are commonly composed of "cold" snow and ice in the accumulation zone, with temperatures constantly

Figure 3.1
Main Zonal, Vertical, and Mass Balance Regimes of Valley Glaciers



Source: Hewitt 2007b. *Note:* ACC = accumulation; ABL = ablation; mm (we) = millimeters water equivalent.

below the melting point of ice, and "warm" ice below, where seasonal melt and runoff occur. These two zones are separate by an ELA at approximately 5,000 m that often coincides with the altitude of maximum annual snow accumulation, and the zone of maximum glacier surface area. The duration of the ablation season increases downward from the ELA, where there is minimal ablation, to the terminus where ablation may persist for several months each year – the "ablation gradient."

In fact, the great majority of glaciers in the HKH depart more or less from the conventional picture. The few exceptions can be valuable for establishing comparative and baseline data, as outlined below. In most cases, however, other and different conditions intervene to govern mass balance in this region. They lie behind the fairly complicated picture in Figure 3.1 and are as follows:

- Direct snowfall is not the main form of input to glacier mass balance;
- Most valley glaciers in the HKH have a very restricted accumulation zone and many have none at all;
- These glaciers are mainly or wholly avalanche nourished;
- Avalanches and wind action intervene to redistribute most of the snow that feeds glaciers;
- ELAs rarely lie close to the snowline and, usually, are found hundreds of meters below it. To the extent they can be determined at all, they have complicated geometries;
- Debris covers in ablation zone areas intervene to regulate patterns and rates of melting. Extensive, heavy mantles suppress ablation, but even more extensive areas with thin ones enhance it;
- Mass balance gradients differ markedly from most in the literature;

- Glacier movement rates rarely follow the conventional pattern. Local sections of acceleration and deceleration are found within accumulation and ablation zones. Velocities further complicate relations to mass balance because they fluctuate widely on timescales from minutes to decades; and
- Sliding and block motion are predominant in most of the valley glaciers. Such movement is sensitive to and varies with meltwater and ice thermal conditions; it may or may not reflect mass balance. The large elevation span of glaciers and the role of avalanches and icefalls in the rapid downslope movement of mass introduce complications in vertical relations of mass balance and the relations (as yet unexamined) to the rates of transformation to glacier ice and the thermal state of snow and ice.

The founding documents and definitions of mass balance work clearly recognized that such conditions create distinct constraints on budgets, spatial and temporal patterns, and glacier dynamics (Meier 1962; Kasser 1967; Paterson 1994). To date, these factors have not been considered very important. Mass balance monitoring has tried to avoid situations or glaciers where these factors exist. An assessment is needed as to what the implications are for appropriate and effective monitoring in the HKH.

3.6.2 Accumulation and Source Zones

[T]he redistribution of snowfall by avalanching from steep slopes, and wind scouring from exposed areas, can result in accumulation patterns that differ markedly from original climatically controlled distributions (Benn and Evans 1998, p. 79).
As noted, the accumulation zone is usually defined as an area of the glacier itself on which snow falls and survives from year to year as firn, to be transformed at depth into glacier ice (Paterson 1994). Some glaciers in the HKH have extensive accumulation zones. They can be invaluable for monitoring strategies, as described below. However, the major inputs sustaining the ice in most glaciers are not direct snowfall.

Three very different types of glacier can be recognized in terms of nourishment:

- The snow-fed or "Alpine" type glaciers have direct snowfall as the dominant input, large accumulation zones, and, usually, well-defined firn limits and ELA. Almost all mass balance studies assume this type;
- The avalanche-fed or "Turkestan" type glaciers are nourished more or less entirely by avalanches of snow and ice from higher areas. Firn basins are small, absent, or not connected to the main ice network. Main ice streams commence below the perennial snow zone (Figure 3.2). In the HKH, countless small ice masses are of the "fall" glacier type, sustained by avalanching well below the snowline; and
- The wind-fed type glaciers depend largely or wholly on snow redistributed and carried to them by wind action. Most are small, mainly high-elevation cornice apron and niche glaciers, or below the snowline on lee slopes.

Virtually all valley glaciers for which well-established mass balance records are available would fall into the Alpine class. The problem is that the other two types are predominant in the HKH. In the Karakoram, three quarters of the larger glaciers are largely or wholly avalanche fed (Hewitt 2011a). Most small and minor ice masses are predominantly wind fed or avalanche fed. However, while it is helpful to identify the distinct type of glacier, in many if not most HKH glaciers all three forms of nourishment are found to occur. One form of nourishment may be predominant, but only a few glaciers are purely of one type (Figure 3.3).

An unknown but large part of high-altitude snowfall is redistributed and modified by wind action. It serves to strip, redistribute, deposit, and compact snow. It affects glacier conditions to a greater or lesser extent at all elevations, but especially around the interfluves and the uppermost parts of glacier basins. A critical function is to prepare and feed the avalanche cascade to the ice streams that commence far below.

Figure 3.2
Typical Avalanche-fed Glacier: Bazhin Glacier, Nanga Parbat East Face

Source: Hewitt, July 2010.
Note: The glacier begins in huge avalanche cones. There is virtually no continuous ice stream linking the ablation zone to the perennial snow and ice zone.

Figure 3.3
Avalanche-nourished Sumaiyar Bar Tributary of Barpu Glacier, Central Karakoram

Source: Hewitt, 1986.
Note: Taken in August, the photo indicates that avalanching is an all-year condition. Note the extent of wind redistribution of snow at higher elevations. There is about 3,000 m of relief in the photo, from the foreground at 4,800 m to Mount Malubiting (7,458 m) in the top right background.

The more obvious features are the cornices and wind slab areas. Also important is snow that drops out of the wind field on lee slopes and into gullies and couloirs where avalanches begin. The indirect evidence of the role of wind is not supported by any quantitative information, because so much occurs in the steepest parts of the basins and along narrow interfluves.

In any case, avalanches and wind action intervene between snowfall and ice to determine the spatial patterns of inputs to the glaciers, their timing, and their characteristics. Most of this intervention between climate and glacier ice occurs above about 4,000 m and, in many parts, above 5,500 m elevation. Now, according to Paterson (1994, p. 55): "Climatic factors influence accumulation on avalanche-fed glaciers only in so far as the size and frequency of avalanches is climatically controlled."

However, nowhere has recognition been accompanied by research. Some of the constraints and consequences for mass balance can be outlined; the neat separation of accumulation and ablation zones in the conventional scheme breaks down. The upper parts of glacier basins, rather than firn basins, comprise largely rock walls too steep for snow to remain on them. Much or all of the snowfall is redistributed in time and space before reaching the glaciers. Wind action serves mainly to redistribute snow laterally, compact it, and help prime the avalanche cascade. An unknown but large fraction of all the avalanched snow descends 1,000–1,500 m to reach the glacier surfaces, where it becomes incorporated into glacier ice. In some ways, it is like transposing the snow through some 10–15° of latitude. In a budget year, it is likely that avalanches transfer quantities of mass downslope in glacier basins equivalent to and, in many cases, greater than that transported by glacier movement.

Some nourishment – or in the strictly avalanche-nourished (Turkestan) glaciers, all nourishment – occurs in what is conventionally called the ablation zone. In the ablation zones, avalanched snow survives from year to year below where the conventional snowline or firn limit would occur. Significant ablation can take place side by side with significant inputs. Mass is added as well as lost. The ELA is not at elevations where firn limits or snowlines are found, but usually hundreds of meters below them. The great effort that has been expended to determine snowlines and ELAs in the HKH – generally placed between 4,500 and 6,500 m – looks at elevations where avalanche and wind redistribution of snow are at their most frequent. This also challenges the assumption that these phenomena will respond to climatic temperature change in any obvious, direct way.

Wind and avalanches not only redistribute snow in time and space, they also alter its character. Wind-packed snow is much denser than snowfall. Avalanche-deposited snow is usually even denser, often close to the densest firn. This speeds up transformation to glacier ice. Avalanches can carry large amounts of debris eroded from slopes and tend to be much dirtier than regular snow. They involve frictional and compressive warming, possibly melting, as they pass to lower elevations.

It seems important to establish the above points. Nevertheless, a grasp is also needed of what the primary inputs of high-altitude snowfall involve. Some sense of this can be gained from work carried out in the Karakoram that has implications for the whole region. The following study of Biafo Glacier is the only known relatively comprehensive profile yet available for high-altitude snowfall as a contribution to mass balance.

3.6.3 High-Elevation Snowfall at Biafo Glacier, Central Karakoram

Biafo Glacier is an Alpine type glacier, which is atypical for the region. However, it has vast, relatively gentle, and accessible accumulation basins between 4,700 m and 6,000 m elevation (Figure 3.4). They offer an opportunity to investigate high-altitude snowfall at elevations where otherwise avalanching and wind redistribution prevail and, since it is located in the heart of the Mustagh Karakoram, it should offer insights for the most heavily glacierized areas. Snow accumulation was observed there in the 1980s to identify sources of precipitation, and seasonal, elevation- and storm-related variables (Wake 1987; SIHP 1990). Such work has not been repeated.

Snowfall was measured between 4,800 and 5,800 m, the elevation zone comprising 70 percent of Biafo's main, connected glacier system (Hewitt et al. 1989; Hewitt 2005). Methods employed snow pits and drill cores to establish vertical profiles, and to retrieve samples for snow chemistry and isotope analyses. Snow samples were taken systematically

Figure 3.4
Biafo Glacier Accumulation Zone: Source of Snow Pit and Drill Core Samples

Source: Hewitt, July 2010.
Note: View from Hispar Pass; middle ground is about 5,000 m elevation; Baintha Brakk peak in the background is 7,285 m. Snow pit and drill core samples were obtained from the gentler, more sheltered areas well removed from avalanched slopes (Wake 1987, 1989).

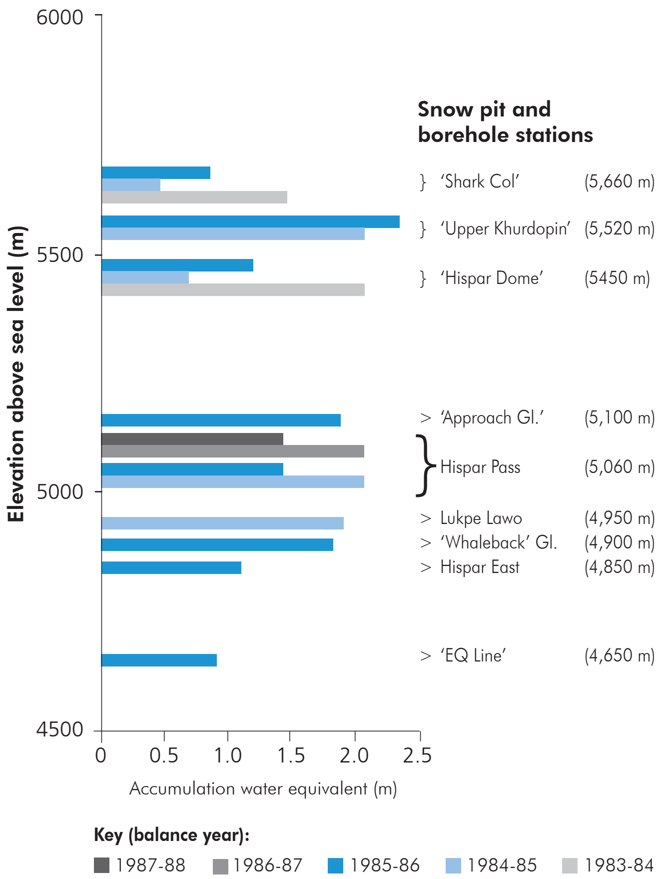
by depth and weighed to determine their density and water equivalent. When compiled for an entire profile, estimates can be made of annual or budget year accumulations. Chemistry and isotope work helped to determine seasonal contributions and variability in more precise ways, and to trace precipitation sources. Some comparative observations were made in the more limited firn basin areas of the Hispar and Khurdopin Glaciers.

Measurements confirmed the relatively heavy snowfall at these elevations. Averages at all sites exceeded 1,000 mm water equivalent in a budget year, an order of magnitude greater than precipitation records for valley weather stations below 3,500 m. Yearly estimates ranged from a low of 850 mm (we) at one site to more than 2,300 mm at another.

The zone of maximum precipitation is of special interest. The data suggest it occurs above 4,900 m, hence it is entirely in the glacier accumulation zone. The broadest elevation range of concurrent data, 1984–86, put the highest inputs at sites between 4,900 and 5,100 m, with some decline indicated above and below. Results in other years and sites leave a distinct possibility that maximum precipitation occurs at or continues up to 5,600 m, possibly higher. The greatest amounts, recorded on the upper Khurdopin Glacier at 5,520 m, may involve "overcatch" – the result of wind-blown snow carried across the watershed. The more exposed "Shark Col" (Wake 1987) may be subject to wind stripping (Figure 3.5).

Sources of precipitation show how glacier nourishment and health relate to climate systems and may be affected by global climate change. Chemical signatures in snow at three higher Biafo sites show, as expected, that winter snowfall comes from westerly sources; the Atlantic Ocean, the Mediterranean, Black Sea, and Caspian Sea (Wake 1987, p. 109). In late spring and early summer, Arabian Sea moisture may be drawn into the Karakoram by the same westerly frontal storms.

Figure 3.5
Snowfall (Water Equivalent) from Selected Sites on Biafo Glacier and Adjacent Basins, 1983–88



Source: Hewitt 2005 (after Wake 1987).

Summer snow samples also include a monsoon component in every year, indicated by isotopes, or chemical signatures, coming from the vast lowland agricultural areas of the subcontinent (Wake 1987).

Seasonal incidence of snowfall is another critical concern. The measurements put a little over half the average high-altitude snow accumulation in winter – but almost half in summer. The data are well constrained at the highest Biafo sites by stratigraphy, chemistry, and isotope signals. On average, 45 percent of accumulation came in May–September (Wake 1989). Summer contribution varied from 30 percent of annual precipitation to as much as 78 percent, in contrast to valley weather stations lower down where it ranges from 20 to 45 percent (Fowler and Archer 2006).

Considerable variability is seen from year to year in winter and summer contributions, according to air mass source, and at different elevations and sites. The snow pits at Biafo also confirmed field experience of the overwhelming role of a few large snowstorms, evident in the incidence of thick, uniform bands of snow, as illustrated in Figure 3.6. Heavy snowfalls were recorded high up in summer when little or none appeared in base camp records at 4,080 m or at valley weather stations. Before considering the mass balance implications, ablation conditions in the HKH must be appreciated.

3.6.4 Ablation in the HKH

In most mountain glaciers, ablation losses are dominated by surface melting below a certain elevation and are controlled by energy exchanges with the atmosphere. The HKH is not unusual in this regard, but important departures from the conventional picture are noted. On the one hand, surface melting is overwhelmingly driven by received solar radiation; on the other, various conditions intervene to modify where and how it operates, in particular the following:

- **Surface albedo.** This varies seasonally and following new snowfalls, but the most important difference is between relatively clean ice and debris-mantled ice;
- **Debris thickness.** In addition to the effect on albedo, there is a critical thickness at which ablation rates are the same as for clean ice, above which they are progressively less and below which they are greater. There is also a critical thinness, usually of a few mm, where dust or dirt veneers support the highest ablation rates; and
- **Summer weather.** Surface melting is affected by summer weather, especially the numbers of cloudy versus sunny days, and the incidence of snowfall in the ablation zone.

Figure 3.6
Accumulation Profile Exposed in a Crevasse, Biafo Glacier

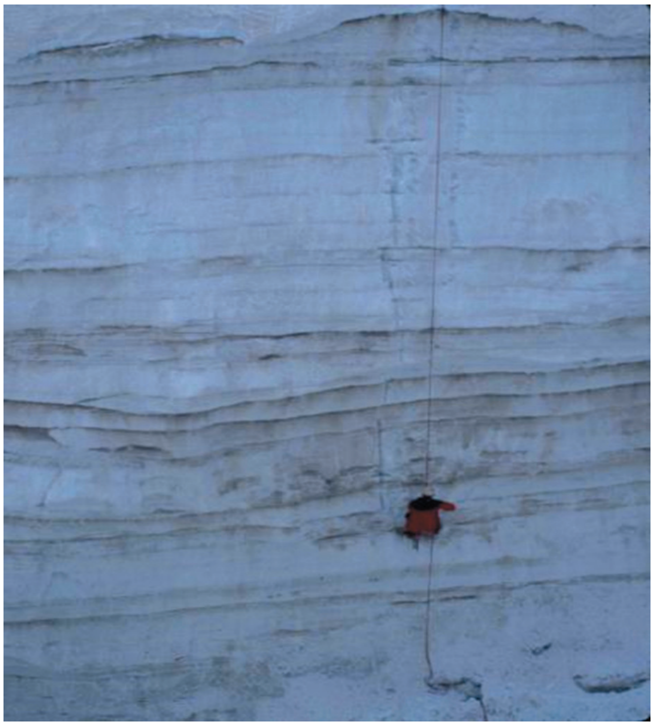
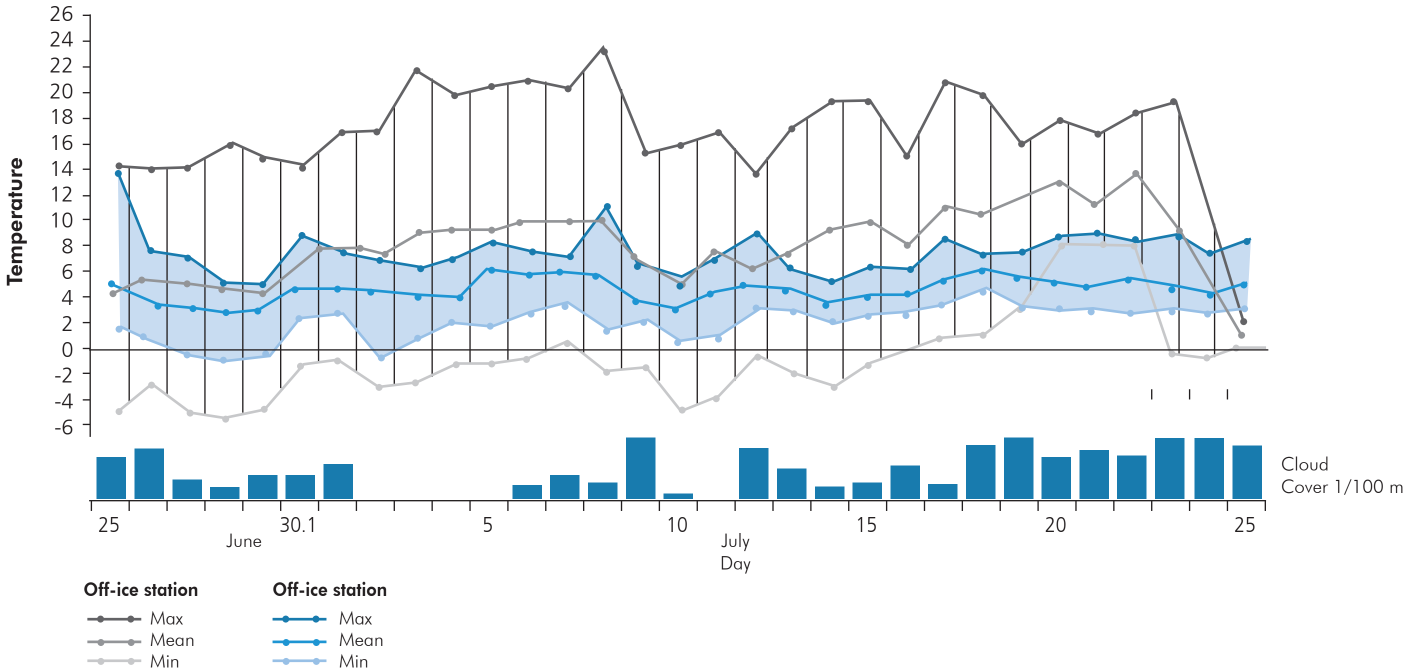


Photo: Hewitt, 1985.
Note: Although chemical signatures were spoiled, the profile indicates the contrasting clean winter and dirty summer layers. The scale of summer inputs is masked by intermittent melting and refreezing in ice layers. Year-to-year variability and the role of single storm events are evident.

With respect to the energy relation of ablation, it should be noted that even off-ice weather stations beside the glaciers, or the few of these that have been maintained, do not exactly represent on-ice conditions (Figure 3.7). In the main ablation season, for similar surface conditions, ablation rates are nearly the same over most of the ablation zone. Differences between conditions and water yields at different elevations mainly relate to the length of ablation season and debris covers. The most critical conditions that intervene between atmosphere and ablation relate to the extent and different thicknesses of debris covers.

Figure 3.7
Ablation Season Weather Observations for On-ice and Off-ice Stations at Same Elevation and 1.5 km Apart at Baintha Profile, Biafo Glacier, 4,050 m, 1986



Source: Based on unpublished Snow and Ice Hydrology Project data.

3.7 Debris-covered Glaciers

Supraglacial debris has a major influence on ablation as a result of the combined influences of solar radiation and large but highly variable amounts of debris delivered to the glaciers by avalanches, rock falls, wind-blown dust, and icefalls. Unlike most aspects of mass balance, ablation of debris-mantled ice has been much investigated in the HKH, although almost all the work has focused on heavy debris covers (Muller 1958; Mattson and Hewitt 2005; Shroder and Bishop 2010; Scherler, Bookhagen, and Strecker 2011).

The research has revealed critical thicknesses of debris that affect ablation. At a certain thickness, ablation rates are about the same as for clean ice, roughly 5–6 centimeters (cm). The higher heat absorption of debris is offset by lower conductivity through it to the ice surface. For progressively thinner covers, ablation tends to increase to a second critical thickness, usually a few mm, at which the highest rates occur – commonly 1.5–2 times greater than for clean ice, and in some cases up to four times greater (Adhikari, Marshall, and Huybrechts 2009). Ablation rates again decline below this critical thickness, as more of the ice is exposed. Scattered particles will enhance ablation compared to clean ice. Rates vary somewhat with surface roughness, the weathering that occurs with rapid ablation, and surface slope and local topography. With debris that exceeds about 10 cm, ablation rates decline to a fourth critical thickness, at which the penetration of warmth approaches zero in a given year and little or no ablation can occur. In detail, the ablation rates under apparently heavy debris

Figure 3.8
Debris Cover on Ablation Zone of Baltoro Glacier, Central Karakoram, June

Photo: Hewitt, 2005.

Figure 3.9
Light, Scattered Debris, Upper Baltoro Glacier, Representative of about Two-thirds of the Ablation Zone, July

Photo: Hewitt, 2005.

cover vary considerably. Impressions are deceptive: what looks "heavy" is rarely more than 50 cm on average and, except in the most slow-moving ice, is highly variable in thickness and constantly shifting around (Hewitt 2005; Mihalcea et al. 2006). For mass balance, it is important to know the distribution of different debris covers. Generally the presence of relatively thin covers (of, say, less than 10 cm) is hard to discern within the heavy covers or to discriminate within the critical thicknesses of about 3–10 cm, where ablation rates can be as high as bare ice, or higher, and may be changing with quite small increases or decreases in thickness. Debris covers vary considerably over much of the ablation zones (Figures 3.8 and 3.9). No satisfactory method has yet been devised to determine debris thicknesses and types, or effects on ablation rates, except by direct observation. It would be beneficial to find better ways to identify and classify surface conditions on ice from satellite imagery, which does show something of the diversity involved.

Heavy debris protects the ice in the lowest, warmest areas with the longest ablation seasons. It is widely believed this phenomenon is decisive for glacier behavior, responses to climate change, and water supply, but the view is difficult to accept. The areas of clean, dusty, and dirty ice are larger in total. In the Karakoram, they average about two-thirds of ablation zone areas. They tend to be at a higher elevation with a shorter ablation season; nevertheless, hydrographs show they are far more important for total ablation losses, glacier health, and water supply. The thinner covers are also more sensitive to weather and climate change.

3.8 Water Yield from Glaciers

The greatest interest in HKH glaciers is as a source of water. It is important, therefore, to be clear about which water yields are being measured or estimated. The main, if not exclusive, focus of conventional mass balance studies is ablation of glacier ice and ablation zone outputs. For the heavily glacierized areas of the HKH, this is surely the largest source of water. When glacier ice is exposed at the surface, under the energy conditions that apply in summer between, say, 3,500 and 5,500 m elevation, ablation yields can far exceed precipitation. A common range for specific losses is 4–8 m water equivalent in a year. At a site at 2,900 m on Batura Glacier, ablation loss exceeded 18 m in a year (Batura Glacier Investigation Group 1979). This reflects a long ablation season, with some ablation on 311 days of the year and a thin debris cover that increases ablation rates.

Of course, other sources of water exist in glacier basins. If gauging stations are at or very close to a glacier terminus, it is still necessary to determine the relative contributions of several sources to isolate the mass balance component. The various sources can include the following:

- Ablation of glacier ice;
- Melting of seasonal snowfall, on the glacier ablation zone and ice-free areas;
- Melting of the seasonal freeze–thaw carapace that develops on subtropical glacier surfaces;
- Rainfall within the basin; and
- Rock glaciers and degrading permafrost in tributary valleys within glacier basins.

Only ablation and melting of the carapace pertain entirely to the glacier and its mass balance, while seasonal snowmelt and rainfall involve precipitation in on-ice and off-ice areas. The scale of contributions from glacier basins in the HKH probably follows the order of the list, subject to variations in different parts of the region, at different times of the year, and with climate change. While ice ablation tends to be a much larger factor from larger glacierized areas, the other sources nevertheless involve amounts and variations that equal or exceed those implied by climate changes over a decade or more.

Discharge hydrographs most directly reflect seasonal conditions in ablation zones, moderated by the length of the ablation season, which varies vertically depending on the following factors:

- Annual migration of above-zero temperatures with elevation;
- Area of ice exposed to ablation, usually increasing through the middle ablation zone;
- How long glacier ice is exposed, which tends to decline with elevation and according to seasonal snowfall and the extent of the freeze–thaw carapace;
- Distribution of debris mantles and the spectrum of thick versus thin covers; and
- Ablation season weather.

Glacier ice exposed to ablation explains why, in much of the HKH, 80–90 percent of water yields from glacier basins occur in two to three months of the year. In this sense, it is the "golden egg" of glacier hydrology and constitutes the so-called Himalayan "water towers." However, how the egg is peeled, so to speak, is important in year-to-year and longer variations, something in which the other factors are critical. Unlike rainfall–runoff or snowfall–snowmelt relations, the roles of annual precipitation and temperatures, so often the best indirect guides, are buffered by intervening conditions in glacier basins and can even seem unrelated. Each ablation season unfolds according to how these various factors work together.

For peak yields, area–altitude relations are critical. At lower elevations, heavy debris covers suppress ablation throughout the year. This adds to the importance of what happens in middle to upper ablation zone areas. In these areas, for ice ablation to start, seasonal snowfalls and the cold season freeze–thaw carapace must first be removed to expose glacier ice with thin or no debris covers. Hardly any data have been collected on this phenomenon, but experience at Biafo suggests these are not trivial aspects, especially in year-to-year variations (see section 3.14).

It should be added that conditions on small or minor glaciers and areas where they prevail are likely to be different yet again. The larger yields from their basins are likely to come from seasonal snowfall, directly or as redistributed by wind and avalanches. Because smaller ice masses generally occur with the lower mountain watersheds, seasonal snowmelt and rainfall assume a much greater significance in water supply and climate responses. Their hydrology differs accordingly.

Another difficult issue for water resources assessment based on river flows is that peak yields from the HKH glaciers coincide with the summer monsoon. In the three major river basins of interest this is when rainfall runoff dominates flows of most sections, especially towards the heavily populated lowlands.

