CHAPTER 3

# Hydrology and Glaciers in the Upper Indus Basin

## Key Messages

- Considerable speculation but little analysis exists concerning the importance of glaciers in the volume and timing of flow in the Indus River and its tributaries, as well as on the potential impact of climate change on these rivers.
- The two principal sources of runoff from the Upper Indus Basin (UIB) are (1) winter precipitation as snow that melts the following summer and (2) glacier melt. In the case of seasonal snow runoff volume, winter precipitation is most important. In the case of glacier melt volume, it is summer temperature.
- Using a simple model of these dynamics, it is estimated that glacier runoff contributes approximately 19.6 million acre-feet (MAF) to the total flow of the UIB, representing an estimated 18 percent of the total flow.
- The most probable source for a majority of the remaining 82 percent is melt water from the winter snowpack.
- Future runoff regimes will be determined primarily by changes in winter precipitation and summer temperatures.
- Given the orographic complexity of the region, general circulation model (GCM) projections are unlikely to have much value for forecasting purposes.
- There is a need for major investment in snow and ice hydrology monitoring stations, further scientific research, and forecasting to improve the hydrologic predictability of the UIB.

The mountain ranges encircling the Tibetan Plateau are a complex highland-lowland hydrologic system involving a range of water supply and use environments. The importance of the mountain contribution to the total flow of the major rivers of Asia, and the sources of runoff within individual mountain catchment basins, varies throughout the region. In addition to the limited studies of the general hydrology of the mountain catchments of these rivers, there are major issues of water use, as populations grow inexorably and many Asian countries begin a transition from agriculture-based systems to more industrialized economies.

Recent concerns related to climate change, retreating Himalayan glaciers, and the role played by these glaciers in the rivers of South Asia (for example, IPCC 2007; Rees and Collins 2004; World Wildlife Fund 2005) have served to illustrate how very little the scientific and water management communities understand about the role of the mountain headwaters (and glaciers in particular) to these river systems. The credibility of these concerns is in relation to several primary areas: (1) the contribution of glacier melt in the annual volume of stream flow; (2) the contribution of other sources, such as snowmelt and the summer monsoon; and (3) the credibility of climate change scenarios used to forecast future relationships in the complex terrain of the Hindu Kush–Himalaya mountain chain.

While there is a long history of scientific visits to the Karakoram Himalaya (Kick 1960), most have been primarily exploratory, resulting more in description than analysis. Much of the present understanding of the climate, hydrology, and glaciers of these mountains is based on a few analyses of a very limited data base. Archer et al. (2010) discussed the extremely limited number of climate stations in the Upper Indus Basin (UIB). In an area of over 160,000 km$^2$ above the Tarbela Reservoir, there are only 5 hydrometric stations in the main stem of the Indus River at the present time, and fewer than 20 manual climate stations. This compares with a total of 28 hydrometric stations and more than 250 climate stations in a comparable area in the Nepal Himalaya. Credible recent glacier mass balance data are available for few glaciers in the Karakoram, the Biafo, (for example, Hewitt 2010), and the Baltoro, (Mayer et al. 2006), and one, the Chhote Shigri Glacier, in the Chenab Basin in the western Himalaya (Wagnon et al. 2007). The most detailed analyses of climate data are a series of papers by Archer and his co-workers written during the period 2003–10. Glacier studies in these areas are largely the work of Hewitt and Young, and their students during several decades (Hewitt, 1968, 1998, 2005; Hewitt and Young 1993; Wake 1988, 1989), with more recent contributions by others (for example, Mayer et al. 2006; Wagnon et al. 2007).