3.9 Glacier Regimes

Glaciers in world mountain regions have been classified and investigated in terms of nourishment, seasonal conditions, mass balance gradients, activity indices, and thermal regime or morphological types. Few other areas confront us with or prepare us for the diversity of types in the HKH. For example, the criteria that identify glaciers with distinct climatic regimes elsewhere – from polar and temperate to equatorial, or in maritime versus continental – *are all found within this one region*.

Mass balance regimes refer to the annual pattern of gains and losses identified with the seasonal incidence of accumulation and ablation. They relate to broad patterns of controls over glacier behavior and water yields, and some potential responses to climate change. They vary substantially across the HKH, with important implications for monitoring. Much has been written about the "summer accumulation regime" of the Greater Himalaya, where summer monsoon snowfall dominates primary inputs (Ageta 2001). However, regimes change from west to east and north to south, partly as a function of latitude, but mainly through relations to different moisture-bearing air masses and the Tibetan plateau. Globally, several distinct mass balance regimes have been identified for valley glaciers, mainly on the basis of latitude or zonal climates of the following types (Kaser and Osmaston 2002, p. 25):

- Inner tropics type, with two-season or year-round accumulation and year-round ablation;
- Outer tropics type, with summer accumulation and strong summer and weak or no winter ablation; and
- Mid-latitudes type, with winter accumulation and summer ablation.

The Greater Himalaya range from Kashmir to Sikkim can be placed in the outer tropics type with, as noted, a summer accumulation regime. The Hindu Kush and Pamirs have a mid-latitude regime dominated by winter snowfall. In the past, the Karakoram was treated as having the same. As described above, however, high-altitude summer snowfall is almost equal to that in winter. It might suggest an intermediate type but involves an accumulation regime at least as distinctly different as the inner tropics type, which in some respects it resembles. Alternatively, the Karakoram annual budget can identify a distinctive, fourth regime – a year-round accumulation and summer ablation type, which also results in two different outer tropics types.

As the discussion has shown, accumulation, even ignoring the intervening roles of wind and avalanche, is the part of HKH mass balance least well understood or measured. Glacier basins in all areas receive winter snowfall for which there is very little information and for which measurement is sorely needed. It may be seriously underestimated for high elevations in the summer accumulation areas. Records for weather stations are usually far away from the glacier areas, mainly at lower elevations; and the data of primary interest, snowfall, are difficult to collect as snow gauges give the least reliable of precipitation data.

Regime classes emphasize annual patterns. Of equal or greater importance in the HKH are spatial patterns, especially the vertical organization of mass balance.

3.10 Mass Balance Gradients

Mass balance gradients reveal the amount and shares of inputs or outputs occurring at different elevations. In the conventional scheme, they are shown to vary systematically with elevation (Benn and Evans 1998, p. 78–79). Ablation losses are shown as greatest at or near the terminus, declining upwards to a well-defined ELA. Accumulation increases progressively above that. The gradients usually appear as straight lines or nearly so. Differences between glaciers and regions are reflected in their slope, or highest versus least ablation and accumulation values. The highest are typically identified with more humid, usually maritime glaciers. A narrower spread reflects drier, colder, more continental settings.

Mass balance gradients for Karakoram glaciers hardly fit the conventional picture, with considerable diversity of profiles. Even Biafo, an Alpine type glacier that might be expected to have a fairly conventional profile, does not. The very low value near the terminus is mainly an effect of debris cover and ablation increases slowly through the lower 15 km of the main glacier (compare Inoue 1977). Ablation expands to a maximum in the middle ablation zone and declines sharply through the upper ablation zone. Through the lower accumulation zone, inputs increase sharply but are expected to decline at the highest elevations. An S-shaped profile results, much different from the near-straight ones typical of Alpine type glaciers elsewhere.

Missing from the Biafo curve are the roles of wind redistribution and avalanche inputs. Since, in a conventional approach, mass balance inputs apply only where the glacier itself is and in effect to the main connected glacier, most sources in the perennial snow zone of avalanche-fed glaciers are excluded from mass balance calculations and gradient. Where the accumulation zone would normally be, wind and avalanche movement of snow and ice prevail. In avalanche-fed glaciers the S-shape remains but is unlike anything in the conventional picture. Most or all net inputs occur below snowlines or firn limits, so that both positive and negative curves are in the ablation zone.

Virtually no work has been done on just how and where inputs occur from snow and ice avalanches and from wind-redistributed snow. Clearly, some of the most widely applied notions relating to mass balance need reconsideration. At the heart of the problem is how elevation, hypsometry, steepness, and ruggedness intervene to reconfigure the processes determining the relation of the mountain "climate" to glaciers and glacier dynamics.

3.11 Verticality

In the high mountains, mass balance is as much about spatial as seasonal regimes. The latter depend mainly on regional climates, the former on altitude, elevation range or relief, topography, and orientation of glacier basins. In the main concentrations of glaciers of the HKH, the larger masses have exceptional elevations and relief (vertical span).

The Karakoram glacial zone spans more than 6,300 m vertically, that is, from the summit of K2 (8,610 m) to the lowest glacier termini in the Hunza valley, which reach down to 2,300 m. No individual basin spans the entire whole range, but several basins span over 5,200 m, and at least 40 more than 3,000 m. Two of the larger Everest region glaciers, the Khumbu in Nepal and the Kangshung on the Tibetan side, commence on Mount Everest (8,848 m), higher than any Karakoram glacier, but terminate at 4,800 and 4,560 m, respectively, a range of just over 4,000 m. For many of the larger Karakoram glaciers, available relief is the main constraint of elevation range, whereas mass balance is more critical for the Everest glaciers. The latter, unlike many Karakoram glaciers, terminate where valleys continue steeply down, as do glaciers on the west and south faces of Nanga Parbat. The well-known Rakhiot Glacier, which descends from the summit of Nanga Parbat (8,125 m) to 3,070 m, has a vertical span of almost 4,500 m. The terrain drops over 7,000 m in 21 km. However, the terminus lies some 2,000 m above the Indus River, to which the valley falls steeply.

Altitude itself is a factor in that, for any given part of the HKH, the higher the mountains the greater the ice cover, and the further ice streams extend downslope. For mass balance, glacier dynamics, and responses to climate change, it is also necessary to address the extreme range of environments that the elevation spans imply. The scope of avalanching, icefalls, and meltwater drainage accelerate linkages between elevation zones with very different conditions. The relations to mass balance parameters involve the various controls in which elevation, hypsometry, and topography (steepness, ruggedness, basin orientation) are important.

The term "verticality" encompasses these various aspects, while helping to emphasize how they work together. Verticality encompasses issues "relating to or composed of elements at different levels" and "of, constituting, or resulting in, vertical combination".[5] As such, it speaks to conditions addressed in the "vertical zonation" of Klimek and Starkel (1984), the "altitudinal belts" of Ives, Messerli, and Spiess (1997), and the "elevation effect" and "altitudinal organization" of Hewitt (1993, 2005). However, in addition to the virtue of brevity, verticality directs attention to the spectrum of spatial–physical relationships in which gravity is of primary significance, drawing together conditions such as:

- **Vertical gradients.** Environmental conditions can change with height, notably temperature, pressure, and humidity;
- **Area–altitude distributions.** The extent and share of conditions or features vary with elevation, such as debris mantles or seasonal snow cover;
- **Altitudinal zones.** Conditions and processes can be concentrated in certain elevation zones, including ablation and accumulation zones; they are generated in different ways, but with similar effects to "zonal" climates, in different latitudes or according to distance from the ocean;
- **Aspect.** While orientation of mountain slopes is not itself about verticality, variations between slopes change and increase with available relief and steepness, giving aspect a diversified and intensified role; and
- **Vertical cascades.** Connections occur upslope and downslope in which slope angles and steepness are key; mass balance and climatic responses relate to the vertical moisture and debris cascade and valley wind systems.

The scope of such verticality relations in the HKH – notably compared to those of the mountain glaciers whose mass balance guides current practices and analyses of global conditions – necessitates attention to conditions and events in certain elevation zones. By way of illustration, on-ice and glacier nourishment conditions in the upper Indus basin vary with elevation as follows:

- 4,500–8,000 m, where avalanching redistributes snowfall over the off-glacier terrain and wind action plays a dominant role around interfluves and an important one in the preparation of avalanches;
- 4,800–6,000 m, the zone of maximum precipitation and for accumulation in Alpine type glaciers;
- 3,800–5,500 m, where avalanche deposits provide most or all nourishment of Turkestan type glaciers;
- 3,500–4,500 m, the most extensive areas of exposed glacier ice in ablation zones, where dust and thin dirt enhance ablation and from which annual ablation losses and water yields are greatest; and
- 2,300–4,000 m, where the lowest ice tongues terminate and most ice areas are protected by heavy supraglacial debris, giving them a comparatively small role in water yields and conservative response to climate change.

Several other conditions will now be considered as controls or aspects of glacier behavior that may affect or reconfigure mass balance parameters. The factors are glacier motion, thermal classes, and neglected seasons.

3.12 Glacier Motion

The balance between inputs to and losses from glaciers is maintained through ice movement. Glacier motion is a crucial part of mass balance,

[5] http://dictionary.reference.com/.

but because conventional studies see it as a direct function of accumulation and ablation, it appears straightforward. Velocities and throughputs are shown as increasing in the accumulation zone towards maxima around the ELA, and decreasing with ablation losses towards the terminus. HKH glaciers depart from this picture in various ways.

Three main types of motion have been established for glaciers: internal creep, basal sliding, and through deformation in soft, subglacial sediments. Glacier ice responds to applied stress above a certain limit by permanent deformation. Microscopic melting and recrystallization in the ice structure are involved, and microshearing. The resulting internal creep is the characteristic form of motion, or "glacier flow." Movement can also occur through basal sliding, usually considered important only in "warm" or temperate ice, not frozen to the bed. Sliding is substantially influenced by meltwater. Rates of sliding movement are usually greater in the ablation season, a response to higher meltwater availability. Observations from HKH glaciers generally show winter movement rates are 20–50 percent less than summer.

The third component of ice motion can arise from deformation in soft, subglacial sediments. It is thought to apply mainly, if not only, to unfrozen bed and sediment conditions, and to occur where basal sediments are in the sand to clay grades, or where coarser particles are supported by a fine-grained matrix. The quantities of debris suggest this could be important in the HKH. Many lower glacier tongues sit on thick ramps of moraine with fines-rich horizons. It has also been proposed that surge type glaciers, common in the Karakoram and Pamirs, may involve soft sediment deformation (Jiskoot 2011). However, there are no actual measurements to establish the presence and extent of this type of movement. In many if not most HKH glaciers, sliding is the greater component of motion and it is in this context that block movement phenomena have been widely reported (von Klebelsberg 1925–26; Finsterwalder and Pillewizer 1939). Where sliding occurs, there is a boxlike velocity profile across the glacier and a well-defined line of shear at the ice margin. In the larger glaciers, extensive ice stream sections appear to move and respond to changes as slablike units. They seem related to the sharp fluctuations in velocities observed in virtually all timescales from minutes to decades. These suggest chronic instabilities, probably related to steepness, basal sediments, and thermal complexities, as well as meltwater availability. Such aspects of ice dynamics are important because they intervene to create irregularities in response to changes in mass balance and suggest why terminus fluctuations may be unreliable indicators. In the HKH, there may be little or no consistency between terminus advance and retreat in adjacent glaciers, or for those of apparently identical characteristics. It also directs attention to another distinctive feature and complication in HKH ice masses, the thermal state of ice.

3.13 Thermal Classes

Two main thermal types of glacier recognized are warm (or temperate) and cold. Where ice is at or very close to pressure melting point throughout, glaciers are called "warm;" their surface layers may become subzero for a time in winter. In "cold" glaciers, all or most of the ice is below the pressure melting point. There are two subcategories or polythermal types: polar, where geothermal or frictional heating develops a zone of "warm" ice at the bed; and subpolar, with a period of surface warming and ablation in summer (Benn and Evans 1998).

As the terms suggest, these various thermal types have been named or attributed to latitudinal zones or zonal climates. However, in the HKH, a complete range of possible thermal types is present. The extreme cold at high altitude means glaciers have properties identified with polar or subpolar types. Smaller, south-oriented glaciers and the lower tongues of many large glaciers have the warm ice and unfrozen beds of the temperate thermal type. This supports Hambrey's (1994) view that the thermal categories of polar and subpolar are "misleading and best avoided." For similar reasons, in the HKH context, the same applies to temperate, tropical, and subtropical categorizations – geographic designations for thermal phenomena that are not confined to these regions or any particular region. In the Karakoram, for example, despite the limited number of observations, it is evident that the larger glaciers and many intermediate ones are of mixed thermal regimes.

The importance for mass balance concerns is how the thermal regime affects the following processes:

- The rate of deformation, with "warm" ice deforming faster than "cold" and affecting velocities of ice flow;
- Meltwater production and distribution, depending on glacier temperatures;
- Cold ice requires energy to raise it to the melting point before ablation begins. There is no discharge in winter. Meltwaters tend to spread over to the margins of the glacier and travel mainly in surface drainage lines;
- Warm ice develops subsurface drainage lines and, for glaciers that are warm throughout, meltwater more readily penetrates to the bed and there is some discharge in winter;
- Type of motion: cold ice is frozen to the bed, and there is usually no sliding motion; and
- Warm ice is unfrozen, so that sliding can comprise a more or less large fraction of total movement, and the amount of moisture reaching or generated at the bed influences this.

Pertinent here is Paterson's (1994, p. 337) observation that "only in temperate glaciers is the effect of a climate change restricted to a change in mass balance." Changes in ice thermal regimes, or meltwater availability, can also lead to changes in glacier behavior and extent without mass balance change. The exceptional number of surging glaciers in some HKH ranges suggests mixed and thermally unstable conditions at the bed. Surges are the most substantial fluctuations not driven by climate but related to other controls over mass balance relations, most likely involving thermal instabilities (Hewitt 2007b).

3.14 Neglected Seasons

Mass balance is generally measured over a budget year and used to track annual changes. However, almost all investigations in glacier basins of the HKH have taken place in July and August, a very few as early as June or as late as September. For water supply, summer appears the critical time. However, can it be assumed that nothing important happens in the other nine to10 months?

Only a handful of expeditions have left any kind of instrumentation or sites to track events through the rest of the year; fewer still remained there to observe what happens. Of course, the importance of winter snowfall in accumulation is acknowledged. Avalanching varies seasonally in given elevation zones, but how it does so is little understood. Its inputs to glacier masses continue throughout the year, but are affected by the vertical shifts in temperatures.

Almost wholly ignored is whether anything significant happens to ablation zones outside the ablation season. New snowfall and snow covers through the winter must be considered. Some important developments certainly occur in the "shoulder seasons," October–November and April–May. The migration of a zone of frequent freeze–thaw cycles is crucial. Freeze–thaw and wind action affect snow and the buildup of a carapace of icy layers and refrozen and wind-packed snow. Before ablation in the mass balance sense begins, these layers must also be degraded. Slush flow activity can be important as a pre-ablation process, following the retreat of the snowpack on the glacier up to and beyond the firn limit and onto the higher avalanche cones.

A similar case could be made for looking at two other largely neglected phenomena that affect mass balance relations. One concerns detached ice masses at high elevation and ice avalanches from them. The other is the role of icefalls, which especially affect middle and upper ablation zones. However, these are all in the realm of detailed glacier processes, poorly understood and raising questions of whether and just how far monitoring should consider them or simply continue to ignore them.

3.15 Discussion

Attempts to derive mass balance estimates and changes have been based largely on temperature and precipitation data extrapolated from weather stations outside the glacier zones, or climate models, or sometimes on assumptions about snowlines and ELAs. Conditions known to influence mass balance in the HKH, but largely lacking in direct measurements, include high-elevation snowfall, avalanche and wind redistribution of that snow, avalanche-fed glaciers, all-year conditions and cycles in glacier basins, glacier thermal regimes, and glacier movement.

3.15.1 Field Programs and Instrumentation

Two strategies that are the norm in regions with well-established monitoring may not work in the HKH: a set of benchmark glaciers or a glacier network. Both imply mass balance monitoring for whole glaciers. The former has succeeded mainly by choosing small, relatively simple glaciers that nonetheless seem representative for the region. It is doubtful this approach can work in the HKH, which is an environment that requires strategic engagement between field and indirect approaches. Glaciers would need to be chosen for their suitability for training, ground control, historical reconstruction of glacier change, and experimental efforts. The value must be decided of the following suggested approaches:

- Identification and setup of selected glacier basins for experiments, testing of instruments, procedures, and training;
- Short-term observational projects of key variables and zones on glaciers to calibrate datasets coming from existing, accessible, long-term hydrometeorological stations and to provide ground control for remotely sensed parameters from glacier surfaces;
- More rigorous testing or calibration of the relations of such permanent meteorological and river gauging networks as indicators of glacier contributions; and
- Identification of better-located and more representative stations.

Global benefits and efficiencies can be derived from information sharing, coordinated monitoring, and cooperation across relevant administrative and state boundaries, such as the following:

- Coordinated analyses of satellite imagery and ground-truthing for both broad glacier-related parameters and glaciers of special concern;
- Coordination through joint projects with institutions of higher education and research in the country concerned;
- International collaboration on glacier and related hydrometeorological research projects to address outstanding scientific and technical questions regarding the glaciers; and
- International collaboration on courses, diplomas, higher degrees, and visiting professionals in glacier-related scientific fields.

3.15.2 Personnel and Safety

In each country, direct observations will require one or more teams trained and permanently ready to work in glacierized areas, whether to repeat and update key observations or to investigate hazardous situations and events. None of this is likely to happen or be successful without a core of personnel experienced in mountain environments, usually with mountaineering and winter skills, and enthusiastic about the environment and the work. In this context, important and special problems of personnel safety and training must be considered.

Looming over any plans for direct monitoring of glaciers is the fact that field activities are constrained by often large problems of funding, personnel, training, instrumentation, and safety. Working conditions on glaciers generally require constant attention to safety – in the preparations, equipment, work schedules, and health care and fitness of personnel involved. In most of the HKH, safety needs and imperatives are unusually high. While it is unlikely that any monitoring programs will extend to the highest and steepest areas, there is hardly anywhere that teams will not need to acclimatize to working altitudes and be equipped with appropriate clothing and gear for harsh weather and traveling over difficult terrain. Specific kinds of safety issues arise with crevasses, avalanches, icefalls, and accumulation zones where there is deep snow. Such matters should be addressed in planning and training with the help of qualified and experienced mountaineers.

Everywhere that well-developed snow and ice monitoring and glacier investigations exist, the people who play the largest part have two distinct but necessary attributes. First, there are the relevant qualifications in technical, engineering, or scientific fields. Second, there is mountain experience, at least basic mountaineering skills, and enthusiasm for working in mountain environments. Personnel who have worked everywhere that well-developed snow and ice monitoring and glacier investigations exist have two necessary attributes: relevant qualifications in technical, engineering, or scientific fields; and at least basic mountaineering skills and enthusiasm for working in mountain environments. For anyone not so equipped, working on glaciers can seem extremely difficult, frightening, and dangerous, in which case the turnover will be high and the work may be done improperly or not at all.

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4. Mountain Hydrology

4.1 Background to Mountain Hydrology

Mountain hydrology is defined here as the methodologies associated with the monitoring and measurement of the water balance of the HKH mountain catchment basins. Traditionally, hydrological monitoring undertaken for purposes of water resources planning or management has been based on "rainfall–runoff" or "black box" correlation modeling, in which input, as measured precipitation, is correlated with output, as measured streamflow, to provide an estimate of the timing and volume of streamflow from a basin. This type of modeling produces useful information for engineers and water managers concerned with lowland rivers originating in the mountain basins. This modeling approach, however, provides relatively little insight into questions about the relative contributions of rain, snow, or glacier melt to streamflow volumes, or the role of glacier retreat and climate change in the streamflow regimes of the great rivers of South Asia, a major ongoing debate.

Two important features distinguish mountain hydrology models. The first is that the input is not identical to precipitation, as is the case in other hydrological models, but also includes energy inputs as an indispensable component. While in the classical rainfall–runoff model, energy inputs are required only to determine the evapotranspiration output from the basin, in mountain hydrology models energy inputs are essential to determine the "active" portion of the total precipitation input, that is, to separate the liquid part, which immediately contributes to runoff, from the solid part, which remains temporarily inactive in storage.

The second feature, less obvious but perhaps more important, is that, unlike in a standard hydrological model, the inputs typically are not simply entered into the model but must themselves first be modeled. This necessity arises from the fact (discussed earlier) that measurement of precipitation and energy inputs can often not be made where they are most needed but only where they are technically feasible – usually in the accessible mountain valleys. Thus, what in the standard models is merely a processing of inputs (typically a simple or weighted areal averaging of point measurements) becomes input modeling in mountain hydrology. Its aim is to estimate, from the scarce and ineffectively located point measurements of precipitation and energy components, the areal and elevation distributions of: (a) precipitation amounts; (b) precipitation form; and (c) energy (or at least temperature).

The hydrological regime of the HKH mountain catchment basins is not well studied or understood. The countries of the Indus and Ganges basins customarily treat all data describing streamflow as confidential. While this practice varies among the countries of India, Nepal, and Pakistan, none of the three have produced readily available, digitized monitoring records of streamflow that would permit assessments of the hydrological variability of the catchment basins. Because much current concern is centered on the role of the glaciers in streamflow production and the potential impact of glacier retreat for the region, discussion of the role of glaciers in the mountain hydrology is included here (see chapter 3 for a full discussion of glaciers). Given the general lack of analysis, however, the primary emphasis in this chapter is to illustrate the various hydrological relationships along the east–west transect of the HKH Mountains.

The volume and timing of runoff as measured in the annual hydrograph are indicators of the nature, timing, and volume of the water and energy budgets of a basin. In the absence of an extensive climate monitoring network, the hydrograph provides the most direct link to any assessment of the effect of climate change on streamflow from a catchment basin by reflecting variations in the climate-related water and energy exchange processes. The precise form of the annual hydrograph will be strongly influenced by location, as well as the time period in which data are collected. Data based on daily values in close proximity to a glacier or the snowline during the melt season will reflect the diurnal freeze–thaw cycle that is characteristic of both snowmelt and glacier melt during summer months, while those at increasing distances will be increasingly subdued as dilution from other sources – seasonal snowmelt, rainfall – with distance downstream in a basin.

The Himalaya is characterized by a complex three-dimensional mosaic of meteorological and hydrological environments, in a geography ranging from tropical rain forests to arctic deserts and in an altitudinal range of more than 8,000 m. A few reliable maps of the region exist and essential climate and hydrological data are often not readily available. With the lack of a basic understanding of runoff sources and timing in the rivers of South and Central Asia, usage issues related to the water budget, such as glacier retreat, cannot be resolved. And the general unavailability of data describing the hydrology, climate, and topography makes it difficult to apply hydrological concepts and models developed for mountain catchments in Europe or North America.

The hydrometeorological environments of the HKH between eastern Nepal and Afghanistan are defined primarily by two major seasonal air masses – the southeast monsoon in the eastern and central Himalaya and winter westerlies in the Hindu Kush and Karakoram – interacting with the 8,000 m of mountain relief. This interaction involves primarily variations of water and energy transfer with respect to the topographic variables of altitude, aspect, and slope as both air mass properties and mountain terrain vary from east to west.

The literature provides only the most cursory analyses of the hydrological regimes of the HKH Mountains, and the number of serious studies is quite limited. Drawing a clear distinction between the runoff volumes resulting from snowmelt and glacier melt is difficult. If data reported in the literature are correct, the primary zone of meltwater from both sources is maximized at around 4,000–5,000 m as a result of a combination of maximum terrain surface area, maximum glacier surface area, and maximum snow water equivalent deposition that occurs there. This is the altitudinal zone generally reached by the upward migration of the freezing level during the months of July and August, which is also the time of maximum runoff. The transition from snowmelt to ice melt that occurs during this period may be a result of a transition from snowmelt to glacier melt as the winter snow disappears. Additional studies of the factors determining the volumes of snowmelt and ice melt would be required to permit a definitive distinction between the two. Even the most cursory analyses, however, demonstrate the increasing importance of snowmelt in the extreme western portions of these mountains as the summer season monsoon, dominating the hydrology of the eastern Himalaya in Nepal, is replaced by the summer melting of snow deposits resulting from winter westerlies in the Hindu Kush ranges of northern Pakistan.

From the standpoint of studies and monitoring of components of the mountain water budget, the major concern of the region should be water, not glaciers. A factor in the hydrology of the Himalayan mountain chain, glaciers may have a profound impact on life at the scale of mountain villages but are less important factors at the scale of the major river basins of the region. In the recent past, emphasis has been placed on the relationship between climate change and glacier retreat in the mountains of Asia, with limited attempts to define the climate of these mountains, or on the relationship between glaciers and climate there. Recent discussions have accepted the conventional wisdom that the mountain climates and glaciers of the Himalaya may be described by the Alpine models with which Western science is most comfortable, and that the scales of global circulation models and mountain catchment basins are compatible. Both these interpretations are most likely in error.

Both the Indus and the Ganges are transnational rivers. The Indus River has headwaters in Tibet (China), India, Afghanistan, and the northwest territories of Pakistan. The Ganges River arises primarily in India, with an estimated 10 percent contributed by the central Himalaya, 50 percent from the lowlands to the south of the mountains, and 40 percent from Nepal. Uses of this water are those customary everywhere: hydroelectric energy generation, multipurpose reservoir management, irrigation, urban and industrial water supplies, and recreation. Primary problems are contamination, flooding, and drought.

No single monitoring network exists that will provide useful input to the management of each of these uses or problems. Each will have differing needs in terms of variables to be monitored, and the scale appropriate to the problem.

Much of the ongoing debate concerning the role of glaciers in the volume and timing of the flow of Asian rivers has emphasized air temperature at the expense of any serious consideration of the total water and energy budgets of the Himalayan catchments. Given the relative lack of climate studies of large mountain ranges, climate-glacier relationships have been based on models at the scale of the global circulation models, in many cases driven by satellite-derived data, at a comparable scale.

A typical global circulation model has a grid cell size of 105 km^2 at 40°N latitude. At the same time, most Himalayan catchment basins are on the order of 103 km^2. This great disparity in scales makes the findings of recent comparisons of climate and hydrological models for the catchment basins of the Himalaya questionable. At the scale of the global circulation model, it is generally not possible to undertake more than two-dimensional analyses of spatial climate variation, involving only latitude and longitude. At the scale of the mountain catchment basin, an analysis of the relationship between climate and any water budget variable will require a three-dimensional model that includes altitude.

4.2 Monitored Streamflow of the HKH Mountains

Ultimately, the concern for the future of the glaciers of the upper Indus basin is a concern for the water resources the river represents. As a component of the hydrology of the mountain headwaters of the mountain basins, it can be expected that changes in the glaciers will be reflected in changes in the volume and timing of runoff from the mountain basins. In seeking answers to the concerns related to the potential impact of climate change and glacier retreat on runoff from the mountain basins, very little use has been made of the existing records of measured runoff from these basins.

4.2.1 The Indus River

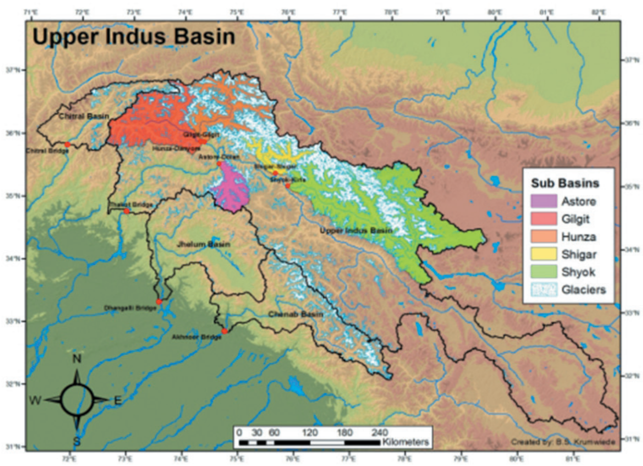
The Indus River is transnational, with headwater tributaries in the countries of Afghanistan, China (Tibet), India, and Pakistan. The river originates north of the Great Himalaya on the Tibetan plateau. The main stem of the river runs through the Ladakh district of Jammu and Kashmir and then enters the northern areas of Pakistan (Gilgit-Baltistan), flowing between the western Himalaya and the Karakoram Mountains. Along this reach of the river, streamflow volume is increased by gauged tributaries entering the main river from catchments in the Karakoram Mountains – the Shyok, Shigar,[6] Hunza, Gilgit, and, in the western Himalaya, the Astore (Young and Hewitt 1993), as well as ungauged basins on the north slope of the western Himalaya. Immediately

[6] The gauging station for the Shigar basin has reportedly been discontinued (personal communication, D. Archer, 2010).

north of Nanga Parbat, the westernmost of the high peaks of the Himalaya, the river turns in a southerly direction and flows along the entire length of Pakistan, to emerge into the Arabian Sea near the port city of Karachi in Sindh. Tributaries to this reach of the river from the western Himalaya are the Jhelum, Chenab, Ravi, and Sutlej Rivers, from the Indian states of Jammu Kashmir and Himachal Pradesh, and the Kabul, Swat, and Chitral Rivers from the Hindu Kush Mountains. The total length of the river is about 3,180 km, and its total drainage area exceeds 1,165,000 km^2. The river's estimated annual flow at the mouth is 207 cubic kilometers (km^3), making it the 21st largest river in the world in terms of annual flow.

Figure 4.1 is a digital elevation model of the gauged mountain catchment basins of the upper Indus River, in which the highest altitudes are dark brown and the lowlands are green. Gauging sites are shown as red circles, and the general area of glaciers is shown as stippled blue and white. The geomorphometric data on which this map is based – latitude, longitude, and altitude – provide the terrain variables used in the calculation of the water and energy budgets of Karakoram glaciers.

Figure 4.1
Mountain Catchment Basins of the Indus River



Source: B. Krumwiede, in Alford 2011.
Note: The speckled blue area is the approximate area of glaciers and perennial snowfields.

Table 4.1 shows the general topographic and hydrological characteristics of the gauged basins of the upper Indus River.

The general hydrology of the lower Indus basin is assumed to be reasonably well understood as a

Table 4.1
Descriptive Statistics of the Basins Considered in the Study

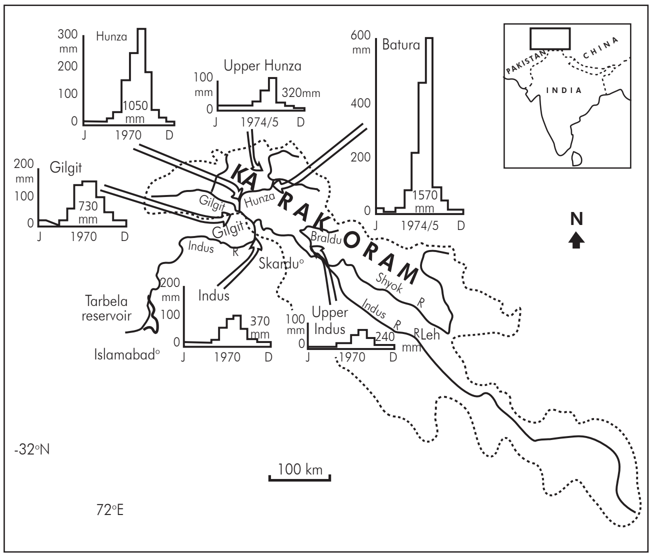
River	Basin	Gauge site	Area, km^2	Specific runoff, mm	Annual streamflow, million m^3	Average altitude, m
Indus	Astore	Doyen	3,988	1,291	5,184	3,981
	Gilgit	Gilgit	12,680	692	8,777	4,056
	Hunza	Dainyor	13,732	761	10,448	4,516
	Shigar	Shigar	6,922	917	6,350	4,611
	Shyok	Kiris	33,350	312	10,705	5,083
	Indus	Besham	166,096	440	71,679	4,536
	Chitral	Chitral	12,504	712	8,118	4,120
Jhelum		Dhangalli	27,122	1,075	29,156	2,628
Chenab		Aknoor	22,422	1,222	27,424	3,542

Source: Alford 2011.

result of a network of gauging stations, reservoirs such as the Tarbela and Mangla, and irrigation barrages on the piedmont immediately south of the mountains. While this network provides data on which to base management decisions concerning water uses in the lower basin, the hydrology of the upper basin remains largely undefined. Under normal circumstances, this is not a problem. In recent years, however, concerns regarding the possible impacts on rivers such as the Indus as a result of climate changes in the mountain headwater regions have become increasingly alarmist (see for example Rees and Collins 2006; IPCC 2007, chapter 10.6), with only minimal data from the mountain headwaters for support. Without a better understanding of the timing and sources of runoff from the catchment basins of the upper Indus, the nature and severity of any climate change impacts cannot be assessed with confidence.

The general outlines of the hydrology of the upper Indus basin have been defined in recent studies by foreign geoscientists (for example, Goudie et al. 1984; Young and Hewitt 1993). Streamflow gauging stations are maintained by Pakistan's WAPDA (Figure 4.2).

Figure 4.2
Diversity of Annual Streamflow from Catchments in the Upper Indus Basin, One Year



Source: Goudie et al. 1984.
Note: This pattern illustrates the fact that major sources of runoff in the upper Indus basin are quite localized and average values applied to the entire basin will have little relevance in assessing the potential impacts of climate change.

4.2.2 Upper Indus Basin Hydrology

The characteristics of upper Indus basin hydrology are as follows:

- The mean annual flow of the upper Indus basin is approximately 72 km^3 from the main stem above Tarbela reservoir, 29 km^3 from the Jhelum basin, and 27 km^3 from the Chenab basin, a total of 128 km^3. The total estimated flow of the Indus River at its mouth is slightly more than 200 km^3 annually;
- The total surface area of the main stem of the Indus above Tarbela is approximately 166,000 km^2, with an estimated glacier area of approximately 17,000 km^2. The other glacierized basin, the Chenab in the western Himalaya, has a surface area of 22,500 km^2 and a glacier area of 2,700 km^2;
- The two principal sources of runoff from the upper Indus basin are: (a) winter precipitation, as snow, which melts the following summer; and (b) glacier melt. Winter precipitation is most important in producing seasonal snow runoff volume; summer temperature most affects glacier melt volume;
- Variability in the main stem of the Indus, based on the record from Besham, has ranged from approximately 85 percent to 140 percent of the period of record mean of 72 km^3;
- The wide diversity of hydrological regimes in the mountain basins complicates the problem of relating streamflow timing and volumes to a uniform climate change; and
- The mountain headwaters of the Indus River contribute approximately 60 percent of the mean annual total flow of the river, with approximately 80 percent of this volume entering the river system during the summer months of June–September.

4.2.3 The Nepal Himalaya

Three major tributaries of the Ganges have headwaters primarily in the Nepal Himalaya: the Karnali, Narayani, and Sapta Kosi Rivers. The total average annual gauged streamflow volume from the three rivers is approximately 145 km^3 (Nepal DHM 1988). Total streamflow from Nepal, including that from the ungauged lowlands to the south of the mountains, has been estimated at 200 km^3 annually (Sharma 1983). The topographic and hydrological characteristics of the Nepal gauged basins with a glacier cover are shown in Table 4.2.

An analysis of the existing hydrological and glaciological data for the Nepal Himalaya (Nepal DHM 1988; Mool et al. 2001) indicates that glaciers are not a major factor in determining the volume of flow in the rivers of South Asia. For glacierized catchments of Nepal that also had hydrometric data available, the approximate findings were:

- Calculated total ice melt volume from glaciers in these basins was approximately 4.5 billion m^3, approximately 5 percent of the total streamflow from the glacierized basins, and approximately 3 percent of the total annual streamflow from Nepal into the Ganges basin. This ice melt presumably will enter the normal hydrological budget of the respective basins, some fraction becoming storage, some fraction evaporating, and the remainder becoming runoff (Alford et al. 2009);
- In the eastern and central Himalaya (Nepal and India to Himachal Pradesh), the volume of runoff will be determined by the strength of the southeast monsoon (which will determine the orographic rainfall pattern) and the area–altitude distribution (hypsometry). Most precipitation will be convective, on windward slopes, reflecting the importance of aspect in determining runoff volume and timing. Timing will be determined by the arrival – and persistence – of the southeast monsoon. The predictability of the southeast monsoon has declined during the last decade and the monsoon regime has become more erratic;
- The eastern HKH basins of Nepal contribute 40 percent to the total flow of the Ganges River as measured at Farraka, approximately 500 km^3; runoff from the Indian Himalaya contributes

Table 4.2
Descriptive Statistics of the Glacierized Catchment Basins of the Nepal Himalaya

River	Basin	DHM ID#	Area, km^2	Ave. altitude, m	Qb, m^3/s	qb, mm	Qv, million m^3
Karnali	Bheri	**270**	**13,677**	**4,400**	**435**	**1,116**	**13,718**
Narayani	Kali Gandaki	420	6,553	3,200	267	1,270	8,420
	Marsyangdi	439	4,781	4,200	212	1,737	6,686
	Budhi Gandaki	445	3,707	5,400	169	1,182	5,048
	Trisuli	447	3,623	5,200	173	1,382	5,456
Sapta Kosi	Tama Kosi	647	2,382	4,900	145	1,661	4,573
	Likhu Khola	660	1,297	3,500	57	2,184	1,798
	Dudh Kosi	670	4,515	4,400	223	1,715	7,033
	Tamor	690	6,330	2,600	336	1,879	10,596
Total			46,164				63,328

Source: Alford et al. 2009; data from Nepal DHM 1988.
Note: DHM = Nepal Department of Hydrology and Meteorology (ID no.); Qb = streamflow volume, m^3/s; qb = specific runoff, mm; Qv = annual streamflow volume, million m^3.

10 percent, and 50 percent comes from runoff originating south of the river. The Indian portion of the HKH Mountains contributes approximately 50 km³ to the estimated total flow of 200 km³ of the Indus River (Sharma 1983);

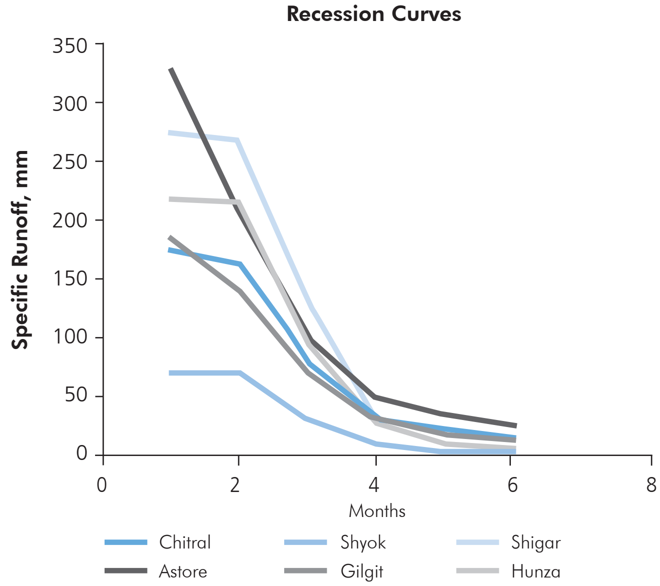
- Current monitoring in Nepal involves weather stations and streamflow gauging at altitudes generally below 1,000 m above sea level. No public data are available for Indian HKH basins (Bookhagen and Burbank 2010); and
- It is estimated that runoff from the glaciers of the Nepal portion of the Himalaya contributes less than 5 percent of the total flow of the Ganges River. No public data are available for Indian HKH basins (Alford et al. 2009).

4.2.4 Recession Flows

The recession curve is a characteristic feature of a hydrological basin, reflecting the relationship between inputs, in this case snow and ice melt, that determine the nature of peak flow; and storage, which determines the slope of the curve between the peak flows, and the annual low flow. The recession curve represents a powerful forecast tool, once the hydrological characteristics of the basin have been determined. In the upper Indus basin, these characteristics are determined primarily by the relative importance of snow and ice melt and summer season temperatures. There is minimal postmelt storage in any of the gauged basins for which data are available. Recession curves for glacierized basins of the Karakoram, based on mean monthly data for the months July to December, are shown in Figure 4.3. Two basins, the Gilgit and Astore, with a glacier cover of about 10 percent, have a single summer peak in July, followed by recession to a base flow level. The remainder, with glacier covers of 20–50 percent, has a flood peak persisting through July and August, on average.

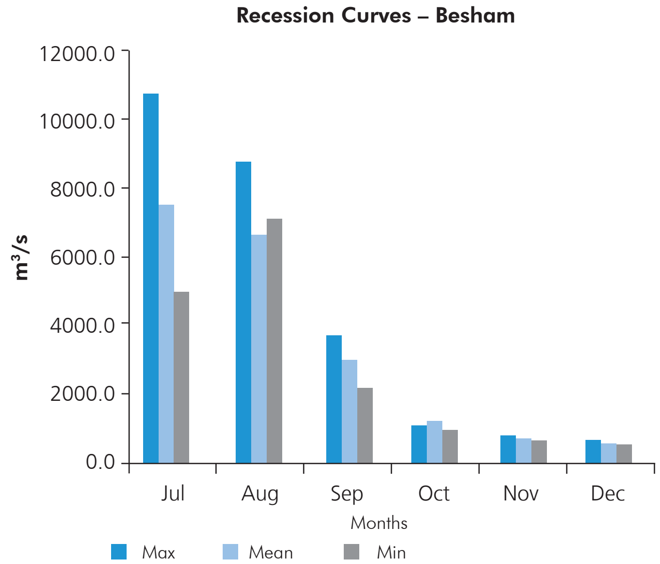
A comparison of recession curves for a single hydrometric station – Besham Qila, on the Indus River main stem, immediately above the Tarbela reservoir – is shown in Figure 4.4. The Besham

Figure 4.3
Recession Curves for Glacierized Basins of the Karakoram, Based on Mean Monthly Data for July–December



Source: Alford 2011.

Figure 4.4
Recession Curves for Besham, Based on Mean Monthly Data for July–December



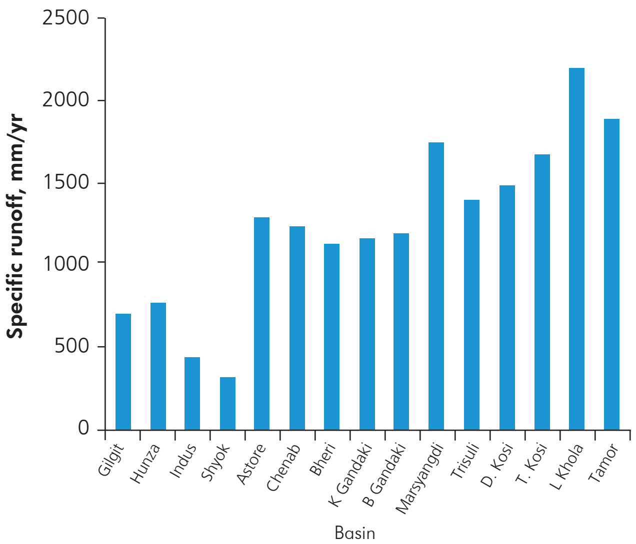
Source: Alford 2011.

recession curves for years with maximum, mean, and minimum volumes of flow are typical of most basins in the western HKH Mountains. For all flows exceeding the long-term mean value, the peak flow occurs in July, presumably reflecting the period during which the maximum surface area of snow-covered terrain is producing meltwater. The peak flow occurs in August during years of lower-than-average flows, presumably as a result of a decreased winter snowpack, and a greater dependence on glacier melt runoff. In all cases, the bulk of the annual streamflow volume occurs in a period of about 90 days, and base flows are independent of the volume of the peak flow.

4.2.5 East–West Variation in Runoff

It is generally recognized that there is an east–west gradient of water exchange in the catchment basins of the HKH Mountains, resulting in decreasing runoff values. Recent studies have considered the entire transect, using satellite imagery such as MODIS in the extreme western portion (for example, Immerzeel, Beek, and Bierkens 2010), or using the Tropical Rainfall Monitoring Mission (TRMM) in the eastern and central portions of the range (for example, Bookhagen and Burbank 2010). The values of specific runoff – from the data maintained by Pakistan's WAPDA in the west, and the Nepal Department of Hydrology and Meteorology in the east – serve as a useful check on these estimates based on data from satellite imagery. The sudden change from the monsoon-driven hydrological regimes of the eastern basins of the Nepal and much of Indian portions of the HKH, to the snowmelt and glacier melt hydrology of the upper Indus basin, can be seen in the change between the Astore basin, located on the eastern flank of Nanga Parbat, the westernmost Himalayan peak, and the Shyok basin, to the north in the eastern Karakoram Range (Figure 4.5).

Figure 4.5
East–West Variation in Specific Runoff in HKH

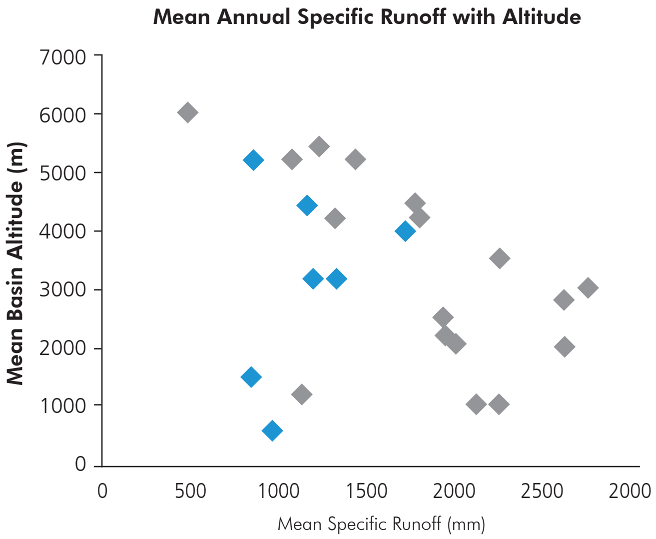


Source: Data from WAPDA files, transcribed by Archer, 2010; and Nepal DHM 1988.
Note: The figure shows east–west variation in mean annual specific runoff, in millimeters, along a transect extending from the Tamor basin in eastern Nepal to the Gilgit basin in the upper Indus basin.

4.2.6 Altitudinal Gradients of Runoff

While the negative orographic air temperature lapse rate characterizing the HKH Mountains has been accepted without question (see chapter 2), the existence of an orographic gradient defining the water budget of the mountain catchments has received much less consideration. It is becoming increasingly apparent, however, that the areal distribution of both precipitation and runoff may vary widely over the surface of a Himalayan catchment basin. While the variation may be of minor importance in determing water supply for the adjaceent lowlands, for an analysis of water budget or climate-related questions, such as the role of glaciers in streamflow formation, it is paramount. While Figure 4.6 is based primarily on data from the Nepal portion of the Himalaya, a comparison of the trend shown is essentially duplicated by data from the Karakoram at altitudes above 4,000 m (Alford 2011).

Figure 4.6
Regional Orographic Runoff Gradient for the Himalaya Based on Data from Glacierized and Nonglacierized Basins



Source: Data from Nepal Department of Hydrology and Meteorology 1988.
Note: While there is an overall trend to decreasing runoff depths with increasing altitude, it can be seen that there is a distinct difference between eastern (red) and western (blue) basins. While both are curvilinear, runoff from the eastern basins is greater at all altitudes below 4,000 m than in the west.

4.2.7 Initial Uses of the Existing Network

A modern tendency in hydrological analysis is first to consider building a model or to apply a new set of data to an existing model. However, all models, no matter how detailed, will always remain a highly simplistic representation of real-world complexity (Oreskes, Shrader-Frechette, and Belitz 1994). They inevitably reflect a specific set of assumptions about dominant hydrological processes (Van Dijk 2011). In the extreme, "all models are wrong, but some are useful." With respect to the HKH, still little is known of the dominant processes in runoff generation at levels above 3,000 m.

Before proceeding to describing a full distributed model of a catchment, it is profitable to apply preliminary data analysis to establish boundary conditions and also as a means of establishing the reliability of the data. Some of these conditions might be considered simple models in themselves, as they have a predictive capacity. The number of examples that follow are by no means exhaustive.

4.3 Assessing Comparative Contribution to Streamflow

Because runoffs resulting from glacier melt, from melt of seasonal snow, and from monsoon rainfall generally coincide in time, it has proved most difficult to establish the comparative contributions from each and how each of them differ across the HKH. Majeed, Hussain, and Asghar (2010) used a simple technique of hydrograph separation to assess the direct rainfall contribution to inflow of the Indus to Tarbela reservoir, a catchment of some 200,000 km^2. They found that significant monsoon rainfall only occurs in the lowest part of the catchment, and the streamflow response shows sharp runoff spikes overlying the prolonged seasonal melt peak. They assessed the rainfall contribution by identifying and calculating the volume of these spikes in relation to the underlying snowmelt (and glacier) hydrograph. Their conclusion was that the maximum annual rainfall contribution was 20 percent, the minimum was 1 percent, and the average was 5 percent of the total inflow. Majeed (1995) similarly calculated the contribution of direct rainfall to Mangla reservoir on the Jhelum River as generally in the range of 10 to 20 percent but, in the most extreme case, 35 percent.

Although it might be anticipated that model outputs would generally correspond to these boundaries, they do not necessarily do so. Based on a model output, Bookhagen and Burbank (2010) suggest an average rainfall contribution to the Indus of 26 percent and to the Jhelum of 65 percent. The magnitude of the different estimates illustrates the level of uncertainty in basic understanding of HKH hydrology.

Analysis by Archer and Fowler (2008) tends to support the Majeed interpretation, although it does not specifically attempt to assess the comparative runoff from rainfall and snowmelt. The authors examined the relationships between climate parameters and runoff. The analysis found no significant relationship between summer rainfall and summer runoff for the main Jhelum inflow to Mangla. On the other hand, there is a very significant correlation (at 1 percent level) between winter precipitation and summer runoff for the Jhelum and its principal tributaries. More puzzling is a very significant negative correlation between preceding winter and spring temperature and summer runoff, and a weak but consistent negative correlation between summer temperature and summer runoff.

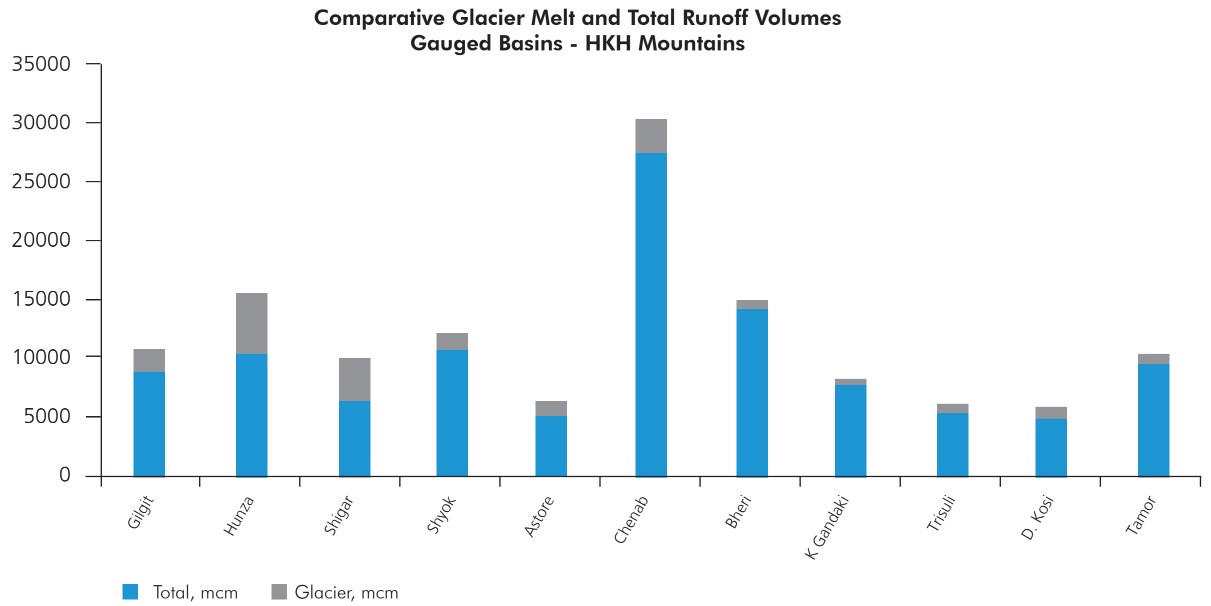
Archer (2003) similarly used regression analysis between climate variables and runoff to show that the controlling factors in runoff were essentially different between high-level subcatchments of the Indus, with runoff primarily derived from glacier melt, and catchments where runoff was primarily derived from melt of seasonal snow. Summer runoff from the glacier-fed catchments is controlled by concurrent temperature (and not at all by winter precipitation), while runoff from seasonal snowmelt-fed catchments is controlled by preceding winter and spring precipitation (and not at all by concurrent temperature). While this analysis does not attempt to calculate the comparative contribution of glaciers and seasonal snow, it does provide an indication, via the strength of the respective correlations, of the comparative contribution of glacier melt and seasonal snowmelt to catchment runoff. Given the consistent patterns of correlation between independently measured climate variables and streamflow, this analysis also serves to indicate that both sets of data are reliable, at least at a seasonal level.

Alford, Armstrong, and Racoviteanu (2009), Alford and Armstrong (2010), and Alford (2011) attempted to distinguish the glacier contribution to total flow in basins in Nepal and Pakistan (Figure 4.7). They first used a simple methodology to compute glacier melt based on a regional ablation gradient (Haefeli 1962) and the area elevation curve of the glacier from its terminus to the highest annual altitude reached by the mean 0°C isotherm. Melt summed in elevation bands over this area of the glacier is assumed to represent the net annual loss of mass to the glacier; it does not represent the loss of seasonal snow. Glacier melt was then compared with catchment runoff computed in a similar way as a summation of runoff from altitudinal belts, in turn based on gauged flow data.

Alford and Armstrong (2010) conclude that the contribution of glacier annual meltwater to annual streamflow in the Ganges basin from the glacierized catchments of the Nepal Himalaya represents approximately 4 percent of the total annual streamflow volume. While it is widely believed that a serious decline of glaciers and resulting loss of runoff from them would result in major downstream rivers from the Himalaya becoming seasonal (IPCC 2007), this assessment suggests that glacier meltwater is not a major factor in determining the volume of rivers flowing from the Nepal Himalaya. However, this study is by no means definitive and requires more detailed field data from glaciers and downstream river flows to clarify regional and local variations.