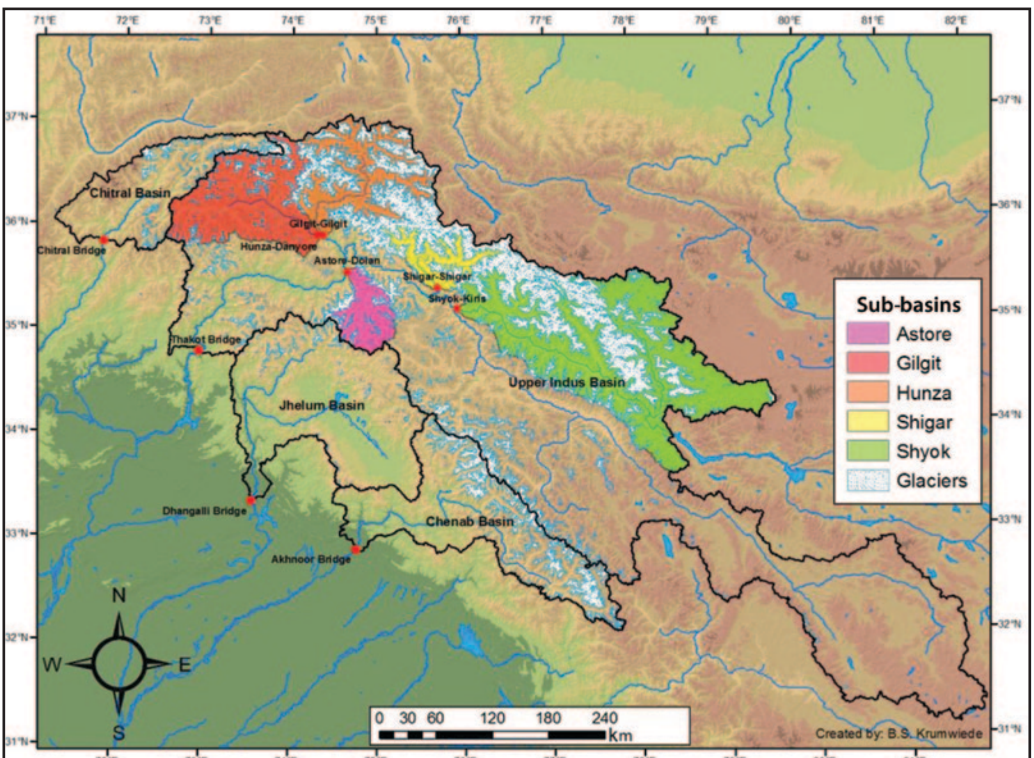
There is no compelling evidence either for or against the impact of a changing climate on the hydrometeorology and glaciers of the UIB. Part of this is because there is a very limited database describing the climate and hydrology of these mountains, part has to do with the relative lack of familiarity of the climatological community with analyses of the three-dimensional mosaic of topo-climates within the extreme terrain of the UIB, and part from the fact that at least some of glaciers of the Karakoram are presently advancing (Bolch et al. 2012) rather than retreating, counter to the global trend. Additional scientific studies are clearly warranted as well as major investment in snow and ice hydrology-monitoring stations to improve the hydrologic understanding of the UIB.

## The Indus River

The Indus River is an international river, with headwater tributaries in China (Tibet), India, Pakistan, and Afghanistan. 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 Karakoram Mountains. Along this reach of the river, stream flow volume is increased by gauged tributaries entering the main river from catchments in the Karakoram Mountains—the Shyok, Shigar,[1] Hunza, Gilgit, and, in the western Himalaya, the Astore River (Hewitt and Young 1993), as well as ungauged basins on the north slope of the western Himalaya (Byrne 2009). Immediately north of Mt. 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 merge into the Arabian Sea near the port city of Karachi in Sindh province. Tributaries to this reach of the river from the western Himalaya are the Jhelum, Chenab, Ravi, and Sutlez 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 c. 3,180 km (1,976 miles [mi]). The river's total drainage area exceeds 1,165,000 km$^2$ (450,000 square miles [mi$^2$]).

This chapter covers the mountain headwaters of the Indus River, commonly referred to as the UIB. The UIB is considered here to be the glacierized catchment basins of the western Himalaya, Karakoram, and northern Hindu Kush Mountains (map 3.1). The Hunza, Shigar, Shyok, the Gilgit Basin in the Karakoram Himalaya,