Much of the concern about changes in the water resources of rivers downstream from the HKH has arisen from studies of what might happen to glaciers and to resulting runoff if they were to experience projected global increases in temperature. The paper by Rees and Collins (2005) is particularly pertinent, having been quoted in a World Bank study of water problems in Pakistan by Briscoe and Qamar (2007). Rees and Collins applied a rate of 0.06°C per year transient climatic warming to two hypothetical glaciers in the eastern and western HKH. Their modeled results suggest a rapid decline in glacier volume accompanied by an initial sharp increase in river flow, lasting perhaps for five decades but followed by a sharp decline in flows on the main stem of the Indus by 30–40 percent

Figure 4.7
Estimated Glacier Melt Contribution to Total Annual Flow, HKH Mountains



Source: Alford, Armstrong, and Racoviteanu 2009; Alford 2011.
Note: The figure shows a transect of the estimated glacier component of runoff from selected basins of the Nepal Himalaya and the upper Indus basin.

by the end of the century. They also concluded that impacts of declining glacier area on river flow would be greater in the west (Pakistan), where precipitation is scarce, while summer snowfall in the east would suppress the rate of initial flow increase, delay peak discharge, and postpone eventual disappearance of the ice. Such a scenario prompted understandable concerns, described by Briscoe and Qamar (2007) as "terrifying."

Despite these concerns, little attempt has been made as yet to assess historical trends in streamflow, which, given the global increase in temperature over the past several decades, might be expected already to show signs of increasing glacial runoff and a change in timing of those flows. Sharif et al. (2012) have examined trends in magnitude and timing of flows at 19 gauging stations in the upper Indus. The response is quite opposite to that suggested by Rees and Collins (2005) in that high-level glacial catchments show a falling trend in runoff and a declining proportion of glacial contribution to the main stem of the Indus. On lower subcatchments, depending on melt of seasonal snow, annual flow has predominantly increased, with several stations exhibiting statistically significant positive trends. Analysis of timing of the annual hydrograph using spring onset date and center of volume date indicated no clear trends, in direct contrast to what has been observed in western North America. The results of the analysis indicate that the magnitude and timing of the streamflow hydrograph in general is influenced both by the seasonally varying snowpack and by trends in temperature.

It is now recognized that historical climate trends in the upper Indus basin have not mirrored global trends (Fowler and Archer 2006). Over the period 1960–2000, summer temperature trends were generally downward, although winter and annual trends were rising. It is now also clear that trans-Himalayan glaciers behave quite differently from those in the eastern and central Himalaya, where significant retreat and depletion of glacier volume has occurred (Eriksson et al. 2009; Berthier et al. 2007). Thickening and advance have been reported in many Karakoram glaciers in recent decades (Hewitt 2005, 2007, 2011). Analysis of ice loss using satellite gravimetry during 2003–09 (Matsuo and Heki 2010) seems to confirm that glacier loss is lower in the Karakoram compared to the neighboring Himalaya.

There is now an appearance of a measure of agreement in estimates involving relationships among climate, glaciers, and river flow in the trans-Himalayan upper Indus. However, there is a tentative indication that some of these relationships may not have applied in the first half of the 20th century, when summer monsoon rainfall appears to have played a bigger role in the flow of the Jhelum River. It is uncertain as to how far eastward these relationships and trends extend, given the change to a monsoon-driven climate and hydrology. Shrivastava (2011) indicates that between 1960 and the mid-1990s, over a broad stretch of the Indian Himalaya, the trend in summer temperatures has also been downward, a trend clearly at variance with the observed glacier loss. Trends in the magnitude and timing of runoff response do not appear to have been investigated.

The whole region would benefit from a more comprehensive review of climate, glacier mass balance, and river flow, building upon extensive work already carried out by Singh and colleagues (see, for example, Singh, Ramasastri, and Kumar 1995; Singh and Kumar 1996, 1997a, 1997b; Singh et al. 2000). Modeling, using satellite remotely sensed data, would clearly benefit from a close inspection of such analyses.

A large, essentially unanalyzed amount of streamflow data is available for the Nepal and Pakistan catchment basins of the HKH Mountains. This simple assessment of the data demonstrates that a deeper investigation of these data might yield considerable insight into many aspects of climate change debates. Coupled with basic procedures describing energy exchange, such as application of the degree-day and ablation gradient concept, it may be possible to develop preliminary hypotheses concerning the water budget and components of streamflow formation within a mountain basin, as well as the relationships between climate change, glacier retreat, and glacier meltwater runoff volumes.

The goals of a hydrological monitoring program must be clearly defined. The design of a stream gauging network intended primaily to provide data on the timing and volume of mountain runoff for downstream uses, such as irrigation, hydroelectic energy generation, or domestic water supplies, will differ from one intended to supply data for a water balance analysis that includes the role of glaciers in runoff formation within the mountain basin. If the goal is forecasting of water supplies for lowland users, then the existing monitoring network is probably sufficient; what will be required is better management and analysis of the data. If the goal is a better understanding of the relationship between climate, glaciers, and streamflow, installation of additional hydrometric stations in the immediate vicinity of selected glacier termini, at altitudes between 3,000 and 5,000 m, would be useful for any studies dealing with the mesoscale hydrological regime of the HKH catchment basins.

It would be simpler to resolve problems related to supply and use of runoff from the mountain basins if all countries of the HKH Mountains prepared digital databases of streamflow measurements and made these data generally available on request by legitimate data users.

4.4 Streamflow Monitoring

"Streamflow" is the combined result of all climatological geographic factors that operate in a drainage basin (Herschy 1995). It is the only phase of the hydrological cycle in which the water is confined in such a way as to permit accurate measurement of the overall catchment response. Other measurements are point measurements for which the uncertainties on an areal basis are difficult to estimate. The objectives of any streamflow monitoring network are to provide flow and runoff information over a sufficient range of catchments with differing input sources for application to water resources design and management, hydropower development, flood risk assessment, and river ecology. Additional objectives to establish such a network in the HKH are:

- To provide a sufficient duration of record to assess trends and periodicities, especially as these may be related to global climatic change; and
- To provide sufficient information to assess year-by-year and decadal variations and trends in the comparative contribution to streamflow from glaciers, seasonal snowmelt, and liquid precipitation.

The initial design of a hydrometric (river gauging) network is to gather a broad impression of the variability of water resources of a country or region. Stations may be added on an ad hoc basis to meet specific needs such as hydropower development or water resources planning. With the exception of a few high-level research measurements, streamflow gauging stations in the HKH have not been installed individually or as a network to answer questions associated with climate change or to assess the comparative contributions to flow from melt of glaciers, seasonal snow, and liquid precipitation. However, stations installed for one purpose are often found to provide useful or essential information for another purpose. This has certainly been found to be the case with respect to the use of existing HKH stations to assess questions of climate change impacts or the comparative contribution to runoff from different sources.

While serious climate change uncertainties still remain, the existing streamflow network in the HKH, in conjunction with the climate and glacier network, has not yet been considered in addressing climate change and comparative contribution issues. However, it is anticipated that the existing network will prove inadequate to resolve all these issues and additional targeted stations will be required.

Closely connected with network design and development is an appreciation of the quality of the streamflow data. Hydrometry or streamflow measurement is a science in its own right, and a range of techniques have been developed to provide a continuous measurement of flow (discharge) at a gauging site (Herschy 1995). All methods are subject to error or uncertainty but these errors can be magnified when river conditions are unfavorable, for example, as typically apply in the turbulent and mobile rivers of the HKH, and also when human resources and skills are limited. Data users may well be unaware of the many ways they can be wrong. The application of sophisticated modeling techniques to poor data can prove misleading or, at worst, worthless. Problems of data quality need to be addressed both in the design and management of new stations and in the evaluation of existing flow records.

4.4.1 Quality of Streamflow Measurements

The measurement of discharge in a river is the subject of the science of hydrometry. Discharge, unlike most climate measurements, is not simply a matter of recording a reading from an instrument. It involves several stages, all of which pose difficulties or are subject to error. Difficulties and errors are magnified in the steep mobile channels of the HKH. Therefore, a cautionary approach is necessary in using discharge data supplied by a national agency; the records should not be assumed to be accurate and homogeneous. The measurement of liquid flows in open channels is the subject of a series of international standards set by the International Organization for Standardization (ISO), and of national standards set by such bodies as the Bureau of Indian Standards.[7] Selected here from the full spectrum of topics in these standards are

[7] For example, IS 1192–1981: Velocity: Area Methods for Measurement of Flow in Open Channels.

those particularly related to the HKH, which will be covered in the remainder of this chapter.

4.4.2 Site Selection

Establishing a new measurement site (gauging station) requires thorough consideration of channel characteristics, the range of expected flow, and winter access.

The most important requirement for the location of a gauging station is that downstream features of the river channel – which control the water level at the station and determine the relationship between water level and discharge – are stable and sensitive to changes in discharge. Stability implies that the rating curve for the station should not change over time, and sensitivity implies that a measureable change in discharge should be matched by a measurable change in level (most relevant to low flows).

In the HKH, channel controls are inevitably natural features of the channel, such as a rock bar or constriction (rather than a gauging weir which is impractical or uneconomic). Since upland sites often have mobile banks and beds of gravel and boulders, it may be difficult to find a suitable site with stable control. Suboptimal sites are often chosen, but they require more frequent discharge measurements to ensure that the rating curve has not drifted. Inevitably, the accuracy of measurement at such sites is lower than at locations with stable control. Accessibility of sites is also a significant limitation.

4.4.3 Water Level Measurement

The traditional approach to water level measurement in the HKH has been manual observation of a staff gauge at fixed time intervals, and often more frequently during high flow when the level is more variable. Local observers are recruited to carry out this task. However, in the absence of supervision, it has been frequent practice for the observer to visit irregularly and then to fill in the intervening values by guesswork. Such interpolation by untrained observers can usually be recognized, for example, by changes that are stepped, but unless checked can lead to serious errors in discharge assessment.

A long-established alternative to manual observation is the use of a float mechanism with the levels traced on a chart recorder or, now more frequently, using a digital recorder. This is still generally the most accurate method of measurement of level, now most commonly using an optical shaft encoder and digital logger. However, as a float recorder needs still water for measurement, it requires the capital cost of a stilling well and housing for the recording instruments. This arrangement is appropriate for major water resources stations, but may not be necessary on many rivers.

There are now several alternative types of instrumentation that can be installed in or over flowing water and therefore do not need the installation of a stilling well (although they may need protection from erosion damage), including downward-looking ultrasonic devices and pressure transducers, bubble sensors, and radar level sensors.

Over the last 20 years, the accuracy and reliability of pressure transducers has significantly improved and the cost has decreased. Many thousands of devices are installed around the world, and they are the level measurement method of choice for many applications. The term "pressure transducer" is applied to devices that convert changes in water pressure and hence water level into electrical signals, which are then converted to a digital signal of water depth at suitably short intervals (such as hourly). Data can then be stored on a digital logger from which they can be downloaded periodically on site or transmitted by modem to a base station. A further advantage is a low power requirement: typical dry cell battery life is at least several months. Additionally, such transducers will continue to operate when partly covered in sediment. An example of such an installation on a tributary of the upper Indus is shown in Figure 4.8. They remain the cheapest and most effective solution for most remote installations.

Figure 4.8
Typical Arrangement for Water Level Measurement by Pressure Transducer in the HKH

Source: D. Archer.
Note: The typical arrangement for water level measurement by pressure transducer shows staff gauge, pipe to protect pressure transducer cable, and instrument housing for logger and solar panel.

Significant technical developments in radar level sensors and bubble sensors now make these viable alternatives to pressure transducers. Both can be used at open water sites without stilling wells. Radar sensors provide noncontact measurement from above the water surface (for example, attached to a bridge) by downward transmission and receipt of a reflected radar pulse from the water surface. The time delay provides an accurate determination of distance to the water surface. Unlike traditional bubble recorders, new bubble sensors do not require replaceable gas cylinders but operate by compressing gas through a measuring tube into the water at each selected interval (typically 15 minutes). They have a measuring range up to 30 m. Both bubble and radar sensors have low power requirements; they do not need mains power, and therefore are suitable for remote stations.

It is recommended that stations where stage measurements are currently based on manual observation of a staff gauge be equipped with a pressure transducer, bubble or radar sensor, and associated logger to provide a more continuous and reliable record. They have a very low battery power requirement. An observer should be retained to manually read the staff gauge at less frequent intervals as a check on the calibration of the pressure transducer. Pressure bubble and radar sensors are also suitable for installation at remote stations where no observers are continually present.

4.4.4 Establishing a Relationship between Water Level and Discharge

Since river discharge cannot be measured directly and continuously, the usual procedure is to make a continuous measurement of stage, and then convert the stage time series to a discharge time series using a relationship between water level and discharge (the rating curve).

The rating curve is developed by repeated measurement of discharge over the full range of observed stage. Normally, the lower and medium ranges present little difficulty, but since the highest flood discharges are infrequent and difficult to measure, extrapolation is usually necessary to convert the highest range of stage to discharge. The extent of extrapolation can place a severe limit on the accuracy of the discharge series.

If the channel and downstream control are stable, comparatively few discharge measurements may be needed once the rating curve is initially established. However, in typical HKH rivers, where the bed and channel are unstable due to scour or aggradation, frequent measurements may be needed through the life of the station to retain the reliability of discharge estimation.

The most frequent method of discharge measurement is using a current meter (cup type, propeller type, or electromagnetic) to measure velocity and depth at a series of segments across the channel. At low depths and velocities, a measurement may be made by wading (Figure 4.9.a), but at greater depths they must be made by suspension of the current meter from a fixed cableway or bridge or from a boat. Fixed cableways are an expensive option and are usually limited to the most significant stations for water resources (Figure 4.9.b). Hence, many gauging stations are located at or near bridges where bridge suspension can be used (even if these are not otherwise the most suitable sites in terms of channel stability). Boat gauging is usually limited to wide rivers of limited velocity.

The acoustic doppler current profiler (ADCP) is being used increasingly, with many thousands deployed internationally. In some developed countries, the ADCP has replaced the current meter as the principal method of flow measurement; its use is possible at most sites where a current meter can be used. Flow measurement can be made from a cableway, bridge, or temporary ropeway across a river; it thus provides the opportunity for a wider choice of location for new stations and for calibrating the upper range of existing stations (Figure 4.10). The device uses acoustic fields to measure water velocities and depths. As the ADCP is moved across the channel, mounted on a powered or remote-controlled boat or towed on a float, it collects a velocity profile and depth across the section. The instrument is connected to a rugged bankside laptop with data processing software that gives the section discharge on completion of the traverse. Incorporated instruments and software ensure that only the downstream component of flow is measured. In the past, the ADCP was mainly used in larger rivers such as the Amazon, but smaller versions are now available that can be used in river depths of less than 1 m. Velocities up to 10 m per second can theoretically be accommodated but, in practice, turbulence will limit its use above

Figure 4.9
Typical Discharge Measurement Devices in the HKH

a. Taking a measurement by wading in a glacier-fed Indus tributary, in low flow

b. Fixed cableway gauging on the Astore River at Doyien, in low flow

Source: D. Archer.

Figure 4.10
Typical Examples of ADCP in Use for Discharge Measurement

a. ADCP device is towed by rope across a river

Source: Nick Everard.

b. ADCP mounted on a trimaran designed to cope with fast, choppy water

Source: D. Archer

4 m per second. Turbulence can make it difficult to maintain the stability of the towed ADCP, and entrained air can affect the accuracy of velocity measurement. Very high sediment loads can also prevent penetration of the signal to the riverbed, but these can be countered by using a lower operating frequency.

In many situations in the HKH, the ADCP is the only viable means of discharge measurement, especially in high or flood flows. It is recommended that agencies responsible for streamflow gauging in the HKH evaluate the ADCP for use as a standard flow measurement device. Capital costs are high, but the compensations are greater efficiency and flexibility of measurement.

In the most extreme conditions, typical of glacier outflows but also common elsewhere, highly turbulent flow in rocky steams is transmitted in rapids and waterfalls. No in-river sensors are possible. In this situation, dilution gauging methods can be used, which have already been deployed in mountain river studies in Nepal for the past 20 years (Spreafico and Grabs 1993).

Dilution gauging involves the injection of a tracer of known concentration at a constant rate into a stream and then sampling downstream where complete mixing of the tracer with river water has occurred. The discharge is a function of the ratio of the injected tracer to the downstream sampled concentration. Turbulence here is a positive advantage as it promotes mixing over a short river length. Fluorescent tracers have proven most effective; preliminary analysis can be carried out in the field but are best verified in the laboratory. Dilution gauging requires no power source and can be used to measure discharges up to about 100 m^3 per second. This method is recommended to all monitoring agencies for steep turbulent streams across the HKH.

4.4.5 Transforming the Record of Stage to Discharge

Once the rating curve has been established, it seems a trivial matter to apply it to the time series of river level (stage) to create the time series of discharge. Simplicity is certainly the case if the time series has been collected digitally and the rating curve can be expressed in a functional (rather than graphical) form. The usual functional relationship is logarithmic. However, even here, there are possibilities of introducing errors, as shown in the following examples:

- It has been past practice, in some cases, where stage data were collected manually to compute the daily mean flow by taking the average daily level and converting this single value to discharge. This method will underestimate the daily flow, derived as the average of individual-level measurements converted to discharge (since the relationship is logarithmic rather than linear). The effect will be greatest on small, flashy rivers affected by intense rainfall. Digital processing of the level record to discharge eliminates the need for such simplification;
- It has also been past practice to compute a new rating curve on an annual basis. This has some benefits at low flow, if there are many gaugings contributing to each rating curve. However, for basins where the rating is stable, it can be seriously detrimental to the reliability and homogeneity of high flows, because extrapolation from different ranges of low flows to the highest levels may yield quite different discharges for the same stage. In such cases, it is better to retain all the high flow gaugings over the period of stability and use the same rating throughout the period; and
- Where the riverbed is unstable, as in sand or gravel channels, and the rating is constantly or frequently shifting, a procedure known as Stout's shift method is appropriately applied to cope with the constantly changing rating. By the shift method, the distance by which the level for a given discharge measurement differs from the rating curve (delta h) is determined, and then Δh is interpolated between successive gauging and added (or subtracted) from the measured stage time series before converting to discharge. The shift method is inappropriately used where the control is stable, as it incorporates all the errors of individual gaugings and does not benefit from the improvement achieved by fitting a mean line to the gauging in the rating curve.

4.4.6 Evaluating Historical Discharge Records

While the above discussion provides some guidance on improvement in future measurement, it is still difficult to determine how to respond to error and uncertainty in historical records. It is practically convenient to assume that all records are reliable as provided and to proceed directly to analysis and modeling on that basis. However, results from such analysis may be unreliable. This is neither to the advantage of the analyst nor agencies who depend upon the results. Two ways in which agencies can provide information to give a better appreciation of the reliability of their data are as follows:

- Metadata on each station are held on station files. The files contain records made by inspecting officers of the agency on the reliability of the level measurements made both by manual observation and by level instruments. In addition, they contain a listing of all the discharge measurements that have been made at the station and a graphical display of the rating curves. Key metadata information could be displayed on a website for each station, which can then be accessed by all users, who could then make their own assessment of the potential use of the record. An example of such a website is HiFlows-UK, which provides flood data for around 1,000 river flow gauging stations throughout the United Kingdom. It is specifically targeted at flood estimation as a part of risk assessment.[8] The website requires individual users to make a judgment on the quality of the data on the basis of the information provided, and is mainly for use in flood studies; and

[8] http://www.environment-agency.gov.uk/hiflows/91727.aspx.

- An alternative and more comprehensive system is provided in Lamb et al. 2003 on the development of an objective system for representing gauging station data quality (GSDQ). The system is now used throughout the Environment Agency of England and Wales. The quality information is provided alongside actual river flow time series to users on request.

GSDQ includes statistically based estimates of uncertainty in flow measurement, derived from international standards where possible; quantitative attributes, such as the number and deviations of check gauging; and categorical attributes, such as assessment of the significance of bypassing and the extent of missing or truncated data. Basic station information (including ratings, flow gaugings, and station dimensions) are entered and stored in the GSDQ software, a customized Excel spreadsheet application. The GSDQ spreadsheet calculates all the required attribute values from basic inputs and returns a classification score. This is a number between 0.0 and 1.0, where 1.0 indicates best quality. The numerical score is also subdivided into three classes – caution, fair, and good. A review of international practices at the time of Lamb's publication did not reveal any other established, quantitative, objective measure of data quality in widespread use.

The application of such a system in HKH would provide significant benefit to all data users, including those in national agencies and consultants involved in water resources development and flood risk management.

In the absence of information on data quality, the analyst can usually make some judgment on the quality of the data. A hydrometric network is more than the sum of the individual stations and checks can be made on the consistency of a station by comparison with neighboring stations in association with information on precipitation. For example, it can be determined whether the runoff and flow volume are consistent between successive stations on a river or between the sum of tributary flow and downstream flow. These attributes can be checked for an entire record or as a time series of annual values.

4.5 New Network Requirements

As discussed, significant progress can be made by further application of statistical tests and modeling procedures on existing data. An additional benefit could be gained from the release of recent climate and flow data, which could be used in conjunction with remotely sensed climate and glacier data, for which coverage is most comprehensive during the last decade.

The one clear location where new gauging stations are required is sites recording the outflow from glaciers. A sufficient number of sites are required to assess differences between categories of glacier by region, size, orientation, and range of elevation. Hydrological understanding would benefit, even if flow measurement is made from glaciers on which glacier mass balance studies are not proceeding. Such glacier outflow records must be combined with the main river gauging network as a basis for assessing comparative flow contributions.

4.6 Summary

- Streamflow is the only phase of the hydrological cycle in which the water is confined in such a way as to permit measurement of the overall catchment response. Therefore, accurate measurement of streamflow is critical in linking climatic inputs of moisture and energy with storage and melt of ice and seasonal snow;
- Understanding of streamflow hydrology would particularly benefit from the release of recent climate and flow data, which could be used in conjunction with remotely sensed climate and glacier data, for which coverage is most comprehensive during the last decade;
- Manual observation of river levels should be

replaced, or complemented, by automatic level measurement at all stations with the use of pressure transducers or radar or bubble sensors with data stored by digital loggers. Data storage of level data and transfer to the agency database enables more rapid and reliable conversion to a discharge time series and subsequent analysis;

- Reliability of stage discharge relationships (rating curves) is currently limited by the frequency and difficulty of current meter gauging. Dilution gauging is recommended for wider use in steep, turbulent, glacier-fed streams. The ADCP is recommended for testing and application on larger streams and rivers;
- The principal requirement for new gauging sites is with respect to high-elevation tributaries fed primarily by glaciers or permanent snow. A sufficient number of sites are required to assess differences between categories of glacier by region, size, orientation, and range of elevation; and
- Release of streamflow metadata would enable users to judge the quality of the data for particular applications.

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5.

Indigenous Glacier Monitoring

When the early Western mountain climbers approached Mount Everest, the Sherpa living at its base could not understand why the foreigners would want to climb the mountain. Today, with training and economic incentives, the Sherpa are among the leading high-altitude climbers internationally, with dozens of ascents of Mount Everest and other high Himalaya peaks made possible each year by their expertise. Drilling in an ablation stake or maintaining a climatological station on or near a Himalaya glacier is no more technical than climbing an 8,000 m Himalayan peak. The ability to move safely and function efficiently in the often-hostile environment at the high altitudes of potential monitoring sites in the HKH Mountains is presumed to be a characteristic of the indigenous mountain peoples throughout the region. To successfully monitor the climate and glaciers of the HKH, the mountain people must be involved. For example, Dipak Gyawali, Former Minister of Hydrology and Research Director of the Nepal Water Conservation Foundation, illustrates a possible role for local people. He explains that an area as diverse as the Himalaya needs localized, "toad's-eye" science if it is to learn how to adapt to climate change (Thompson et al. 2007):

> We have some suggestions for how to do it. For instance, you put a weather monitoring station in every school in Nepal, and get the children to do the readings and get the schoolmaster to fax the readings back, your data points increase from around 450 to around 4,000. You are suddenly rich in data, and the local people are involved in understanding the dimensions of the problem.
>
> It will be a long, drawn out process, but it is starting with rain gauges in the schools, linked up with the local FM radio stations. Suddenly the FM stations are very excited because they are talking about what is happening in their area instead of reading out a weather report from Kathmandu that might have no relevance to them.
>
> The remote sensing and the satellites give us the eagle-eye view, which is essential but not enough. In a country as diverse geographically and socially as Nepal – there are more than 90 languages and 103 caste and ethnic groups – the eagle-eye view needs to be complemented by the view from the ground, what I call "toad's-eye" science … High science should … meet up with civic science and traditional knowledge, in order to understand what is happening, so that national governments can also plan. …
>
> The solutions have to come out of the watershed and out of the problem-shed. You can talk about big solutions – building high dams – which can take 40 years. We don't know in Nepal if a government will last 40 days. The solutions have to be what these millions of households can take. Can they be helped? How can they be helped? We just haven't done the science for that. We need civic science; ground-level truth.

Over the past decade, increasingly with international news about climate change impacts on indigenous communities, the movement has broadened to include special considerations for social science data and an indigenous research paradigm (Pulsifer et al. 2011). This chapter explores the potential for engaging mountain communities in the HKH in a research agenda that would involve them in monitoring their environmental conditions, specifically glaciers and glacier-related conditions. It demonstrates how community-based and collectively held knowledge can provide valuable insights, complement scientific efforts, and support adaptive strategies. Recently, concerns about adaptation to climate change have moved to center stage. A "climate change adaptation has been enshrined in the policy debate through its appearance in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), where the ultimate objective of the Convention concedes that adaptation to climate change in relation to food production, ecosystem health and economic development can and will occur." Adger et al. (2009b, p. 336):

Residents of the HKH region as well as elsewhere in the Global South are predominantly poor and underrepresented in the political and scientific arena, and thus lack the capacity to influence hazard planning and adaptation efforts taking place at the national and international levels (CCCD 2009; Tschakert and Dietrich 2010). Mountain communities, with limited assets, information, and support, have little choice but to attempt to adapt to changing environmental conditions, which can create a troubling dilemma for the scientific and humanitarian community. A report by the Global Leadership for Climate Action (GLCA 2009a, p. 6) states: "The world's poor, who have contributed the least to greenhouse gas emissions, will suffer the worst impacts of climate change and have the least capacity to adapt." These vulnerabilities underscore the need for proactive engagement with the populations and social groups that will likely continue to face acute social stress and environmental risks.

5.1 Indigenous Monitoring: Overview and Purpose

Historically, models of cooperation between the scientific community and indigenous communities were structured for scientists to assist communities with research projects that were shaped by the scientists' research plans. The models for interaction have largely been unequal and one-sided. Rarely, if ever, is there a reciprocal aspect in which indigenous knowledge is formally structured at the outset into the content of scientific research questions and methods. Effective, positive working relationships between mountain communities and research institutions take time and commitment to develop and require a substantial level of institutional investment and support. These factors need to be considered as much as possible when it comes to weaving traditional ecological knowledge or local participation into the monitoring and data collection structures that support the aims of glacier hazard mitigation and support resilience under conditions of climate change.

Traditional ecological knowledge and indigenous knowledge are, for the most part, synonymous and refer to the evolving knowledge acquired by indigenous peoples over hundreds, in some cases, thousands of years through direct contact and interaction with the natural world. This knowledge is place specific, reflecting long-standing relationships between natural phenomena, biota, landscapes, aquatic systems, and the timing of events. Cultural adaptations to the risks and hazards posed by life in the extreme mountains of the Hindu Kush, Karakoram, and western Himalaya are well known – for example, building practices and architectural styles in the region reflect indigenous knowledge about the geophysical environment and approaches to coping with a range of mountain hazards. The traditional timber-laced construction pattern proved highly resistant to the earth movements caused by the Kashmir earthquake.

As a number of researchers have pointed out, the linkages between traditional ecological knowledge and understanding climate change is essential for verifying and evaluating climate change scenarios developed by scientists. For others, the traditional ecological knowledge of indigenous peoples is now seen as a repository for solutions to the vagaries and uncertainties associated with climate change. As Raygorodetsky (2011) emphasizes, community-based, collectively held knowledge – along with local processes of observing and interpreting changes in land, sky, and sea – is essential to complement scientific data with chronological and landscape-specific precision.

In light of the "tipping points" being approached in several agro-ecological zones, United Nations agencies, including the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the Food and Agriculture Organization (FAO) of the United Nations, have been exploring the collective knowledge of indigenous peoples. A tipping point is described by Lenton et al. (2008) as the critical threshold at which a tiny perturbation can qualitatively and quantitatively alter the state of development of a system, often with unanticipated, rapid, and abrupt changes. Interest in traditional ecological knowledge has grown in the past decade in part because it has become increasingly recognized that such knowledge can help the global community avert tipping points, and can also inform the conservation of biodiversity, protection of rare and endangered species (Colding and Folke 2001), management of protected areas, development of ecological processes (Alcorn 1993), and proliferation of sustainable resource use in general.

Involving indigenous people in observing and monitoring glaciers and the glacial environment has been done for the following reasons: (a) to build collaboration between indigenous knowledge, science, and technology; (b) to develop tools for active engagement of mountain communities in glacial science and community-based monitoring; (c) to develop approaches to engage indigenous communities in mapping glacier hazards and glacier hazard management; (d) to expand the use and understanding of glacier science and technologies in everyday life in ways that resonate with indigenous systems and technologies; and (e) to preserve data created from indigenous knowledge as a lasting legacy and a benefit for current and future generations. Ultimately, a major goal should be to serve not only the scientific community but also the vast range of glacier-dependent mountain communities. In this regard, data gathering and documentation could serve as new cultural, educational, and technical instruments for dealing with changing environmental circumstances.

Data construction and management should be designed to serve the expressed needs of communities. It is recommended that an exploratory study be conducted on the potential of an interactive global positioning system (GPS) to be of local interest and of practical use in mountain conditions. Another strategy would be to assess whether the technical hardware and software is robust or adaptable enough to support potential uses without an unacceptably high probability of failure. Data gathered could be hydrometeorological and glaciological impact assessments of water access, agricultural production, and food security, enabling the generation of enhanced profiles of vulnerability and adaptation across the region. Potential recruits for data gathering and monitoring could include high-elevation hunters and pastoralists, given their knowledge of local geography and their direct experience with the physical dimensions of mountain environments. Indigenous monitoring should enhance communication about the process of land use planning and classifying areas in terms of hazard, risk, and vulnerability.

5.2 Vulnerability of Mountain Communities: Some Considerations

The HKH region is similar to other ecologically and socially vulnerable areas that are already experiencing the impacts of climate change (Barnett, Adam, and Lettenmaier 2005; Battisti and Naylor 2009; GERES 2009; Orlove, Wiegandt, and Luckman 2008). Temperature and precipitation are exhibiting increased variability and more pronounced and frequent extremes than historical norms (Bahadur 2004; Mool et al. 2001). It is well established that mountain environments are susceptible to climate-induced environmental change (Salick, Zhendong, and Byg 2009). These changes have affected the productivity and reliability of local agricultural practices, threatening existing household livelihood strategies and increasing vulnerability to water-related hazards among already vulnerable, resource-dependent populations (Erikkson, Fang, and Dekens 2008; Halvorson and Hamilton 2010; Ives 2004; Jodha 2005; Marston 2008; Norberg-Hodge 1992; Siebert and Wangchuk 2011; Xu et al. 2007; Xu et al. 2008; Xu et al. 2009).

Along with these changes, glacier-related risks and hazards in the HKH are threatening mountain communities. Human vulnerability to glacier recession, particularly in this region, has recently come into the focus of investigation and analysis among research institutions and the scientific community. The Intergovernmental Panel on Climate Change (IPCC 2007, p. 15) defines "vulnerability" as the "degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change." Recent work on vulnerability to climate change focuses on "exposure, sensitivity, and resilience of human systems to various forms of climate-related risk," and IPCC argues that the strengthening of adaptive capacity and livelihood security must be a central concern of development efforts. Nevertheless, in the HKH region, consistent empirical datasets drawn from grounded and detailed analyses of the consequences of glacial recession and climatic variability for mountain communities are lacking. As a result, there is no coherent picture of the complex socioecological processes that influence vulnerability to glacial recession at the local level across the region, and the ways in which particular social groups – the poor, ethnic minorities, women, children, and the elderly – that are at risk are regularly overlooked.

5.2.1 Glacial Recession

What has been reported is that glacial recession has increased rapidly and is currently affecting the rates of seasonal glacial discharge and the array of water resources upon which communities rely. Moreover, local perceptions of glacier recession in the region confirm the scientific observations and underscore the worrisome trends as glaciers disappear. Other documented local issues include declining water availability, changing patterns in precipitation, demise of springs, increasing extreme weather events, and shifts in the length of the growing season, adding uncertainty to an already challenging situation where new economic growth in various sectors, including mining, hydropower development, industrial agriculture, and tourism, has led to increasing and competing demands for water.

A major shortcoming in the work to date is that the potential of communities and households to adapt to glacier-related climate change has not been effectively addressed, nor have there been studies of how households are already shifting resources and labor in response to climate changes. Future scientific efforts need this information so they might support the community's particular adaptation strategies and capacity-building activities, for example, by forming indigenous monitoring networks in the region.

The high-mountain regions of the HKH lie within an active glacier hazard zone. The impacts of glacial lake outburst floods (GLOFs) in this region have been significant and deadly. The catastrophic impacts of the 1994 Thortomi GLOF in Bhutan, where the moraine-dammed lake failed upon heavy rainfall, underscored the country's need for preparedness for such potential disasters. The growing number of dammed lakes in the upper reaches of basins, often behind unstable moraines, makes it a critical time for populations increasingly exposed to GLOFs to initiate glacier and climate monitoring programs. However, the glacier monitoring program in Bhutan is in its infancy. Recently, attention in Bhutan has focused on a GLOF prevention program that involves a United Nations-sponsored engineering project to partially drain one of the glacial lakes in the upper reaches of the Lunana valley.

The changes and social upheaval associated with glacier hazards complicate the mountain development controversies that countries in the HKH already face. The development trajectory of this mountainous region has deepened its involvement in geopolitics and the global economy. The socioeconomic and political conditions associated with these trends, as well as local and regional struggles for access to and control over natural resources, are exacerbated in the aftermath of natural disasters. Furthermore, the highly gendered social structure and social differentiation drawn along class, religious, and ethnic lines greatly influence disaster experiences, resource access, employment opportunities, and coping abilities.

In theory, the population's vulnerability must be considered in relation to the physical environment, social structures, axes of social difference, and the local–global interactions of pressure-applying forces. Both internal and external factors would influence the community members chosen to participate in the monitoring of glaciers and glacial environments in this region. Internal factors such as the status of family members, class, gender, ideology, ethnicity, poverty, education, access to communication networks, and the seasonal or permanent out-migration of community members shape the social fabric and resiliency in coping with glacier hazards. Other contributing factors include externally driven changes such as large infrastructure projects (for example, dams and roads); expansion of industrial agriculture; forest clearing and devegetation through commercial or illegal logging, mining, and mineral extraction; and acts of aggression, war, and displacement. Commerce, construction, urbanization, and economic development in the HKH have continued with little regard for environmental risks and hazards. Several of these factors are discussed in the next sections.

5.2.2 Demographics

The demographic picture of the region, especially the young age of the population, has contributed to risk in several ways. The HKH countries in this study have low median ages: 16.6 years in Afghanistan; 21.7 years in Pakistan; 25.1 years in India; 21.4 years in Nepal; and 24.6 in Bhutan.[9] The relative youth of the population has influenced the level of preparedness, planning, response, and recovery capacity of these countries, because a large portion of the population lacks the experience and skills to deal with such disasters. Those who have been through disasters can help quell fears and encourage hope among victims of glacier-related hazards, as they see that people have survived these events, and they can provide guidance on how to stay alive or, at the very least, what strategies worked in the past to help mitigate environmental risks and damage. Such experiences and memories are fundamental to the development, maintenance, and transmission of disaster recovery knowledge. Typically, this type of information has been held and shared by elders. However, the push for Western-oriented modes of education and population shifts suggests a potential loss of interest in indigenous knowledge.

5.2.3 Gaps in Knowledge and Awareness of Mountain Hazards

Residents of the HKH region tend to lack scientific knowledge about the geophysical processes that cause mountain hazards and awareness of the steps individuals can take to protect themselves from their impacts. Because they lack sound information, indigenous people may blame these types of events on metaphysical phenomena or social groups rather than focusing attention on preparedness and planning. Outside specialists may be perceived as having undue power and influence, thus their information dissemination techniques are generally not well received in the HKH countries, whose populations have strongly hierarchical social and educational structures. The power relationships and informational disconnect between government officials and local residents, and between scientists and the public, result in a large gap between community members' knowledge and vital life-saving information.

[9] United Nations Statistics Division: Social Indicators. http://unstats.un.org/unsd/demographic/products/socind/default.htm.

5.2.4 Male Out-migration

The increase in male out-migration from mountain communities is another cause of the information void. Men who have left rural areas indefinitely to pursue opportunities in urban centers may learn new critical information but fail to pass it on to family back home. This leaves some of the most vulnerable social groups – rural women and children in remote mountain communities – without information about disaster preparedness, medical care, emergency services, assistance, and so forth. Women and girls find themselves burdened with greater responsibilities in caring for family members and doing farm work, thereby constraining the time and resources available for school and attending critical disaster preparedness classes.

5.3 Glacier Hazard Management Issues

Against this complicated regional background, the aim of the current study is to examine potential bridges between indigenous monitoring and scientific glacier monitoring in the HKH. The need is great for applying new frameworks and scientific tools for describing and analyzing glacier hazard vulnerability (IPCC 2007) and glacier hazard management more generally in the HKH context. Glacier hazard management includes a constellation of measures that reduce the risk of glacier-related disasters, including prediction of glacier hazards, drainage or containment of glacial lakes to remove the possibility of a GLOF, minimization of the portion of the population exposed to glacier hazards, and reduction of human vulnerability.

In view of recent changes in HKH drainage systems, special attention should be given to the social conditions that influence vulnerability to assist in preparing for and mitigating impacts. No adequate documentation exists of the magnitude of extreme weather events and measurements of the impact on livelihoods, which is a major shortcoming for modeling the impacts of climate change. Scientific research in the areas of hydroclimatic measurements and glacier monitoring could be enriched with spatially distributed social analyses. Coupling the physical science with the social science is critical to policy planning and the development of methodological tools for glacier change research.

Practical implications of this glacier hazard management discussion continue to emerge. First, advancing glacier science education and mountain hazard education – with a focus on indigenous knowledge and developing a culture of hazard risk reduction – is critical to reducing loss of life and property due to glacier-related disasters in the future. Mitigation and preparedness methods drawing from traditional knowledge have been suggested for use in disaster preparedness, the development of early warning systems, and postdisaster rebuilding. Second, these educational initiatives will create knowledge that will help communities prepare and plan adaptation measures in response to environmental and climate change challenges. And third, disaster risk reduction plans should maintain a combination of community involvement and expert input by teaming elders, educators, and leaders representing both men and women. Education about the physical process and existing geophysical hazards, and training in evacuation and first aid, should be fundamental to all glacier hazard management efforts in the region.

5.4 Solutions for Indigenous Glacier Monitoring in the HKH Region

This review of scientific and social science information about indigenous monitoring of glaciers in the Himalaya revealed, first and foremost, a lack of data and information on indigenous monitoring. This lack hampers attempts to project the likelihood of success in taking action to involve mountain communities proactively in monitoring and glacier hazard management. A glacier monitoring station was established in 2011 by the Pakistan Meteorological Department in the upper Hunza valley at Pasu Glacier (elevation 4,500 m).

Additional monitoring stations will be extended to other glaciated valleys in the Hunza basin.

As with glacier monitoring, there is a need to begin quantifying and qualifying community interactions with glaciers and impacts of glacial recession on water security, hazards, food security, and well-being. Current knowledge comprises mainly anecdotal observations (often conveyed in news media) and pieced-together stories of societal change in relation to changing environmental circumstances. There are only a small number of individual research projects focused on climate change impacts.

From a monitoring perspective, these observations point to two distinct concerns. The first relates to how the information and data generated can be shared with mountain communities and the country government to support adaptation to climate change; the second involves questions about what the data on glacial hydrology actually mean to the local community water user groups or stakeholders based in the drainage basins. Each mountain community is dealing with different sets of problems and geographies of glacier hazards. Solutions must be site specific, if they are to be effective. As suggested by Gearheard et al. (2011) in the context of Arctic environmental monitoring, the development of locally appropriate technology for monitoring in high-mountain settings will require an iterative design process and engineering refinements. These authors suggest that design of the system should consider the inclusion of community representatives to use GPS and field computers to document environmental observations, track their travel routes, log their observations and experiences, and log the weather they encounter. The system would be easily updatable with timely observations. As Gearheard and colleagues noted, it is possible from an engineering and technology design perspective to produce an indigenous software interface as a result of interaction and exchange between local participants and Western scientists.

Data collections from indigenous knowledge projects generally involve an array of media, including text, audio, maps, or even video, to capture individual or collective knowledge. The terms of data-sharing agreements would need to be carefully worked through to adequately recognize intellectual property and privacy.

Developments that could have dramatic implications for hydrological systems are fraught with critical unknowns. A major unknown in many river basins is the downstream–upstream relationships associated with hydropower development trajectories. Also very much unknown are the cumulative environmental and socioeconomic impacts of the hydropower development agenda on freshwater systems. Efforts to promote renewable energy sources that involve major investments in hydropower can come at large costs and risks to local populations.

5.5 Observations and Recommendations

In order to reduce the vulnerability to glacier-related disasters in the HKH, the need for integrating efforts to include indigenous communities seems apparent. The findings from this review underscore several challenges for integrating mountain communities in an indigenous monitoring effort. Scientific research centers, political institutions, and disaster management agencies need to be convinced that local participation in monitoring environmental processes is worthwhile. Governments and international agencies, by recognizing these needs and abilities of local citizen scientists, stand to gain key allies in their efforts to prepare for, mitigate, and respond to glacier hazards. Teaming community elders with disaster preparedness specialists would further create a holistic and trusting venue for conveying data and information.

5.5.1 Observations

The following are observations regarding indigenous monitoring concluded from the current study:

- The countries in the HKH region exhibit weak outreach and communication linkages with

mountain communities and have a high risk of glacier-related hazards and disasters;
- The picture of emergency preparedness and disaster response planning at the local and drainage basin scale is weak, with attention to glacier-related concerns being, in most cases, limited or nonexistent; and
- Countries in the region have weak scientific capacity at the local level.

5.5.2 Recommendations

The authors of the present study recommend that a set of best practices in indigenous monitoring of glaciers and glacial hazards for major basins be developed in collaboration with the scientific community, with minimum standards and indicators that include the social aspects of indigenous monitoring. The intent of these recommendations is to ensure that the specific needs and contributions of mountain communities are institutionalized into glacier-related monitoring and risk reduction plans:

General community interventions

- Establish regional glacier science outreach and training centers;
- Organize curricular initiatives across grades levels and in higher education that provide science-based climate- and glacier-related education;
- Reduce information vulnerability among mountain people. A starting point would be promoting literacy, developing appropriate curriculum materials, and training teachers. Training should address life-saving earthquake drills, basic weather and climate change science, risk awareness, and information about hydroclimatic systems and glacier studies;
- Respect mountain communities as able stakeholders and disaster management professionals; and
- Conduct glacial recession-related vulnerability and needs assessments.

Development of indigenous monitoring teams, as in "citizen scientist" programs

- Educate community leaders in core concepts and methods to raise awareness and community support;
- Train teams in basic methods and methodological approaches, record keeping, core skills, and assessment of household and community perceptions of problems; and
- Project goals should include glacial hazard investigations, glacial monitoring, weather monitoring, informing engineering projects that are scientifically sound and innovative in approach, and disaster risk reduction programs.

Support and enhance hazard preparedness and disaster risk reduction at local level

- The preparedness plan should include a disaster management plan that lays out the line of communication and coordination among the scientific networks;
- The emergency preparedness plan should include an assessment format and prioritization of existing resources and capacities;
- The mechanism for early warning and reporting a potential disaster should be strengthened in coordination with government agencies, nongovernmental organizations, and civil society; and
- Indigenous knowledge and an intergenerational perspective should be considered in designing monitoring systems. Elderly people may have memories of past disasters or environmental stresses that could pass life-saving information on to younger generations.

One important strategy would be to build capacity within regional higher education institutions. Colleges and universities are key players in understanding glacier science and monitoring activities. These institutions can both help build capacity at the local level and provide leadership and technical support to mountain communities.

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6. Satellite Imagery and Digital Elevation Models

Glaciers have been monitored on a large scale since 1894, when the International Glacier Commission was established at the sixth International Geological Congress in Zurich. Today, several global, regional, and national glacier inventorying and monitoring initiatives exist, two examples of which are described in this chapter. While earlier inventories used topographic maps and field observations for glacier monitoring, today indirect measurements from satellite imaging and DEMs are increasingly being used, although direct field measurements are still important. Ideally, direct and indirect measurements go hand in hand, though often circumstances such as remoteness, inaccessibility due to political and security issues, or time and funding limitations for field monitoring campaigns only allow for indirect measurements. However, in too many glacier mapping and monitoring studies, insufficient fieldwork has been done to collect ground-truth data to determine error calculations for results from remote sensing analyses.

Remote sensing technologies are used to identify and delineate glaciers, characterize glaciogeomorphic parameters, describe glacier fluctuations and velocities, and document (through multitemporal analysis) changes in glacial extent and volume, among other tasks. Remote sensing technologies and data collection offer the following advantages:

- Spatial coverage of data of larger regions;
- Availability of data for remote areas with limited field-based glaciological measurements;
- Availability of data of the same area from time slices that often reach back some decades, allowing multitemporal analyses;
- Availability of data at various spatial and spectral resolutions;
- Availability of data at low cost or even no cost; and
- Availability of semiautomated mapping approaches that are cost-effective, because often numerous satellite scenes can be analyzed within a relatively short time or even simultaneously.

However, as Raup, Kääb et al. (2007) have noted, mere availability of satellite imagery and DEMs does not necessarily equate to accurate thematic information production and glacier parameter estimation. Remote sensing has some disadvantages: the necessity for adequately trained operators; analytical problems in glacier identification and mapping; comparability of results from various methodological approaches; interference from atmospheric conditions (for example clouds, smoke); and sensor malfunctions.

6.1 Literature Review

The most recent and comprehensive review of the use of satellite imagery and DEMs in glacier mapping and monitoring is Kargel et al. 2013. This book summarizes results from over 10 years of research on glacier monitoring within the international project Global Land Ice Measurements from Space (GLIMS); the study described in this chapter relies heavily on this source, particularly on the following chapters:

- Bishop, Bush et al. 2013 on remote sensing science and technology for glacier assessment;
- Ramachandran et al. 2013 on satellite image acquisition, preprocessing, and special products;
- Kääb et al. 2013 on glacier mapping and monitoring based on spectral data;
- Quincey et al. 2013 on digital terrain modeling and glacier topographic characterization;
- Racoviteanu et al. 2013 on Himalayan glaciers in India, Bhutan, and Nepal; and
- Bishop, Shroder et al. 2013 on Afghanistan and Pakistan.

Other important reviews of the use and usefulness of remote sensing in glacier monitoring are Raup, Kääb et al. 2007, with a focus on the GLIMS project; and Racoviteanu, Williams, and Barry 2008, with a focus on the Himalaya. The USGS as part of its Satellite Image Atlas of Glaciers of the World (Williams and Ferrigno 2010) includes chapters on Pakistan (Shroder and Bishop 2010), India (Vohra 2010), and Nepal (Higuchi et al. 2010).

6.2 Requirements for Glacier Monitoring Program

With regard to the specific environmental, cultural, logistic, and security circumstances in the HKH region, a glacier monitoring program that makes use of remote sensing data should meeting the following conditions:

- Cover the entire region;
- Respect existing security issues and be safe for all participants;
- Be carried out by regional and local institutions, agencies or others, and be advised by an international expert board;
- Train local and regional geospatial information technology and field specialists in glacier monitoring;
- Employ low-cost or open-source, widely used data types and software packages;
- Develop an inventory of all glaciated areas using one single approach (same imagery and DEM types, same analytical methods);
- Monitor as many glaciers as possible and as often as possible (in a near real-time environment) to describe the general status of glaciers and glacial changes throughout the HKH;
- Monitor a number of benchmark glaciers in more detail and intensity;
- Implement one regional glacier monitoring entity, or at least guarantee the exchange of data and results between participating countries;
- Make status, data, results, reports, and so on, available to the general community (open access) via a web-based portal that is easy to use;
- Reach out to and educate the general community about glacier monitoring activities and results;
- Address the needs of local communities (for example, the implementation of a GLOF warning system); and
- Identify questions for the applied research community.

6.3 Mesoscale Satellite Imagery

Until the early 1970s, aerial photography was the primary remote sensing technology in glacier mapping and monitoring. Although it offers many advantages, this technology also has many restrictions, for example, in ground coverage, its limited availability for study areas such as the HKH, and the high cost of aircraft and regular flights.

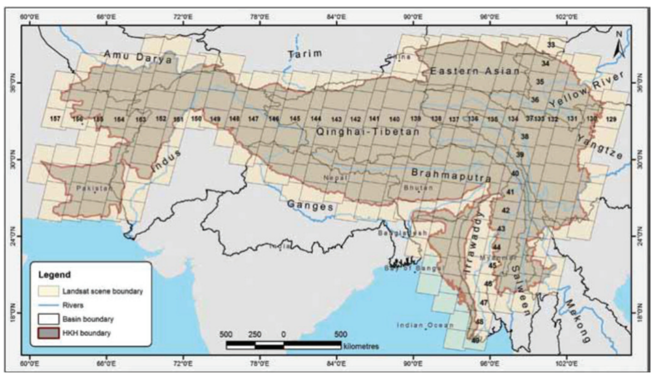
Satellite imagery analysis was then introduced in studies of the cryosphere. Since the early 1970s, medium-resolution (10–90 m) optical satellite data have become available, particularly with the launch of sensors such as the Landsat Multispectral Scanner (MSS), Landsat Thematic Mapper (TM), Système Pour l'Observation de la Terre (SPOT), Indian Remote Sensing (IRS) including Cartosat and Resourcesat, Landsat 7 Enhanced Thematic Mapper Plus (ETM+), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and Advanced Land Observing Satellite (ALOS) (Figure 6.1). Today, large-scale (less than 10 m) imagery suitable for detailed glacier studies at basin scale is available, for example, from IKONOS, Quickbird, and GeoEye-1. However, the narrow swath, long revisit cycles, and high cost limit their use for systematic glacier monitoring of larger regions such as the HKH. CORONA data from 1960 to 1972 were declassified in 1995 but are only available for some glacierized areas within the HKH region.

The Landsat program is the longest-running enterprise for acquisition of satellite imagery of Earth. Since its beginning in 1972, seven individual satellites have been launched, of which Landsat

5 (1984) and Landsat 7 (1999) are still in orbit. Landsat images cover an area of 185 km^2 and come at 15–60 m spatial resolution, depending on the wavelength range. Both Landsat 5 and 7 carry the TM and MSS; the MSS on board Landsat 5 was powered down in 1995. On May 31, 2003, the Scan Line Corrector in the Landsat ETM+ instrument failed, causing the loss of approximately 22 percent of the data in a scene. However, data products are available with the missing data optionally filled in using other Landsat 7 data selected by the user. Scenes can be downloaded free of charge from the USGS imagery archive – and requests placed for processing of scenes not downloadable – or from the Global Land Cover Facility. Landsat imagery has been extensively and successfully used in glacier monitoring studies, particularly for band ratio analysis and land cover classification. As of April 2012, approximately 3,400 Landsat 5 TM scenes and 9,700 Landsat 7 ETM+ scenes displaying the HKH study area were available for downloading from the USGS Earth Explorer website.[10]

The many advantages of remote sensing by ASTER, launched in 1999, have increased its use in numerous glacier monitoring studies (Racoviteanu,

Figure 6.1
Landsat ETM+ Index Map for the HKH Region



Source: Bajracharya and Shrestha 2011.

Williams, and Barry 2008). ASTER's features include the following:

- Spatial resolution of 15 m in visible (VIS) and near infrared (VNIR) is adequate for regional-scale glacier studies;
- High spectral resolution with three VNIR bands, six mid-infrared (MIR) bands, and five thermal infrared (TIR) bands allows for multispectral image classification;
- Off-nadir viewing band in the near infrared (NIR) enables high-resolution along-track stereoscopic vision;
- Adjustable sensor gain settings provide increased contrast over bright areas (snow and glaciers);
- The revisit interval is only 16 days;
- Data are provided at no cost for noncommercial users participating in the GLIMS project;
- High-priority data acquisition requests submitted by the researcher to the ASTER Science Team ensure adequate quality of the acquired data for glacier monitoring; for example, data acquisition requests include specifications on instrument gain settings for each ASTER band, the acquisition window (start and end time for the acquisition), and specific glaciers to be targeted in the field; and
- Various products are available from the Land Processes Distributed Active Archive Center,[11] for example, surface kinetic temperature, surface emissivity, surface reflectance, and the orthorectified product package that includes the relative DEM constructed on demand using Silcast software.

As of April 2012, about 8,000 ASTER scenes were available for download from NASA's Earth Observing System Data and Information System Reverb|ECHO website, providing coverage over the HKH region.[12] Figure 6.2 is an example of this imagery, showing glaciers of Bhutan and China obtained with ASTER imagery.

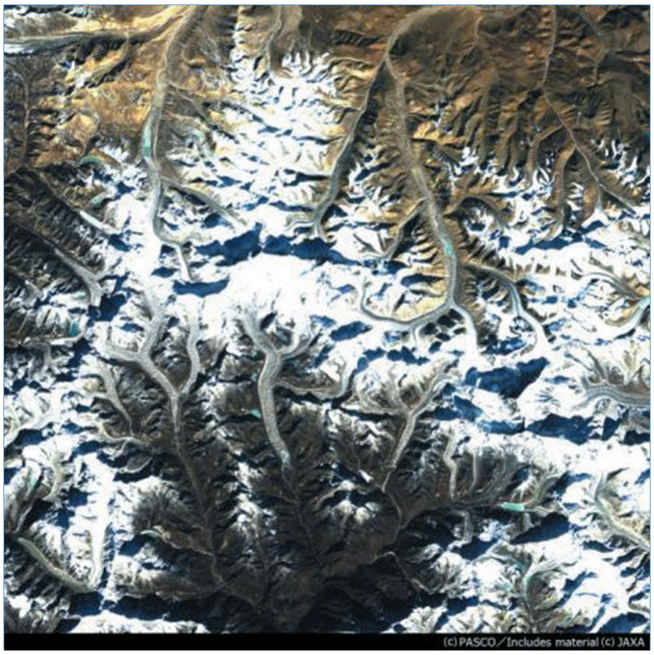
[10] USGS Earth Explorer: http://earthexplorer.usgs.gov/.
[11] Land Processes Distributed Active Archive Center website: https://lpdaac.usgs.gov/.
[12] Reverb|ECHO website: http://reverb.echo.nasa.gov/.

ALOS, launched in 2006, combines visible remote sensing with active microwave techniques using three sensors: the Panchromatic Remote-Sensing Instrument for Stereo Mapping, suitable for detailed digital elevation mapping at 5 m accuracy; the Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2), suitable for glacier mapping and measuring of albedo of the glacier surface; and the Phased Array type L-band Synthetic Aperture Radar, suitable for day-and-night and all-weather land observation, and probably for estimating snow cover depth, which may assist in determining accumulation rates on glaciers. An example of ALOS imagery showing the glaciers of Sagarmatha National Park in eastern Nepal is shown in Figure 6.3. Data can be requested through ALOS data nodes for noncommercial use at costs incurred by the participating ALOS data node organizations by region.

Figure 6.2
ASTER Image of Glaciers in the Himalaya of Bhutan and China

Source: J. Kargel.

Figure 6.3
ALOS AVNIR-2 Scene Covering Sagarmatha National Park, Nepal



Source: PASCO and JAXA.

6.4 Glacier Monitoring Using Satellite Imagery and DEMs

Although today semiautomated glacier mapping from optical satellite imagery is a standard tool in glacier monitoring, problems still exist in the methodology that cause different results in different glacier mapping studies. For example, Kamp, Krumwiede et al. (2013) compared studies of glaciers in the Mongolian Altai Mountains and found that the reported glacier number and glacial extent varied widely: while one study put the number of "glaciers" in the Mongolian Altai at 120, another one identified around 731 "glaciers and glacierized areas;" as a result, the exact number and spatial coverage of Mongolia's glaciers are still unknown. Kamp, Krumwiede et al. (2013) identified two main reasons for the varying results: the definition of a glacier and methods for data collection.

First, for many studies, it was unclear what definition of "glacier" was used and what exactly had been mapped. When inventorying glaciers in western Canada, Bolch, Menounos, and Wheate (2009) mapped only glaciers larger than 0.05 km^2. Bolch et al. (2010) mapped glaciers larger than 0.01 km^2, but then compared only glaciers larger than 0.1 km^2. Also, Paul et al.

(2009) set the lower limit of what constitutes a glacier at 0.01 km^2, because a glacier any smaller would be too difficult to accurately identify through a platform with a spatial resolution of 15–30 m. GLIMS defines a glacier, identified by a single GLIMS glacier ID, as "a body of ice and snow that is observed at the end of the melt season" (Raup, Kääb et al. 2007).

The second reason results vary is that many studies do not – or do so only in a sketchy way – explain employed methods; inaccuracies and errors; source data type (topographic maps, aerial photographs, or satellite imagery); or source data acquisition date. This lack of information calls into question a study's reliability. Kamp, Krumwiede et al. (2013), therefore, concluded that it is important to realize that reported numbers of glaciers, glacierized area, glacial changes, and estimated climate changes from existing studies have to be viewed with extreme caution.

The two indicators used most frequently for a glacier's response to climate forcing are changes in glacial area and terminus position, which are relatively easy to extract from multispectral satellite images (Racoviteanu, Williams, and Barry 2008). Glacial area is calculated from glacier outlines and used as input for volume–area scaling techniques. Glacier outlines combined with a DEM help to derive glacier parameters such as hypsometry and the ELA.

Raup, Kääb et al. (2007) identified the five most commonly used methods in glacier identification from satellite imagery: manual digitization, spectral band ratio and threshold, normalized difference snow index (NDSI), geomorphometric based, and thermal band methods.

6.5 Monitoring Debris-free Glaciers

Clean glacial ice has a distinct spectral signature, with uniqueness in the VNIR part of the electromagnetic spectrum, which makes it relatively easy to map debris-free glaciers (Figure 6.4). Snow and ice are characterized by high reflectivity (albedo) in the VIS wavelengths (0.4–0.7 micrometers); medium reflectivity in the NIR (0.8–2.5 micrometers); low reflectivity and high emissivity in the TIR (2.5–14 micrometers); and low absorption and high scattering in the microwave. While in clear weather the high albedo of snow and ice make them easily distinguished from surrounding terrain using visible infrared (VIR), optically thick clouds are also highly reflective in VIR, hence they confound the classification. However, they are reflective in the NIR, and are thus discriminated from snow and ice.

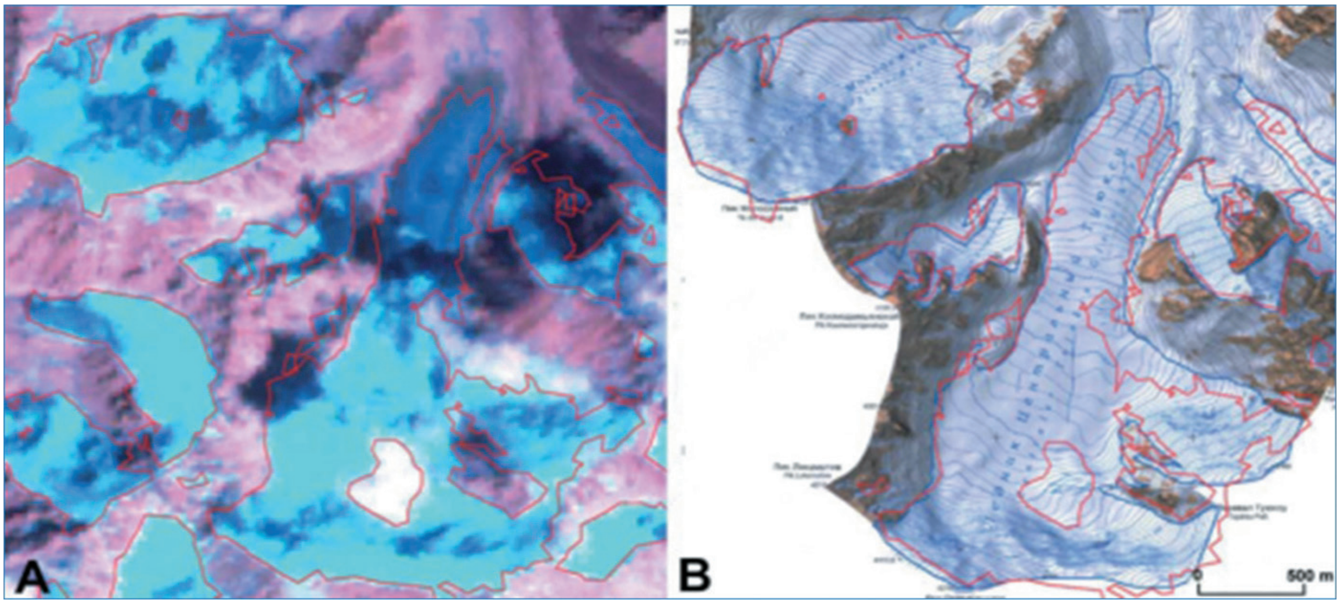
Single band ratios (VIS/NIR) and NDSI are commonly used to separate the bright snow and ice from darker landscape features (Figure 6.5). When applying band ratios, a threshold of 2 was found to be most suitable (Bishop et al. 2008; Bolch et al. 2010); when using NDSI, a threshold of 0.4 was found to differentiate snow from nonsnow, and thresholds of 0.5–0.6 proved successful in delineating glacier ice in the Andes of Peru (Racoviteanu, Williams, and Barry 2008). Both band ratios and NDSI methods produced satisfactory mapping results for shaded glacier parts, and have the advantage of being fast and robust, and thus relatively easy to automate over extensive areas (Bolch and Kamp 2006; Paul, Kääb, and Haeberli 2007; Bishop et al. 2008; Racoviteanu, Williams, and Barry 2008). However, using band ratios has some problems in mapping glaciers due to the presence of fresh snow on the glacier surface, supraglacial debris, and proglacial and supraglacial lakes (Racoviteanu, Williams, and Barry 2008).

Despite present difficulties, Krumwiede et al. (2013) and Kamp, McManigal et al. (2013) argued for a simple threshold ratio mapping approach, allowing for faster processing time by using an unsupervised classification scheme. This scheme

Figure 6.4
Delineation Results for Glaciers in the Northern Tien Shan

a. Delineated glaciated areas (red lines) using Landsat TM4/TM5 ratio images

b. Comparison with glacier outlines (blue lines) in the topographic map 1:10,000

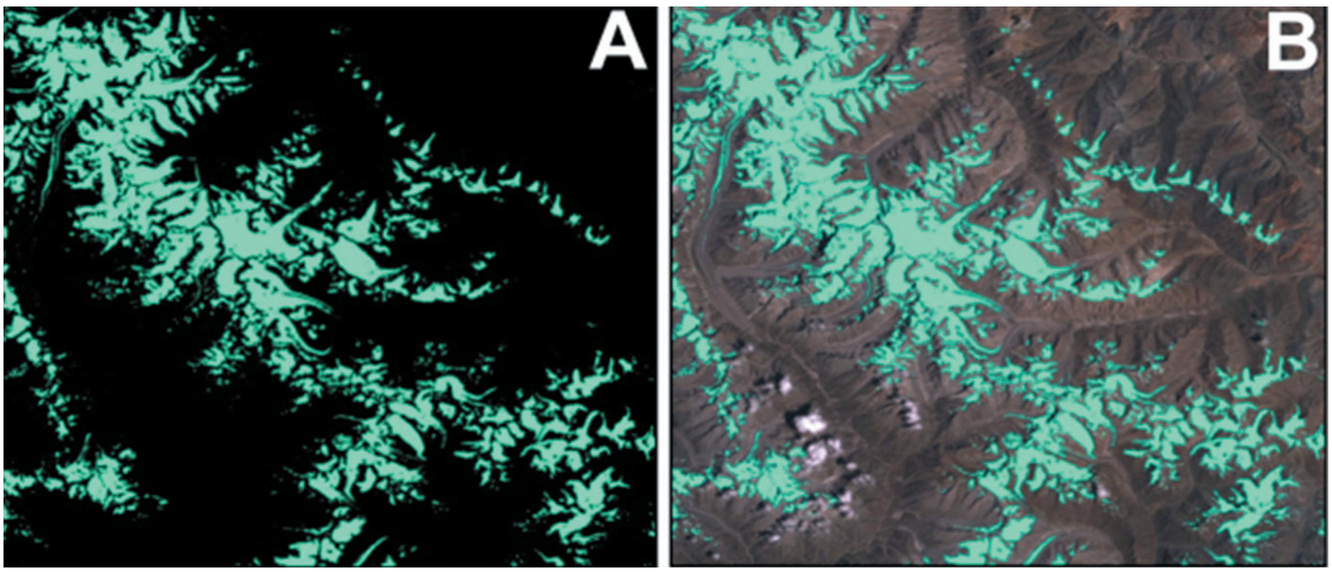


Source: Bolch and Kamp 2006.

Figure 6.5
Simple Threshold Ratio Mapping Approach Using Landsat 7 Bands 4 and 7 for Parts of the Himalaya in India (33°N 77°E)

a. Extraction of snow and ice

b. Extracted snow and ice data draped over natural color composite

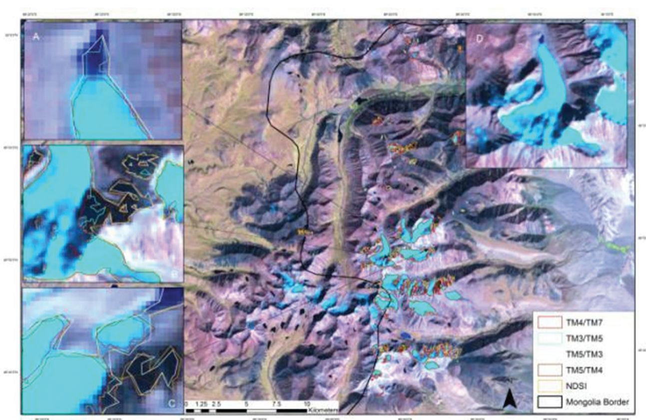


Source: Krumwiede et al. 2013.

uses bands 4 and 7 from the Landsat 5 TM and Landsat 7 ETM+ sensors and performs simple raster mathematical calculations. This approach can be incorporated directly into satellite imagery processing methods and can generate output datasets, including raster overlays and glacier outline shapefiles with area calculations. These output datasets can then be incorporated with DEMs to determine glacier hypsometric areas and glacier area with respect to aspect. Using this simple method makes it is easier to analyze several images in a shorter amount of time and allow for multitemporal change detection and analysis.

These findings of Krumwiede et al. (2013) and Kamp, McManigal et al. (2013) were supported by Pan et al. (2012, who found that band ratio TM4/TM7 produced the most accurate results when compared to results from visual interpretation and from other frequently used band ratios (TM3/TM5, TM5/TM3, TM5/TM4) and NDSI, because it is the only approach that did not erroneously map shadowed terrain and proglacial lakes (Figure 6.6). The Pan et al. (2013) study in the Ikh Turgen Range in the northeastern Mongolian Altai at the Russian border, using band ratio TM4/TM7, identified 52 glaciers. The results also showed, for example, that the number was 59 glaciers using band ratio TM5/TM3, 61 glaciers using NDSI, and 62 glaciers using band ratio TM5/TM4. The "overprediction" of glacier numbers for the latter approaches occurred in particular in the glacier class of less than 0.05 km^2 and was due to erroneous identification of shadows as glaciers. Pan et al. (2013) also compared glacier mapping results using thresholds of 2, 3, and 4, and concluded that a threshold of 2 produced the most accurate results. However, the mapping using band ratio TM4/TM7 also still has problems when differentiating between clean ice and debris-covered ice. Note that TM4/TM7 is the only band ratio that did not have errors and produced the best results when mapping disconnected glaciers.

Figure 6.6
Glacier Mapping Results Using Different Band Ratios Applied to a Landsat Image of Ikh Turgen Range



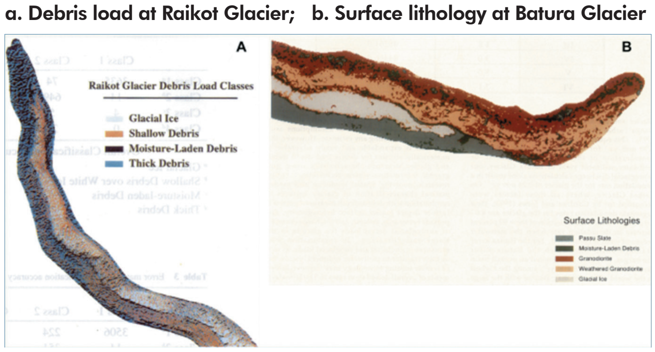
Source: Pan et al. 2012

6.6 Monitoring Debris-covered Glaciers

Debris-covered glaciers are more difficult to map, because the supraglacial material might have very similar VIS/NIR spectral signatures to the surrounding terrain (Figures 6.7 and 6.8), although spectral information has been successfully used to detect characteristics of supraglacial debris load and rock types (Figure 6.9) (Bishop, Shroder, and Ward 1995). This complicates not only the (semi)

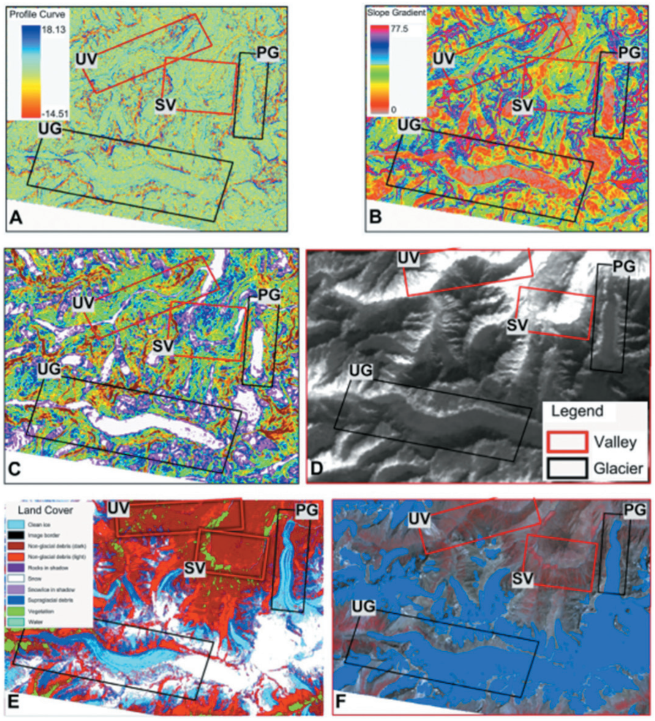
Figure 6.7
Characteristics of Supraglacial Debris of Glaciers in Northern Pakistan Derived from SPOT Imagery Multispectral Analysis

a. Debris load at Raikot Glacier; b. Surface lithology at Batura Glacier



Source: Bishop, Shroder, and Ward 1995.

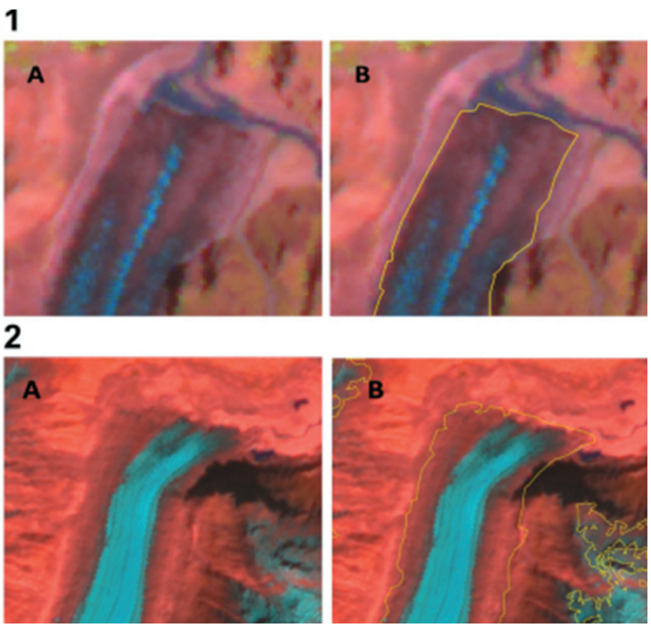
Figure 6.8
Results from Different Glacier Mapping Steps for the Nun Kun Mountains in Zanskar



Source: Kamp, Byrne, and Bolch 2011.
Note: (a) profile curvature; (b) slope angle; (c) cluster; (d) thermal information; (e) supervised land cover classification using the maximum likelihood method; (f) morphometric glacier mapping. PG = Parkachik Glacier; UG = unnamed glacier; SV = Suru valley; UV = unnamed valley.

Figure 6.9
Results from Morphometric Glacier Mapping (MGM) of Glaciers in Himalaya Range of Zanskar, India, Using ASTER Satellite Imagery and ASTER DEMs

1. Parkachik Glacier; 2. Drang Drung Glacier



Source: Kamp, Byrne, and Bolch 2011.
Note: In a. and b. figure 2. MGM-based delineation (yellow line) picks up clean ice as well as debris-covered parts of the glacier.

automated identification, but also, often, the manual identification of the glacier margins, because they appear contiguous with the proglacial zone. As the spectral information alone is insufficient in mapping debris-covered glaciers, DEMs are used to support the mapping process. For example, small elevation differences between the proglacial zone and glacier surface or the exact location of a catchment divide can be more easily identified in a DEM than with spectral information alone (Quincey et al. 2013). Bolch et al. (2010) found that SRTM3 data did provide sufficient results to calculate ice divides, which are important for defining individual glaciers. This finding will help automate the process of delineating glaciers. The combination of band ratios and topographic information has successfully been used to map debris-covered glaciers.

Another promising approach is mapping from thermal imagery, because supraglacial debris that is thinner than 2 cm generally has a lower temperature than the surrounding moraines and terrain. Above this threshold, the thicker debris actually insulates the underlying ice and the supraglacial debris cover might now show a temperature similar to the surrounding of the glacier, which prevents any glacier monitoring. As in most other cases, information about the thickness of the supraglacial debris is not available; thermal information analysis is applicable only to glacier parts under thin debris cover, while any other parts of the glacier that are covered with thicker debris might not be identified correctly. Therefore, the use of thermal information in glacier monitoring can only have a supportive role and is usually performed in combination with other mapping techniques.

More sophisticated glacier mapping approaches "use both first- and second-order topographic derivatives to segment landscape units accordingly, and make use of statistical, artificial intelligence and hierarchical structural methods" (Quincey et al. 2013). Examples include pattern recognition, artificial intelligence techniques, and object-oriented mapping. Object-oriented mapping "employs various DEM derived terrain-object properties such as slope angle, slope azimuth, curvature, and relief to identify locally contiguous portions of the landscape, which are iteratively aggregated to form higher-order landform objects at larger and larger scales" (Quincey et al. 2013). Even more complex, integrative mapping approaches combine sophisticated techniques, for example, a hybrid (anthropogenic–computational) method that includes object-oriented mapping and artificial neural networks (Raup, Kääb et al. 2007); or the MGM method, which combines band ratios, topographic analyses, cluster analysis, supervised land cover classification, and thermal information (Paul, Huggel, and Kääb 2004; Bolch and Kamp 2006; Bolch et al. 2007; Kamp, Byrne, and Bolch 2011). The latter has been found to be useful in distinguishing debris cover on glaciers, and both Landsat 7 ETM+ (at 60 m resolution) and ASTER (at 90 m resolution) include thermal bands (Racoviteanu, Williams, and Barry 2008).

6.7 Global Land Ice Measurements from Space

The international project GLIMS, established in the late 1990s, was designed to monitor the world's glaciers using data from optical satellite instruments such as ASTER. Compared to other glacier inventories, GLIMS is the first attempt to build a globally complete, high-resolution map of glacier extents. It began as an ASTER Science Team project, in which it was able to guide the ASTER instrument to acquire imagery of Earth's glaciers that was optimal (best season and instrument gain settings) for glacier monitoring.[13] Regional centers and affiliated stewards are responsible for a specific region; for the HKH region these are the ICIMOD, as the regional center for the Himalaya (Bhutan, India, Nepal); and the University of Nebraska, Omaha, as the regional center for Southwest Asia (Afghanistan and Pakistan).

Of importance for the glacier monitoring approach in the HKH region proposed here is that for registered GLIMS-related researchers, ASTER data are free of charge. Details about GLIMS can be found in Bishop et al. 2004; Kargel et al. 2005; Kargel et al. 2013; Rau et al. 2005; Raup, Kääb et al. 2007; and Raup, Racoviteanu, et al. 2007.

GLIMS analysis results include digital glacier outlines and related metadata, and they can also include snowlines, center flow lines, hypsometry data, surface velocity fields, and literature references. The program also develops tools to aid in glacier mapping and for transfer of analysis results for archiving to the National Snow and Ice Data Center. These include GLIMSView, documented procedures for GLIMS analysis, and web-based tools for data formatting and quality control. More than 60 institutions across the globe are involved in GLIMS.

The GLIMS webpage[14] has guides and tutorials, for example, for glacier classification, compilation of glacier inventory data from digital sources, analysis algorithms, and specific guides from and for regional centers. It offers the following ways of viewing the database:

- **GLIMS Glacier Viewer.** The GLIMS Glacier Viewer is an interactive map of the data in the GLIMS glacier database. Different layers in this interface can be viewed and spatially

[13] GLIMS: Global Land Ice Measurements from Space – Monitoring the World's Changing Glaciers. http://glims.org.
[14] Ibid.

queried, including GLIMS glacier outlines, ASTER footprints, regional center locations, the World Glacier Inventory, and the fluctuations of glaciers. The GLIMS glacier outlines layer contains the results of glacier mapping within the GLIMS initiative. Each polygon in this layer represents the extent of a particular glacier at a specific time, as well as other possible features of the glacier, such as the extent of debris cover or the location of supraglacial and proglacial lakes. The GLIMS glacier outlines can also be downloaded as ESRI shapefiles, MapInfo tables, Geographic Markup Language files, Keyhole Mark-up Language (Google Earth), and the Generic Mapping Tools multisegment format (Figure 6.10);

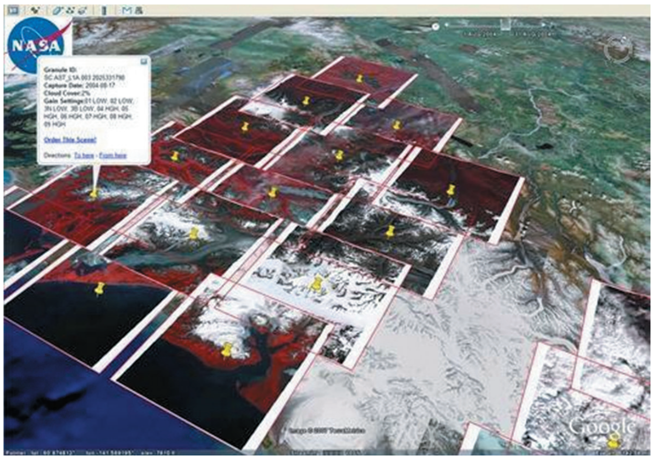
- **GLIMS text search interface.** This interface provides access to the GLIMS glacier database through a text-based search form. The parameters the user can search on, as well as the result fields that can be returned, are customizable. This allows the user to search on and return only the criteria that are relevant to their needs. Query results in this interface can be downloaded individually or as part of the larger result set. Downloaded data are available in the same formats as from the map server interface; and
- **Open Geospatial Consortium server.** Another way of accessing data within the GLIMS glacier database is through the Web Map Service and Web Feature Service protocols of the Open Geospatial Consortium. These services allow access to GLIMS glacier data directly from desktop GIS software products such as ArcGIS, GRASS, or Google Earth, as well as other applications such as MapServer. The data are divided into annual subgroups for the years 2000 to the present. Subsequently, each annual group is divided into three layers representing image center points, image bounding boxes (polygons), and browse image overlays, as shown in Figure 6.10.

As of March 21, 2012, the GLIMS glacier database included 115,051 glacier analyses (snapshots). However, while some regions are covered completely (for example, British Columbia in Canada, the Caucasus, China, and – of importance for this report – Nepal, although based on somewhat old maps), the datasets for India and Pakistan are incomplete, with many glaciers still missing. For example, for Southwest Asia (Afghanistan and Pakistan), the number was 411 glaciers covering around 710 km^2, and for the Himalaya (Bhutan, India, Nepal) the number was 3,707 glaciers covering around 6,860 km^2 (GLIMS database).

6.8 Macroscale Satellite Imagery

Ground-based measurements, whether from manually operated or automatic weather stations, sample the climate at a single point. Assessment of regional or catchment climate depends on interpolation and (often dubious) extrapolation. Satellite remote sensing provides the potential for obtaining complete areal coverage of aspects of the climate of a region, covering locations that are not measured or cannot be measured at ground level. Spatial data derived by remote sensing has a

Figure 6.10
Viewing GLIMS ASTER Browse Data within Google Earth



Source: GLIMS website http://glims.org.
Note: View the GLIMS ASTER browse data within Google Earth by downloading the file GLIMS_ASTER.kmz and opening it in Google Earth.

theoretical basis in identified relationships between the intensity of emission of electromagnetic radiation at specific wavelengths (spectral bands) and specific surface or atmospheric properties. The following sections describe the most important spatial data sources for application to the climate of the HKH, what they are designed to sense, and what are their uses and limitations.

6.8.1 Moderate Resolution Imaging Spectrometer

NASA's MODIS instruments capture data in 36 spectral bands ranging in wavelength from 0.4 to 14.4 micrometers and at varying spatial resolutions. They are designed to provide measurements of large-scale global dynamics, including changes in Earth's cloud cover, radiation budget, and processes occurring in the oceans, on land, and in the lower atmosphere. NASA software extracts time series datasets with given resolution and time averaging from specific sensed wavelengths. Records are available from early 2000 to the present.

With respect to the climate of the HKH, MODIS provides the potential to develop a spatial characterization of the snow-covered area and land surface temperature, which can serve as analogs, respectively, for precipitation and air temperature. Land surface temperature and snow-covered area datasets are available as daily or eight-day aggregates. The eight-day snow-covered area datasets provide 500 m horizontal resolution maximum snow cover extent (product MOD10A2) (Hall et al. 2001). For land surface temperature, the eight-day datasets provide 1 km horizontal resolution mean surface temperature for daytime (near local noon) and nighttime (near local midnight) overpasses (product MOD11A2) (Wan 2008).

The algorithms for both snow-covered area and land surface temperature depend upon "clear sky conditions." This means that, for a given pixel, in order to determine the snow cover state or calculate its land surface temperature, the sky must be cloud-free. Given the cloud climatology of the upper Indus, most satellite scenes are partially cloud covered. In general, pixels over valley bottoms will be cloud-free more often than pixels covering mountaintops. Thus, the count of observations contributing to eight-day aggregates will most often be greater for low-elevation zones than higher ones.

The principal use of MODIS-derived land surface temperature has been to derive lapse rates of temperature over the full altitudinal range of a catchment, rather than over the limited range available to surface weather stations. Derived temperatures are then used in conjunction with a melt model, distributed by altitude.

MODIS, like other radiometrically derived data products, has limitations in its capacity to accurately assess parameters of interest. It detects the presence or absence of snow but cannot measure either falling precipitation or snow water equivalent on the ground. The theoretical basis for assessing snow-covered area and land surface temperature depends, among other things, on relationships identified between the intensity of emission of electromagnetic radiation at specific wavelengths (spectral bands) and specific surface or atmospheric properties. Potential exists for misidentification of radiometrically similar climate features. This is illustrated by the challenge of accurately differentiating snow versus cloud (both are cold and "bright"). Crucial algorithms for determination of snow cover and land surface temperature routinely employ cloud-masking approaches.

In other mountainous study areas, the systematic misidentification of snow as cloud in the transition zone between snow-covered and snow-free areas has been found to occur in earlier versions of the MODIS snow algorithm. The ground-based data available in the HKH generally do not allow assessment of whether such issues have been resolved in the current version of the algorithm. Independent of cloud-masking issues, the topography of the study area for mountainous regions may also affect accuracy of snow cover detection. In winter, large shadows resulting from low sun angles can also result in underdetection of snow in steep terrain.

6.8.2 Tropical Rainfall Monitoring Mission

The Tropical Rainfall Monitoring Mission (TRMM) satellite carries multiple sensors that serve the following functions:

- Precipitation rainfall radar, designed to provide three-dimensional maps of storm structure giving information on intensity and distribution of rainfall, rain type, storm depth, and height at which the snow melts into rain. It has a horizontal resolution at the ground of 5 km and a swath width of about 250 km;
- TRMM microwave imager (TMI), which is a passive microwave sensor designed to provide quantitative rainfall information over a wide swath by quantifying water vapor, cloud water, and rainfall intensity in the atmosphere. TMI supplements the similar special sensor microwave/imager (SSM/I), which has been operating since 1987;
- Visible and infrared scanner, which mainly uses the association between cloud top temperature and height and the occurrence of precipitation. Higher cloud tops are positively correlated with precipitation for convective clouds; and
- Lightning imaging sensor detects and locates lightning over the tropical region of the globe.

The TRMM high-resolution observations are very limited in observational frequency, with direct repeat observations only about twice per month. The TRMM specific observations, however, are merged with additional passive microwave observations from several other satellite-borne instruments (SSM/I, DMSP, AMSR-E, and AMSU-B, among others), as well as the near-continuous low-resolution infrared and thermal imagery from geostationary weather satellites. This multisensor composite can thus provide a balance between good spatial resolution and high frequency observation, although with substantial gaps in the spatiotemporal coverage of the higher-resolution data needed to calibrate the lower-resolution continuous imagery from the geostationary platforms. The TRMM 3B43v006 data product has provided a continuous time series of monthly estimated precipitation totals at 0.25 decimal degree horizontal resolution from January 1998.

The TRMM 3B42 data, while having a high temporal resolution, contain several artifacts and generally result in unreliable measurements in mountain ranges. However, attempts have been made to correct TRMM 3B42. Forsythe et al. (2011) had much stronger reservations about the accuracy of TRMM 3B42 rainfall for modeling flow in the upper Indus basin. They found, for example, that the TRMM catchment average accumulated precipitation over a period of years is only a fraction (40–60 percent) of the observed river discharge. However, this applied to seasonal snowmelt driven subcatchments (with little or no glacial contribution), where an explanation based on drawdown of glacial volume cannot be applied, and, therefore, the reliability of quantitative assessment of precipitation by TRMM 3B42 is questioned. They also found that TRMM precipitation estimates did not correspond well with ground-based data in terms of seasonality or orographic gradient.

TRMM way well provide reliable quantitative estimates of summer monsoon convective rainfall, but application to orographically enhanced winter snowfall from westerly systems may prove more problematic (Dinku et al. 2008). Comparisons to available local long-record observations of precipitation and river discharge data in the upper Indus suggest that the TRMM estimates provide a quantitative index of monthly precipitation rather than a measure of absolute magnitude. In this they are similar to the local long-record meteorological observations, which also do not directly represent catchmentwide precipitation but do correlate well as indicators of mass inputs for seasonal snowmelt-driven catchments.

6.8.3 Advanced Very High Resolution Radiometer

The Advanced Very High Resolution Radiometer (AVHRR) is a radiation detection imager that can be used for remotely determining cloud cover, surface temperature, and snow cover extent. The first AVHRR was a four-channel radiometer that was launched in 1978; the second (AVHRR/2), a five-channel instrument, was launched in June 1981. The latest instrument – version AVHRR/3, with six channels – was launched in May 1998. Although with more limited spectral resolution, this long record offers the potential to greatly increase the overlap of the spatial data products with local observations, thus refining quantification of relationships between them, and to extend the range of observations by MODIS to better capture present spatiotemporal climate variability.

6.9 DEMs and Geomorphometry

DEMs are digital representations of the Earth's surface. In glacier monitoring, they are required for image orthorectification and radiometric calibration, debris-covered glacier mapping, surface energy balance studies, glacier ice volume loss and mass balance estimates, glacier hypsometry, and ELA estimation. DEMs are generated from digitized topographic maps, satellite stereo-imagery (for example, ASTER, IRS, SPOT), and data derived from radar interferometry (for example, SRTM, TerraSAR-X) and laser altimetry (for example, light detection and ranging (LiDAR)). Unfortunately, no perfect DEM type for glacier mapping exists, because the different DEMs all have their advantages and disadvantages. Hence, the user must carefully select the DEM type with regard to the application.

DEM generation and analysis require a high degree of operator expertise. Digital terrain modeling is a complex process involving acquisition of source data, interpolation techniques, and surface modeling. In addition, quality control is necessary, including accuracy assessment (overall planimetric and vertical accuracy), data management, interpretation, and application (Quincey et al. 2013). Accurate glacier assessment using topographic information is frequently an issue of DEM quality and the methodology used in DEM generation. For example, a major difficulty in using digital photogrammetry to generate elevation data over glacier surfaces is that accurate DEMs can only be derived if the glacier surface shows sufficient texture to correlate image pairs; otherwise, grossly inaccurate elevation estimates develop over large expanses of bare ice or snow (Quincey et al. 2013). Without knowledge of the algorithms used to generate the DEM, an operator may accept such results as being reliable. Great care is required to ensure that the data selected for an application are appropriate, processing is carried out with a high level of expertise, and errors in any derived data are accurately reported, so that real geophysical patterns and features can be differentiated from image and processing artifacts (Quincey et al. 2013).

6.9.1 Source Data

Usually DEMs are generated from stereo airborne photographs or satellite images. While the former are not available for the entire HKH, the latter do cover the entire region. Such satellite imagery is collected by different sensors (for example, ASTER, Cartosat, SPOT) and, hence, is of different parameterization and quality. Most of the DEMs used for glacier monitoring represent elevation using a regular grid of constant spatial resolution. Gridded DEMs derived from satellite imagery are available at various scales, which affects their suitability for glacier monitoring. For example, medium-resolution (10–30 m) satellite sensors such as ASTER and European Remote Sensing (ERS) -1/2 cover a larger area but provide less topographic detail, while fine-resolution (less than 10 m) satellites such as SPOT-5, Quickbird, or GeoEye offer much more detail of a smaller area. Quincey et al. (2013) describe the advantages and disadvantages of square-gridded DEMs as follows:

They are directly comparable with remote sensing imagery of equal spatial resolution, simple to analyze statistically, computationally easy to represent and can be saved in a range of formats (for example, GeoTIFF, HDF). Conversely, they are poor at representing abrupt changes in elevation and heterogeneous topography, particularly at coarse resolutions, and can generate large file sizes at fine resolution, as well as having a large amount of data redundancy across flat areas.

ASTER DEMs of medium (30 m) spatial resolution can be relatively easily generated using various software packages or purchased at low costs from Land Processes Distributed Active Archive Center. Numerous studies have shown that ASTER DEMs are suitable in glacier studies, and the GLIMS project employs ASTER DEMs as the main elevation source. However, the production of "absolute" DEMs referenced to mean sea level requires ground control points (GCPs) that have been collected in the field or from other sources, such as orthorectified images or topographic maps.

In addition, other DEM sources come with some disadvantages. For example, while SPOT-derived DEMs produced good results in glacier studies, the high cost of the imagery limits its use over large areas, and the generation of CORONA-derived DEMs is relatively difficult due to complicated image geometry and flight parameters, especially in rugged terrain (Racoviteanu, Williams, and Barry 2008).

A good solution is the ASTER GDEM, the only DEM that covers the entire land surface of the Earth at a high resolution of 30 m. It was produced using the entire 1.5-million-scene ASTER archive acquired from the start of observation in 2000 in cooperation with the Japan-United States ASTER Science Team and it was released free of charge. ASTER GDEM was developed based on a grid of 1x1 degree of latitude and longitude and requires no scene selection or mosaicking. Its relatively high accuracy of 7–14 m is a result of extensive postprocessing that includes cloud masking to remove cloudy pixels, stacking all cloud-screened DEMs, removing residual bad values and outliers, averaging selected data to create final pixel values, and then correcting residual anomalies. While version 1, released in 2009, was an experimental stage and had residual anomalies and artifacts that affected the accuracy of the product and hindered effective utilization for certain applications, these errors have been eliminated in version 2.

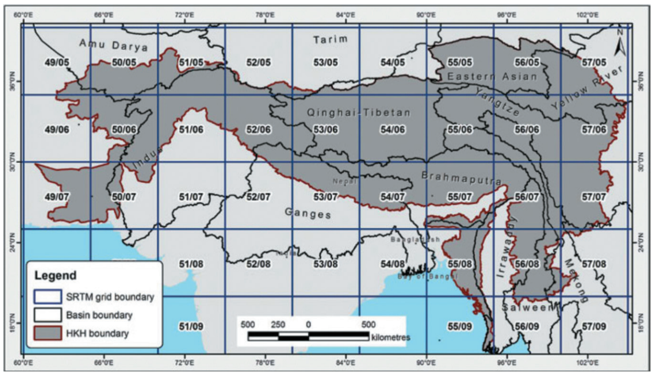
DEMs are also generated from synthetic aperture radar (SAR) satellite images from, for example, ERS-1/2, Radarsat-1/2, SRTM, TanDEM-X, and TerraSAR-X, and from LiDAR datasets from airborne sensors. However, most of these data have significant disadvantages that limit their suitability for glacier monitoring; for example, ERS satellites have large footprints in the range of kilometers, which is of no use for mapping relatively small Alpine glaciers.

SRTM provides near-global elevation data at 90 m spatial resolution and 10 m accuracy (Figure 6.11). However, despite some advantages, the slope-induced errors characteristic of InSAR data make SRTM unsuitable for glacier change detection at small timescales and over small glaciers (Racoviteanu, Williams, and Barry 2008). Furthermore, for the mid-latitudes and the outer tropics, SRTM's acquisition month overlapped with the accumulation season, resulting in possible overestimations of SRTM-derived elevations over glaciers (Racoviteanu, Williams, and Barry 2008). Bishop et al. (2008) noticed that SRTM data were greatly affected by shadows caused by high topographic relief. Despite these disadvantages, SRTM data-derived elevations are often used to fill gaps in DEMs generated from other sources, for example, ASTER. In such cases, postprocessing is necessary to smooth the transition between the original DEM and SRTM elevations. Furthermore, these merged DEMs must be used with caution, because the scale of topographic detail varies across the DEM.

TanDEM-X provides a global DEM to HRTI-3 specifications, that is, 12 m spatial resolution, less than 2 m relative vertical accuracy, and less than 10 m absolute vertical accuracy; studies on the use of TanDEM-X data in glacier monitoring have yet to be carried out. LiDAR DEMs are of high quality, allowing for detailed glacier analyses; however, procuring these DEMs can be expensive. ICESat's Geoscience Laser Altimeter System, a space-based LiDAR, has a smaller footprint of only 60 m but has been found useful only for evaluating other DEMs or to estimate glacier elevation changes when compared with other multitemporal elevation data (Quincey et al. 2013).

Comparative studies of DEMs from different sources demonstrate that some uncertainty still exists about the reliability of extracted elevations. For the Tien Shan at the border between Kazakhstan and Kyrgyzstan, Bolch, Kamp, and Olsenholler (2005) compared elevations from (a) the SRTM DEM and a DEM derived from contour lines (reference DEM); and (b) the SRTM DEM with an ASTER DEM, concluding that, for the former, the average difference between elevations was only about 6 m on average, while for the latter the difference was up to 100 m, particularly at southeast and north-to-northwest exposed steeper slopes. For Cerro Sillajhuay in the Andes at the border between Bolivia and Chile, an ASTER DEM was compared with a DEM from contour lines (reference DEM) and it was found that the ASTER DEM showed increasingly lower elevations with increasing elevation. For the Bernina Group in the Swiss Alps, a comparison of an ASTER DEM and an SRTM DEM with a DEM derived from contour lines (reference DEM) found that ASTER elevations were generally too high (8.3 m on average), and SRTM elevations were generally too low (–9.8 m on average). Berthier et al. (2007) compared SRTM DEM elevations with SPOT-5 DEM elevations for nonglaciated terrain in

Figure 6.11
SRTM Index Map for the HKH Region



Source: Bajracharya and Shrestha 2011.

the Khumbu Himalaya and found a mean difference of 0.43±16.7 m. Fujita et al. (2008) compared SRTM DEM elevations and ASTER DEM elevations with ground survey data in the Bhutan Himalaya and reported a mean elevation difference of 11.3 m for the SRTM DEMs and 11 m for the ASTER DEMs.

The GTOP30 DEM was developed from several raster and vector sources by the USGS and completed in 1996. While it offers global coverage, the horizontal resolution of approximately 1 km does not allow for any detailed glacier mapping, although it provides a useful overview of the study region and has been used to fill data gaps in other DEM datasets.

To overcome the problems regarding data gaps due to cloud cover or removed artifacts in some types of DEMs, data from different DEM types are usually merged. For example, in a first step, existing data gaps in a high-Z-resolution ASTER DEM are filled with data from a low-Z-resolution ASTER DEM; in a second step, remaining data gaps are filled with SRTM data; in a third step, still remaining data gaps are filled with data from the GTOPO30 DEM; the final step is a filtering for smoothing purposes. Although the final DEM includes different horizontal and vertical scales across the study area, it is useful for some applications.

For a proposed glacier monitoring program in the HKH region, gaining access to high-quality DEMs can be problematic. It is crucial that one single type of DEM is available across the whole area and that the data are of sufficient quality and of low cost or, even better, free of charge. These requirements limit the pool of potentially useful DEM sources for glacier monitoring of extensive areas. For example, for the politically sensitive HKH region, many border areas are not accessible to researchers for GCP collection in the field, and the quality of existing topographic map series is often not known. Therefore, at this point, ASTER GDEM and SRTM3 data provide the best (or only) available and least expensive sources. Although errors in ASTER-derived DEMs of steep, high-mountain relief sometimes produce artifacts in classification results, they still provide a quality of output that exceeds classification methods that do not employ a DEM of any sort (Quincey et al. 2013).

6.9.2 Error Calculation

In the DEM generation process, vertical (altimetric) or horizontal (planimetric) errors might be introduced. Planimetric errors result from horizontal shifts of elevation values to erroneous geographic coordinates and can be corrected by quantifying the orthophoto parallax followed by modeling, while altimetric errors are often systematic biases and might increase or decrease elevations in the DEM (Quincey et al. 2013). Knowledge about the planimetric and altimetric errors is of importance, because smaller changes in glacier margin position or glacier surface altitude by only some meters might be within the error and thus might not be detected or be only partly detected. This erroneous mapping could lead to incorrect calculations of, for example, glacier volume, mass balance, and meltwater discharge.

To derive elevation from the stereo images, photogrammetric techniques are employed using suitable imaging processing software. This process requires information about the geometry between the sensor and terrain at the time of image acquisition. After generation of ortho-images, the root mean square error (RMSE), which summarizes the residual values, is calculated. If the RMSE is within an acceptable limit, elevation information can then be extracted from the DEM. Quincey et al. (2013) put the maximum RMSE at two times the pixel size of the imagery. For ASTER DEMs, Lang and Welch (1999) suggested the RMSE should be ±7 to ±30 m. The RMSE has become the standard measure of DEM accuracy, although it does not very well describe the statistical distribution of the vertical error.

6.9.3 Ground Control Points

GCPs can be derived from traditional surveying or from global navigation satellite systems in combination with field receivers (differential and postprocessed), or they can come from identifying landscape features on topographic maps. GCPs are important for DEM quality assessment, as they give relatively accurate information on location and elevation of a landscape feature. Quincey et al. (2013) put the minimum accuracy of any ground control data at twice that of the expected DEM. Toutin (2008) showed that accuracy, number, and distribution of GCPs across the imagery can have a significant impact on DEM quality. It is difficult to give a minimum number of required GCPs; while more than the theoretically necessary four GCPs usually improves DEM quality, low-accuracy GCPs might actually produce low-quality DEMs (Quincey et al. 2013). If no GCPs are available at all, only relative DEMs may be produced.

6.9.4 Postprocessing

DEMs derived from contour maps and satellite data require the interpolation of (calculated) elevation values between (measured) elevation sample points. The interpolators most commonly used are inverse distance weighted (IDW), spline, triangular irregular network (TIN), and kriging. All of these come with advantages and disadvantages: IDW that strongly weights only a few sample points produces a rough surface; TINs often produce a typical “terracing” effect in valleys and on ridges; spline interpolators often produce overshoots (“holes” and “spikes”); and kriging requires experience when applying a semivariogram model (Quincey et al. 2013). For all interpolators, it seems to be the case in general that the smoother the terrain and wider the contour lines on related topographic maps, the lower the quality of the resulting DEM. Although it has been proposed to introduce breaklines in the generation of DEMs for relatively flat terrain, it seems that they do not significantly improve overall DEM quality (Quincey et al. 2013). A solution for relatively flat terrain could be to manually include additional contour lines derived from topographic maps or stereoscopic analysis of aerial photographs, but this editing is time consuming.

DEMs can include different types of errors, such as those that result from pixel matching, correlation failures, cloud cover, shadowing, and low image contrast over clean snow and ice, any of which can erroneously represent real position or elevation (Quincey et al. 2013). If this is the case, in a postprocessing step, manual editing or fusion of data from the originally generated DEM and data from other sources helps reduce the error. For example, artifacts in ASTER GDEM have been successfully filled with SRTM or GTOPO30 data. It is important to understand that this DEM fusion generates a DEM that includes varying spatial resolution or resampling, topographic detail, and accuracy within its grid. Such “corrected” DEMs are specifically problematic in multitemporal DEM analyses, for example, of changes in glacier surface elevation. Quincey et al. (2013) summarized systematic errors in SRTM data reported by a number of authors who found a nearly linear elevation bias for parts of the Alps, Patagonia, the Himalaya, and British Columbia, and reported regional patterns of the bias.

6.9.5 Software Packages

Several institutional, private, and commercial software packages are available for geospatial analyses involving DEM and satellite imagery. The most common software packages in use and currently available are as follows:

Satellite Imagery and DEMs

- **Geomatica OrthoEngine** of PCI Geomatics (www.pcigeomatics.com). Probably the most frequently used software for DEM generation. Horizontal and vertical accuracy of ±15 me and ±20 m (1 σ), respectively. Postprocessing tool for manual editing. Tools can also be incorporated into ESRI ArcGIS. Windows and Linux operating systems. *License costs:* Contact PCI Geomatics customer service for current pricing;.
- **LPS Core** of ERDAS (www.erdas.com). Provides the most comprehensive control over the DEM extraction and editing process. Postprocessing tool for manual editing. Tools can also be incorporated into ESRI ArcGIS. Windows operating system. *License costs:* US$2,800;
- **ENVI DEM Extraction Module** (http://www.exelisvis.com). Accuracy of better than ±20 m for relative DEMs, and for absolute DEMs ±30 horizontal and ±15 m vertical. Postprocessing tool for manual editing. Tools can also be incorporated into ESRI ArcGIS. Windows, Macintosh, and Unix operating systems. *License costs:* about US$3,500;
- **Desktop Mapping System Softcopy**, Version 5.0. Horizontal and vertical accuracy of ±15 m to ±25 m (1 σ). Windows operating system. *License costs:* about US$6,000; and
- **Silcast** of Sensor Information Laboratory Corp., Japan (www.silc.co.jp). Exclusively developed for ASTER DEM generation. Written in IDLR6.1; can be executed with IDL VM without IDL license. Does not accept GCPs. Automatic postprocessing of errors without any operator control. Was used for generation of global (up to 83° latitude) GDEM with 30 m x 30 m ground resolution with ±7 m accuracy (1 σ). Windows, Macintosh, and Linux operating systems. *License costs:* about US$4,500/license noncommercial mode.

Satellite Imagery, DEMs, and GIS

- **ESRI ArcGIS** (www.esri.com/software/arcgis/index.html). ESRI has become the leader with regards to GIS software. Its latest version (ArcGIS 10) includes spatial analysis, data management, mapping, visualization, and advanced imagery processing capabilities. Field capabilities are available through ArcGIS Mobile. Windows operating system. *License costs:* about US$1,500–7,000 depending on license level;
- **IDRISI** (www.clarklabs.org). An integrated raster-based GIS software with nearly 300 modules for the analysis and display of digital spatial information. Windows operating system. License costs: US$1,750 floating license (single user at one time), US$1,250 new single license, US$425 upgrade license;
- **GRASS** (grass.osgeo.org). Originally developed by the United States Army Construction Engineering Research Laboratory in the 1980s, this GIS software is used for geospatial data management and analysis, including image processing, geospatial modeling, and visualization. The software is supported by the Open Source Geospatial Foundation. Windows, Macintosh, and Linux operating systems. *License costs:* Open source;
- **OSSIM** (www.ossim.org). Provides advanced geospatial image processing and GIS capabilities. Has been under development since 1996 and has continued support from the open source software development community. Windows, Macintosh, and Linux operating systems. License costs: Open source;
- **QuantumGIS** (www.qgis.org). User-friendly GIS software licensed under the GNU General Public License and official project of the Open Source Geospatial Foundation. Supports numerous vector, raster, and database formats. Capable of performing terrain analysis, hydrological modeling, and additional analysis through an extensible plug-in architecture. Windows, Macintosh, and Linux operating systems. *License costs:* Open source;
- **SAGA GIS** (www.saga-gis.org). Designed for easy implementation of spatial algorithms and geospatial methods to analyze vector and raster datasets through an easily approachable interface. Developed by the Department of Physical Geography, Göttingen University. Windows and Linux operating systems. *License costs:* Open source; and
- **gvSIG** (www.gvsig.org). Desktop GIS application used for capturing, storing, and analyzing any kind of geographic information. Several features available for the analysis of vector and raster remote sensing data. Licensed under the GNU General Public License and available in several different languages. Windows, Macintosh, and Linux operating systems. *License costs:* Open source.

6.10 DEM Analysis

6.10.1 Geomorphometry

Geomorphometry – the science of quantitative land surface analysis – draws from mathematics, computer science, and geosciences (Pike 1995, 2000). The field of geomorphometry has two modes of study: the study of individual or specific landforms and features (such as glaciers), and the study of the general land surface or region, such as the Himalaya (Evans 1972). Glacier mapping usually includes the geomorphometric analysis of the glacier surface, and most software packages have tools for such geomorphometric analysis. However, as much as geomorphometric parameters help in identifying, describing, and classifying glaciers, their quality depends on the accuracy of the input DEM, and studies have shown that, for many applications, increased DEM resolution only introduces disruptive noise (Quincey et al. 2013). In general, it is essential that systematic biases are removed prior to the geomorphometric analysis.

6.10.2 Land Surface Parameters

Most glacier monitoring approaches include the analysis of primary (first-order derivates of an elevation field) and secondary (second-order derivates of an elevation field) land surface parameters. The most common primary land surface parameters are slope angle, aspect, and hypsometry; the most common secondary parameters are planimetric curvature and vertical curvature, which both describe shape (Kamp, Bolch, and Olsenholler 2003). By clustering surfaces with similar curvature characteristics, it is possible to differentiate between glacier surfaces and valley bottoms (low convexity), ridges and lateral moraines (high convexity), medial moraines (moderate convexity), and the transitions between glacier margins and lateral moraines (high concavity) (Quincey et al. 2013). Since the glacier surface topography changes with time because of glacier movement, mass balance changes, or other factors, so do the geomorphometric parameters. Hence, the description of the latter in multitemporal glacier analysis can provide information about glacial changes. For example, an increasing steepness at the glacier margin over years might reflect a glacier advance. A simple but effective method to describe glacier surface elevation changes is to compare the topographic profiles along the flow line of the glacier from multitemporal DEMs (Quincey et al. 2013). When DEMs are combined with complementary GIS data such as land cover classifications, and neighborhood and change detection analyses, slope angle data can be used as the primary morphological characteristic to delineate glacial terrain. However, specific slope thresholds vary from region to region, with ice masses in the European Alps generally characterized by short, steep tongues relative to the long (greater than 10 km), flat tongues of some glaciers in the Himalaya (Quincey et al. 2013).

Increasingly, automated and semiautomated glacier mapping approaches also include the analysis of the hierarchical organization of topography and aim to characterize individual geomorphic features of the glacial system, such as lateral moraines, crevasses, or icefalls, based on their shape and textural properties (Quincey et al. 2013). Two of the available methods are variogram and fractal dimension analyses. The former has been used to characterize terrain morphological features and to calibrate secondary morphological indices, while the latter helps to improve landform classification accuracy and to explain operational-scale and process–structure relationships (Quincey et al. 2013).

6.10.3 Topographic Radiation Modeling

Glacier monitoring increasingly includes the modeling of solar radiation variation across the study area. Surface orientation and shadowing are important parameters that can easily be calculated using a DEM employing standard software packages; surface irradiance and ablation gradient calculations are input parameters for energy balance melt models that are fundamental to understanding the relationship between glacier behavior and climate (Quincey et al. 2013). Fine-resolution modeling has been used to calculate melt rates of snow and ice; however, accurate field and meteorological data are required.

6.10.4 Altitudinal Functions

Elevation is one of the most important factors responsible for variations in glacier characteristics, and the most fundamental altitude is the ELA that separates ablation and accumulation areas of the glacier. In glacier monitoring, it is usually assumed that the ELA is equal to the snowline position at the end of the melting season (Quincey et al. 2013). One simple method to extract the ELA using DEM elevation values is the toe-to-summit method (Benn and Lehmkuhl 2000), which can be performed efficiently, especially with well-defined valley glaciers. ELA calculations are fundamental for estimating the mass balance of a glacier and, thus, serve as indicators for climate variations.

The area–altitude profile (hypsometric curve) and the altitude–slope function (clinometry) help in describing erosion rates and mass balance fluctuations within a glacial system (Quincey et al. 2013). Differential erosion occurs with altitude, and studies have shown that glaciation produces the greatest mesoscale relief at high altitudes, while warm-based glaciation reduces relief at intermediate altitudes (Bishop et al. 2001). Altitude–velocity profiles are used in mass balance calculations and glacier flow regimes.

6.11 Summary

6.11.1 Satellite Imagery

Despite the great variety of available satellite imagery – including at large-scale resolution – in their review of the use of optical remote sensing in glacier characterization, Racoviteanu, Williams, and Barry (2008) concluded that medium-scale (10–90 m) resolution optical sensors in multispectral mode, with relatively large swath widths and short revisit cycles, are useful for regular glacier mapping over extensive areas, and that ASTER may still be the most suitable sensor for glacier monitoring that includes mass balance applications. Authors of this study support that view and suggest that Landsat and ASTER are probably the most useful sensors for a proposed glacier monitoring program in the HKH region.

However, sensors operating in the visible and near IR (VNIR) ranges, such as Landsat, ASTER, and ALOS, are limited to daylight and cloud-free conditions, which are difficult to obtain in the HKH region (Racoviteanu, Williams, and Barry 2008). Although synthetic aperture radar is efficient at night and in cloudy conditions, the authors caution that:

> [T]he severe geometric and radiometric distortions and speckle ("noise") require complicated processing and accurate digital elevation models (DEMs), which are not always readily available. Other techniques such as passive microwave systems, radar, and laser altimetry show promise for increasing our understanding of glacier characteristics in the Himalayas.

For a proposed institutionalized glacier monitoring program that covers the entire HKH region, it is crucial to keep the costs of source data as low as possible. Thus, it is easier to make use of existing and free available datasets for regionwide monitoring, and then purchase satellite imaging and DEM data for monitoring the glaciers of specific interest, for example, identified benchmark glaciers or glaciers that represent a potential hazard. At this time, imagery from Landsat and ASTER has some important advantages: it covers the entire HKH region; it comes at low cost or even no cost; it has sufficient spatial resolution for most relevant glacier analyses; it has extensive experience in its application in glacier studies, with existing results; and ASTER data are also used for the generation of the ASTER GDEM.

6.11.2 DEMs

After reviewing existing studies, particularly the review by Quincey et al. (2013), authors of this study conclude that, today, DEMs are fundamental and a standard tool in any glacier monitoring project. Square-gridded DEMs are most widely used, because they provide more realistic terrain representations than DEMs derived from other data sources. In particular, ASTER remains the most widely used data source for DEM generation because of its stereoscopic capability, wide spectral range, medium-to-fine spatial resolution, and, importantly, its low cost (Quincey et al. 2013). For many regions with glaciers, ASTER DEMs come with an accuracy of ±15–30 m after some significant postprocessing. However, in areas with steep rock headwalls and large, low-contrast accumulation areas, the accuracy is often only ±60 m.

At the same time, DEMs are far from perfect. Examples of the many drawbacks that still exist are found in the literature (Evans 1972; Kamp, Bolch, and Olsenholler 2003; Pike, Evans, and Hengl 2009; Quincey et al. 2013), and the following are typical:

- It is not easy to detect abrupt changes in topography;
- Producing fine-resolution DEMs with low data storage requirements is difficult;
- It is also difficult to generate reliable elevation data at any resolution finer than that offered by SRTM (90 m) for many regions;
- Persistent cloud cover affects optical sensors, particularly in mountain regions;
- Lack of ground control data, particularly in areas of political sensitivity and rugged terrain, makes it difficult to verify results;
- Inconsistencies occur between studies in the manner in which errors are reported. A limited number do not even quantify the expected error (or uncertainty) in the presented data, and, of those that do, the accuracy data can sometimes be highly dependent on the number and positioning of chosen checkpoints. This makes it difficult for an independent researcher to replicate results, or even establish the exact error quantification that has taken place and how reliable it is;
- The interaction between topography and most geophysical processes occurs over a range of spatial scales, which cannot currently be truly represented in DEM data. Therefore, while the resolution of the generated DEM is limited by the resolution of the input source data, those making scientific interpretations should also be mindful to restrict analyses to the natural scale of the terrain-dependent application;
- As a guide, the resolution of the derived DEM can provide a practical indication of the scale of information content; analyses of processes or features that occur on a finer scale than this should be made with caution;
- Currently, scientists employ a range of analytical tools, algorithms, processing approaches, and software for the generation, manipulation, and interpretation of topographic data. Methods are highly empirical, thus the type and quality of the derived data are dependent, to a large extent, on the analyst. Consequently, the replication of existing results can be difficult; even more so the application of one published technique to a new area; and
- Finally, challenges remain in identifying and quantifying altimetric errors, particularly when comparing DEMs from different sources, and in simply gaining access to reliable data for some of the most politically sensitive regions of the world.

Several methods have been prescribed by Quincey et al. (2013) to correct for the limitations on achieving optimum results that are present with all current DEMs:

- Longer observational periods to detect magnitudes of change in multitemporal studies;
- Adhering to the limitations of resolution in the scale of the information and terrain-dependent applications; and
- Developing standards and protocols for information extraction and integration in order to maintain data quality and accuracy across different study areas and research efforts.

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7. Monitoring of the HKH Cryosphere

If it is to be successful, cryosphere monitoring in the HKH Mountains must be developed as a broad program, involving institutional collaboration, staff training, instrument network development, coordination of monitoring methodologies and procedures, and competent management and oversight. The Integrated Global Observing Strategy (IGOS) cryosphere theme serves as a useful guide in meeting these requirements. IGOS unites the major satellite and ground-based systems for global environmental observations of the atmosphere, oceans and land in a framework that delivers maximum benefit and effectiveness in their final use. It is a strategic planning process, involving many partners, that links research and operational programs as well as data producers and users. IGOS has compiled the experiences of high-mountain monitoring programs and has produced lessons learned and recommendations that are now integrated in the follow-up Global Cryosphere Watch program. This chapter will summarize these observations on snow and glacier issues. The recommendations made here will build on the experience of past programs, look at future requirements, and work on the basis of well-known, robust, and reliable technologies and procedures

7.1 Considerations and Technical Procedures for HKH Monitoring

In addition to the physical challenges of remoteness, altitude, terrain, and temperature, the challenges of carrying out monitoring of glaciers climate and runoff in very high mountains, especially in the HKH region, include insufficient funding of continued, long-term observation programs, weak institutions, and the difficulty of regularly sending government officials to remote, high-mountain regions on missions that often last several weeks. Also, civil service rules in the countries of the HKH Mountains considered here make no special provisions for extra allowances that would make it attractive to staff to work under harsh conditions.

Institutional approaches for HKH monitoring are as follows:

- Monitoring through institutionalized government authorities and procedures with a long-term perspective and through dedicated units anchored in the responsible institutions;
- Monitoring through indigenous and foreign research programs on a longer-term basis at well-established sites;
- Monitoring through nongovernmental organizations, or even local companies, that execute monitoring tasks under well-defined framework conditions. If governments were to outsource monitoring to private entities, the advantage would be that payments are then made independently of government rules that apply to civil servants; and
- Periodic research expeditions similar to the Japan Glaciological Expedition to Nepal, which collected over 15 years of data and observations, could offer an opportunity complementary to institutionalized monitoring activities. These would be complementary because local governments, thus far, have not been prepared to take up monitoring at the end of a project, either in terms of cost or expertise.

Depending on local conditions, logistic arrangements are made by the executing entity or with the assistance of a well-established trekking agency as a partner. Finding human resources (for example, porters) for logistic support has recently become difficult and more expensive, at least for the conditions in Nepal, as younger people migrate out of the country in large numbers for better job opportunities.

7.2 Selection of Monitoring Sites and Logistical Considerations

Monitoring sites should meet the following technical and organizational criteria:

- Sites should be representative of the phenomena to be monitored;
- Existing sites should be refurbished or upgraded to a working condition to allow continuity of earlier data collection programs;
- Sites should be accessible for as long as possible throughout the year;
- En route support from local villages should be available; and
- Establishment of telecommunication links should be possible.

Local observers should be available close to the site to keep equipment in repair and guard against vandalism, and have access to station houses set up with essential supplies and spare parts.

In general, field visits and station maintenance need to be undertaken using local facilities. For cost-effectiveness and sustainability of the installed infrastructure, it is not advisable to leave all observations, maintenance, and station surveillance to office staff back in the city; rather, this effort should be delegated as much as possible to locally available staff, who may take great pride in performing these works if their services are adequately recognized and rewarded.

For example, after a project ends, using helicopters for supplying stations is not usually affordable for a government organization or any other locally operating entity. Thus monitoring programs need local, well-trained technical personnel to reduce travel and mission costs and time lags in reaching a station after a problem has occurred. This is technically feasible through adequate capacity-building programs that enable local personnel to perform essential technical functions based on well-defined, station-specific, standing operating procedures.

7.3 Practical Procedures for Monitoring the HKH Cryosphere

7.3.1 Guiding Principles

Recommended guiding principles for establishing a cryosphere monitoring network in the HKH are as follows:

- Adopt Global Climate Observing System (GCOS) monitoring principles for all operational satellites and in situ sites; and
- Observations should follow, to the extent possible, the well-established Global Hierarchical Observing Strategy that has been developed by the Global Terrestrial Observing System, and which is a standard applied by the World Glacier Monitoring Service.

7.3.2 Essential Variables

Essential (climate-sensitive) variables, as defined by GCOS, that should be observed in a monitoring program include the following hydrometeorological variables:

- Solid precipitation: In situ climate and synoptic (manual, auto), remote sensing;
- Snow: Snow water equivalent, depth, extent, density, snowfall, albedo, in situ climate and synoptic (manual, auto), remote sensing;
- Glaciers: Mass balance (accumulation/ ablation), thickness, area, length, (geometry), firn temperature;
- Snowline/equilibrium line: Snow on ice, ground based (in situ), remote sensing;
- Frozen ground/permafrost: Soil temperature/ thermal state, active layer thickness, borehole temperature, extent; and
- Snow cover: In situ (manual, auto), remote sensing.

In addition, the following factors need to be measured on a regular basis:

- Temperature;
- Wind;
- Radiation;
- Humidity;
- Stream flow;
- Observation of glacier ablation;
- Monitoring glacier lake changes;
- Monitoring of glacier tongue changes;
- Mass balance studies (as snapshots perhaps and not continuously);
- Glacier varve observations and sedimentation observations in glacier lakes and moraines; and
- Snow cover and seasonal changes, snow depth and water equivalent.

Note that observations of hydrological factors, the foremost of which is streamflow, are essential in the monitoring and evaluation of snow and glacier melt runoff characteristics and trends. More than any other variable, streamflow observations provide an insight into hydrological processes in glacierized or largely (seasonal) snow-covered basins.

7.3.3 Requirements Document

Development of core information:

- Description of core variables to be observed;
- Minimum density of networks for terrestrial observations;
- Minimum requirements for space-based observations, including repetition frequencies, ground resolution, and observation paths;
- Preferred methods of observations (for terrestrial and space-based observations);
- Error bandwidth of observations, achievable levels of accuracy of observations;
- Spatial and time resolution;
- Reporting frequency;
- Quality assurance procedures;
- Minimum technical qualifications of staff performing the observations;
- Required capacity-building programs; and
- For field visits and on-site explorations, required field equipment and gear, and minimum required logistic preparations.

7.3.4 Components of a Cryosphere Monitoring Network

Network components could include dedicated snow and glacier hydrology stations at high altitudes, with preference to the rehabilitation or refurbishing of older existing stations with station records, and establishment of potentially new stations at high altitudes (above 3,500 m) in glacierized basins. In addition, multi-tiered observation and monitoring networks could include the following elements:

- Terrestrial observations, including specialized networks, existing synoptic and hydrological stations, and stations of the GCOS (terrestrial and upper air observations), and stations affiliated to the WMO Global Telecommunication System;
- Space-based observations;
- Observations from core network stations in discrete time intervals (near real time, for example);
- Observations from complementary networks, including research stations; and
- Snapshot-type observing campaigns, regularly scheduled (every six months, once a year), such as those in place for glacier mass balance observations.

7.3.5 Historical Data Records

A necessary activity is recovery and processing of long time series archived data relevant to the development and construction of cryospheric fundamental climate data records. This includes the documentation of glacier inventories in the countries and in relevant centers.

Likewise, it would be useful to detect old records and undertake data rescue activities as an important part of a monitoring program, as these records constitute the “climate memory” of hydrometeorological and cryospheric processes.

7.3.6 Telecommunications

Priority should be given to the utilization of existing telecommunication facilities, such as code division multiple access (CDMA) protocols, general packet radio service (GPRS) (a mobile phone standard communication protocol), and high frequency (HF) radios in Nepal; HF in Bhutan, with GPRS expanding rapidly; and GPRS, HF radios, and, to some extent, meteor burst communication in Pakistan. Conditions in India vary, with HF radios in place and transition occurring to GPRS communication and satellite communication facilities. While these technologies have been established, are robust, and are reasonably reliable, and are supplied by commercial providers in all countries, the costs of these services (that is, prepaid mobile services) are an issue, especially when dues are not paid in time or SIM cards are not electronically recharged, or budget lines have not been established to ensure continued payments and thus reliable service and maintenance (for example, if a server breaks down). The use of dedicated satellite connections, such as through Inmarsat, needs to be carefully considered because of the high operation costs. Access to and use of data from the WMO Global Telecommunication System are encouraged and can be achieved through the national meteorological services. Global data streams from satellite operations can be acquired, but based on the availability of broadband connections, may have limitations in use.

7.4 Data Management

Only main guiding principles are outlined here, as the field of data management is very wide. However, these principles must be specific under well-defined conditions in the operational planning and implementation phase of the monitoring program. In general, data lose their value if they are not managed in a transparent, replicable manner; it must be ensured that data management systems are built on established principles of data quality control and the interoperability of different data management systems in different countries and institutions. The WMO Information System provides detailed guidance and information in this regard.

7.4.1 Access to Data and Information

As has been learned in past projects and programs, an agreed data policy needs to be developed, covering the different data streams the program will monitor from a multitude of sources, though mostly from national sources (such as national hydrometeorological networks).

The guiding principles for data collection and management are as follows:

- There should be equal, nonhierarchical access to all project or program data by all partners;
- Data providers are the custodians of the data they generate and continue to be the owners of these data, even if they are pooled or aggregated in program-related databases and data management systems;
- Selected data are published for the general public in a fashion agreed to by program partners along the lines of WMO Resolution 40 (on access to meteorological data) and WMO Resolution 25 (on access to hydrological data);
- Data from research projects that are partners in the program can be utilized by partners as they become available and, in the interest of researchers, are made public at the latest two years after generation of the data; and
- All data have to undergo a rigid data quality control procedure that has to be designed and implemented.

7.4.2 Metadata

A web-based metadata catalog must be established to ensure accessibility to data generated, including critical information concerning the physical properties of observations and related data, data sources and dates, an indication of the quality of the data, information on the source and format of the data, and conditions for acquiring the data.

All metadata must conform to the ISO 19115 standard for geographic metadata, and to the WMO Core Metadata Profile, allowing metadata to be easily updated from all data centers or data services of partners in the context of the program.

7.4.3 Database Management Systems

The development and establishment of a uniform data management architecture does not seem realistic, as national entities or organizations already have well-established systems in place. However, links have to be developed that allow the interoperability of different data sources and centers, including the management of (near) real-time data with a central program database that preferably should be established in a dedicated regional center or regional centers of excellence for the purpose of the program. Components of the overall data management system must include the following:

- Data archives for physical observations in (near) real time;
- Data archives for physical observations, quality controlled;
- Data archives for physical time series observations;
- Data archives for related observations, including image archives;
- Libraries for observation campaigns, such as for glacier mass balance studies;
- Libraries for literature, meeting reports, contact partners;
- Product archives, including for visualized products and model results;
- Management of real-time data; and
- Dedicated data quality assurance control protocols and quality control reports.

7.4.4 Data Integration and Management

With data from a multitude of networks, a data management scheme needs to be defined. A major outcome of the program should be the establishment and operation of a cryosphere integrated data and information service. Recent land data assimilation technologies provide an integrated approach to generating spatial and temporal consistent datasets of snow, glaciers, hydrology, frozen soil, and other cryospheric (and related land surface) variables.

Consequently, there is the need to develop integrated, operational analysis products based on cryospheric data assimilation, models, satellite-generated data, and in situ data, and to develop requirement-oriented, operational cryospheric forecasting capability. For example, the World Data Center for Glaciology and Geocryology in Lanzhou, China, has developed a land data assimilation system that can assimilate remote sensing observations into land surface models and then produce reanalyzed cryospheric datasets with high spatial (0.25 degrees) and temporal (one hour) resolutions.

To make the products interoperable under different institutional and country settings, standard data formats and protocols must be established for distributed (Web-based) data visualization services.

A wide range of relevant approaches to the use of models to generate advanced data products as well as publications are available (for example, Schaefli and Huss 2011) that use specific hydrological modeling approaches coupled with glacier mass balances. From a strategic viewpoint, it would be advantageous to assimilate cryospheric products in next-generation global circulation models, medium-range, seasonal, and interannual forecasting, and climate models. From an applications viewpoint, it will be necessary to develop interannual forecasting capabilities for snow and glacier dynamics, including mass balance changes. However, modeling aspects must be considered in a separate study when discussing the generation of user-oriented products from the observation networks.

7.4.5 Data Management and Reanalysis

Reanalysis of past cryosphere data presents a clear picture of past conditions, independent of the many varieties of instruments used to take measurements over the years. Through a variety of methods, observations from various instruments are added together onto a regularly spaced grid of data. Placing all instrument observations onto a regularly spaced grid makes comparing the actual observations with other gridded datasets easier. In addition to putting observations onto a grid, reanalysis also holds the gridding model constant—it doesn't change the programming, keeping the historical record uninfluenced by artificial factors. Reanalysis gives a level playing field for all instruments throughout the historical record. It also:

- Promotes detailed validation of reanalysis projects for cold climates and cryosphere-related elements;
- Promotes the use of reanalysis as a monitoring tool;
- Evaluates the maturity of new data products that can be assimilated by models or used for model verification;
- Promotes the further development of data assimilation schemes and objective analyses for cryospheric variables, together with a thorough treatment of error covariances;
- Establishes appropriate dynamical downscaling techniques of reanalysis of data to facilitate their use in cryospheric impact models that operate in high-mountain terrain at about 10–100 m spatial resolution or better;
- Facilitates the development of a climate system reanalysis with inclusion of cryospheric components;
- Improves the utilization of satellite data in automated analyses and incorporate fractional ice cover and ice dynamics in global circulation models.
- Investigates indirect methods of combining multiple remote sensing products and physically based models to infer ice thickness; and
- Improves algorithms for estimating global sea ice concentrations from passive microwave sensors by using data assimilation techniques, and compare results with those from sensors with a higher spatial resolution.

7.4.6 Development of Analysis and Forecast Procedures

Development of complex, model-based analyses and forecasts will certainly take time and staff with sufficient scientific and practical operations background. Following a pragmatic approach, it is recommended to first develop a suite of initial procedures that build on quality-checked observations. The following provides a first list of recommended procedures for a variety of uses and general information in the educated public domain:

- Time series and analysis of observations with recurrence periods and associated probabilities of exceedance and threshold values, for example, for established warning levels;
- Analysis of current observations and projections (perhaps on a seasonal basis) in the context of historical seasons; and
- Use of proxy observations at lower altitudes to deduce hydrometeorological and glaciological processes at higher elevations based on simple regression models where this is appropriate.

7.5 Institutional Setup and Organization

The underlying assumption for the institutional setup and governance of any envisaged program activities in a monitoring program is that its implementation and day-to-day management would be facilitated through a regional institution such as ICIMOD or another dedicated center of excellence in one of the participating countries. Preferably, this would be a national hydrometeorological service that is also mandated to undertake, on a routine basis, snow and glacier observations. Because university staff have a much higher level of fluctuation, it is advisable that higher education institutions be included as support partners in underpinning the science of program activities rather than as day-to-day implementing partners. Universities would also be useful in helping to conduct glaciological measuring activities in the context of the program and in the configuration of data and information products generated from observational data.

To ensure broad-based governmental support, it is also essential, right from the start, during country consultations to obtain backup from relevant ministries and their line agencies, particularly as products will be generated on the basis of a sustained demand for specific products from these line agencies.

The program consortium should comprise the following participants:

- Core consortium, including those national services that contribute the majority of the data required for the program;
- Partners that contribute to the program with complementary data and information;
- Research partners and those organizations and individuals that execute field expeditions, including periodic observation campaigns;
- Partners that contribute through the generation of products and services;
- Donors and representatives of the hosting organizations; and
- Invited experts and observers on an ad hoc basis.

The full group of partners should meet initially for the program commencement and, thereafter, periodically, especially when major program milestones have been achieved and consensus needs to be reached about follow-up program phases (as an indication: every 20 months). However, the group would be too large to effectively manage the program. This requires a dedicated group that provides the governance of the program. Thus members of this group should be as follows:

- Identified national focal points;
- International organizations;
- Donors and representatives of the hosting regional organization; and
- Invited experts on an ad hoc basis.

Financial oversight, as well as a technical and scientific monitoring and evaluation, is also provided within this group, essentially a program steering committee. Meeting frequency of this group could be twice a year. Day-to-day execution of the program is ensured through a management unit housed within the principal regional organization, which would include the following personnel:

- Scientific officer;
- Technical officer;
- Asset management officer;
- Financial controller; and
- Administrative support (secretary).

7.6 Cryosphere Monitoring Program Components

With a view to ensuring sustained program services, a long-duration program is envisaged. A reasonable cost estimate cannot be made at this time and needs to be discussed in light of more advanced program planning and approaches for the implementation of the project. It is envisaged that the program will involve the following components:

- Expert services;
- Financial support to national executing institutions;
- Financial support of implementing regional center with its project management unit;
- Capital investments (instruments);
- Capital investments (spare parts);
- Capital investments (civil works at stations);
- Communication (satellite observations, telecommunication, data streams in general);
- Routine field observations (visits to stations);
- Dedicated expedition-like observation campaigns (such as glacier mass balance studies);
- Capacity-building activities at national and regional levels;
- Study tours;
- Project coordination (for example, through steering committee meetings);
- Project planning, country consultations, overall

project coordination at donor level with main implementing organizations; and
- Contingencies and holdback for unrealized currency exchange losses and gains.

An in-kind contribution from national governments and partners in the order of an additional 30–40 percent of the estimated cost of the project seems reasonable. A key indicator for project sustainability would be the demonstration of by-the-year increasing budgets for national partners to counterbalance project implementation costs, which ideally should reach 100 percent by the time the project is completed within the funding cycle.

7.7 IGOS Monitoring Principles

- The impact of new systems or changes to existing systems should be assessed prior to implementation;
- A suitable period of overlap for new and old observing systems is required;
- The details and history of local conditions, instruments, operating procedures, data processing algorithms, and other factors pertinent to interpreting data (that is, metadata) should be documented and treated with the same care as the data themselves;
- The quality and homogeneity of data should be regularly assessed as a part of routine operations;
- Consideration of the needs for environmental and climate-monitoring products and assessments, such as IPCC assessments, should be integrated into national, regional and global observing priorities;
- Operation of historically-uninterrupted stations and observing systems should be maintained;
- High priority for additional observations should be focused on data-poor regions, poorly observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution;
- Long-term requirements, including appropriate sampling frequencies, should be specified to network designers, operators and instrument engineers at the outset of system design and implementation;
- The conversion of research observing systems to long-term operations in a carefully-planned manner should be promoted; and
- Data management systems that facilitate access, use and interpretation of data and products should be included as essential elements of climate monitoring systems.

Furthermore, operators of satellite systems for monitoring climate need to:

- Take steps to make radiance calibration, calibration-monitoring and satellite-to-satellite cross-calibration of the full operational constellation a part of the operational satellite system; and
- Take steps to sample the Earth system in such a way that climate-relevant (diurnal, seasonal, and long-term inter-annual) changes can be resolved.

Thus satellite systems for climate monitoring should adhere to the following specific principles:

- Constant sampling within the diurnal cycle (minimizing the effects of orbital decay and orbit drift) should be maintained;
- A suitable period of overlap for new and old satellite systems should be ensured for a period adequate to determine inter-satellite biases and maintain the homogeneity and consistency of time-series observations;
- Continuity of satellite measurements (for example, elimination of gaps in the long-term record) through appropriate launch and orbital strategies should be ensured;
- Rigorous pre-launch instrument characterization and calibration, including radiance confirmation against an international radiance scale provided by a national metrology institute, should be ensured;
- On-board calibration adequate for climate system observations should be ensured and associated instrument characteristics monitored;

- Operational production of priority climate products should be sustained and peer-reviewed new products should be introduced as appropriate;
- Data systems needed to facilitate user access to climate products, metadata and raw data, including key data for delayed-mode analysis, should be established and maintained;
- Use of functioning baseline instruments that meet the calibration and stability requirements stated above should be maintained for as long as possible, even when these exist on decommissioned satellites;
- Complementary in situ baseline observations for satellite measurements should be maintained through appropriate activities and cooperation; and
- Random errors and time-dependent biases in satellite observations and derived products should be identified.

7.8 General Considerations

7.8.1 Costs of Field Trips

These are highly variable from country to country and by location, and need to be assessed during country consultations. The duration of the visit includes access by car or plane to the nearest accessible point, then walking with porters.

- Expedition-style campaigns, for example, for the purpose of process studies or full-scale assessment of local meteorological, hydrological, and glaciological conditions, need to be costed separately. Also, the costs of establishing a new station (including civil works) need to be estimated, including the following items:
  - Duration of establishment: Four weeks for station house and station;
  - Construction costs: Building materials, porters, labor, food on site;
  - Maintenance requirements: As per manufacturer's specifications, mostly performed during regular visits to the stations, which should occur three times a year, pragmatically. Typical maintenance jobs are cleaning, recalibration (on site), painting, dehumidifying, changing batteries, replacing consumables, checking functionality, and retrieving backup data from loggers;
  - Maintenance costs: Generally, 25–35 percent of the capital investment in instruments over the standing time of the instruments, which is in the order of 8–10 years before replacement is necessary. Some instruments last longer, depending on the manufacturer and operating conditions; and
  - Emergency contingency to cover loss of sensors, destruction of stations (for example due to flood or avalanche): In the order of 10 percent of the capital investment costs.

7.8.2 Selection of Location

As the network will continue to be sparse in such high-altitude environments, the key criteria for the selection of locations are:

- Stations are situated in glacierized basins;
- Altitudes are above 3,500 m;
- Station location is representative of a larger area or comparable to other stations in similar altitudes; no stations are placed in locations with a specific microclimate that bears no similarity to other station locations;
- Locations are preferably in the glacierized headwaters of streams that have importance for water management (for example, hydropower, irrigation, water supply);
- Local observers can be found, which may require the establishment of solid station houses where the observer can stay. They may then be allowed to run the station house as a small lodge for tourists in order to earn some extra income to maintain the house and to act as an incentive for the observers to stay there;
- Stations have year-round accessibility, with the exception of glacier stations that work as satellites to the main stations; and
- Telecommunication (GPRS, GSM, HF radio) is possible.

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