**Map 3.1 The Mountain Catchment Basins of the Indus River**

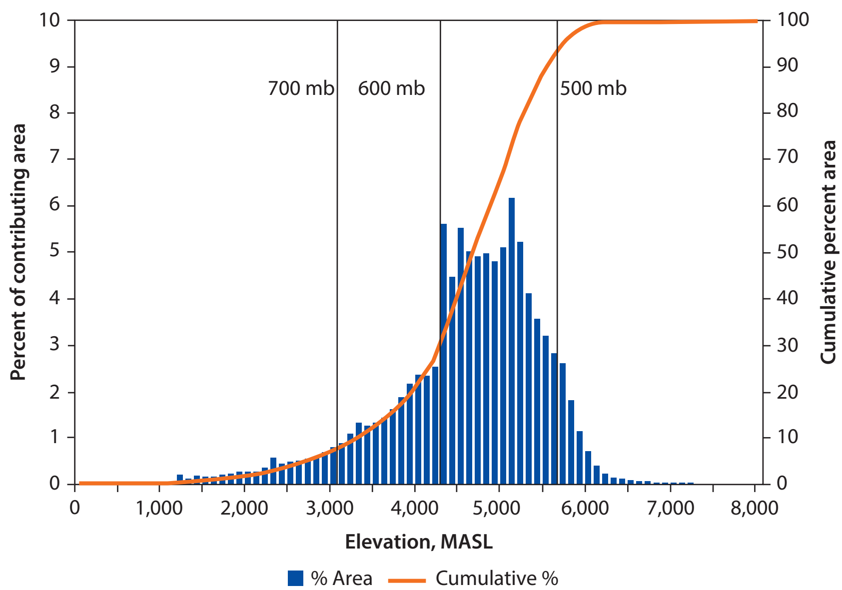



*Note:* The speckled blue area is the approximate area of glaciers and perennial snowfields. Gauging stations are represented by red dots.

and the Astore in the western Himalaya, contribute directly to the main stem of the Indus, with a total surface area of 166,065 km$^2$. The Jhelum and Chenab are tributaries from the western Himalaya, with a combined area of about 50,000 km$^2$, and the Chitral in the Hindu Kush Mountains extends approximately 12,000 km$^2$. Together these basins have a combined surface area of approximately 220,000 km$^2$ and contribute an approximately 110 MAF of the annual flow of the Indus River.

Within the mountain headwaters of the Indus River, the scale of vertical altitude differences and local relief has few analogues elsewhere in the world. Altitudes range from below 1,000 meters (m) where the river emerges on the plains at the two major controlling reservoirs of Tarbela and Mangla, to several mountain peaks above 8,000 m, including K2, the second-highest mountain on earth. As shown in figure 3.1, the mean altitude of the catchment above Besham, the gauging station immediately upstream from Tarbela Reservoir, is more than 4,000 m. This means that the greater part of the catchment surface is thrust up into the middle troposphere (ground level atmospheric pressures 700–500 millibars [mb]). The vertical lines in figure 3.1 represent atmospheric pressure levels often used by meteorologists as key heights for summary of circulation and weather processes. In lowland areas the behavior of climate variables, such as diurnal variations in air temperature, specific and relative humidity, wind

**Figure 3.1 Area-Altitude Distribution (Hypsometry) of the UIB Catchment above Besham Gauging Station**




*Source:* © British Hydrological Society. Reproduced, with permission, from Forsythe et al. 2010; further permission required for reuse.
*Note:* MASL = meters above sea level, mb = millibars.

strength and direction, and cloud formation, are significantly different at these pressure levels than near to the ground surface.

Figure 3.1 is a graphical illustration of what may be a problem in the interpretation of most current climate change scenarios. While approximately 70 percent of the total surface area of the UIB above Besham is above the 600 mb level, the climate scenarios are generally more appropriate for altitudes considerably below the 700 mb level.

## Hydrology of the Upper Indus Basin

Glaciers are a component of the hydrology of the mountain headwaters of this basin, and it is quite reasonable to expect that changes in the glaciers will be reflected in changes in the volume and timing of runoff from the mountain basins. The general hydrology of the Lower Indus Basin is assumed to be reasonably well-understood as learned from a network of gauging stations; reservoirs, such as the Tarbela and Mangla; and irrigation barrages on the piedmont. While this network provides data on which management decisions concerning water uses in the lower basin can be based, the hydrology of the upper basin remains largely a "black box." The general outlines of the hydrology of the UIB have been defined by several studies conducted in recent years, including Archer and Fowler 2004; Ferguson 1985; Goudie, Jones, and Brunsden 1984; Hewitt and Young 1993. The hydrology of the UIB has been described as having the following general characteristics:

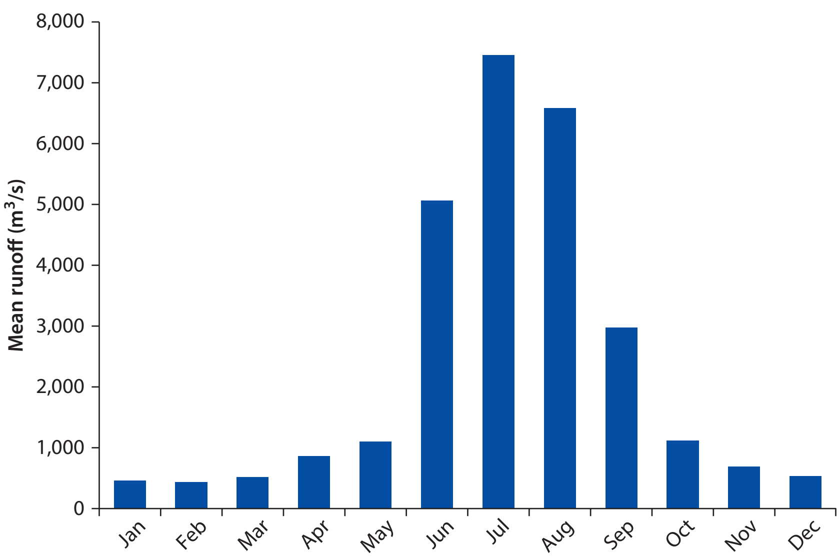
- The mean annual flow of the UIB is approximately 58 MAF from the main stem above Tarbela Reservoir, 24 MAF from the Jhelum Basin, 22 MAF from the Chenab Basin, and 6 MAF from the Chitral Basin, for a total of 110 MAF.
- The total surface area of the main stem of the Indus above Tarbela is approximately 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 UIB are (1) winter precipitation as snow that melts the following summer and (2) glacier melt. In the case of seasonal snow runoff volume, winter precipitation is most important. In the case of glacier melt volume, it is summer temperature.
- Variability in the main stem of the Indus, based on the record from Besham, has ranged from approximately 85 to 140 percent of the period of record mean of 60 MAF.
- The wide diversity of hydrologic regimes in the mountain basins complicates the problem of relating stream flow timing and volumes to a uniform climate change.
- 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.

### *The Annual Hydrograph*

Based on the mean period of record, stream flow begins to increase in May, with maximum runoff occurring in July in all sub-basins. This is consistent with what would be expected as the air temperatures increase and the freezing level migrates upward over the winter snow accumulation each spring. The July peak flow represents the end of snowmelt as a major source of surface runoff, as the winter snow deposit is removed by the rising freezing level. For Gilgit and Astore sub-basins, recession flow begins in July. This is interpreted as an indication that a glacierized area of 10 percent is not sufficient to produce a measureable stream flow volume. For the remaining gauged basins, all with glacierized surface areas greater than 20 percent, the summer runoff peak is maintained at a slightly lower volume through August, presumably by glacier melt. In early September, on average, the freezing level begins to migrate downward from near or slightly above 5,000 m. At this time each year, glacier melt ceases to be an important contributor to stream flow, and all runoff from the sub-basins enters the recession phase. Glacier melt becomes a component of stream flow, during a period of 1.0–1.5 months during August–September. The seasonality of both snowmelt and glacier melt for a specific basin appears to be determined by the area-altitude distribution of the basin, and varies among basins.

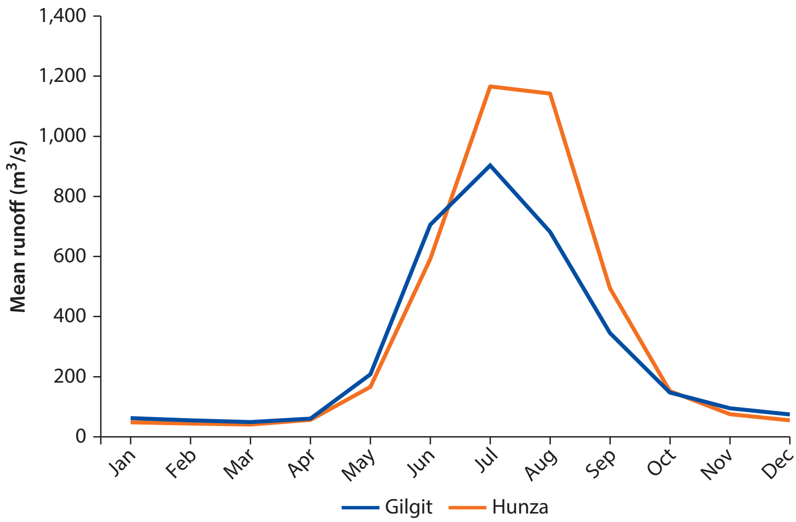
The Besham hydrograph, reflecting the combined contributions of all upstream sub-basins, shows a seasonal peak in July, assumed to represent peak snowmelt, but rather than beginning a recession phase at that point, has a secondary, slightly smaller, peak in August (figure 3.2). This is assumed to represent the glacier melt

**Figure 3.2 Hydrograph Showing Mean Monthly Runoff per Year at Besham**




*Source:* WAPDA (unpublished data).
*Note:* Besham is a gauging station located immediately upstream from the Tarbela Reservoir on the main stem of the Indus River.

**Figure 3.3 Annual Hydrographs of Gilgit and Hunza Basins**




*Source:* WAPDA (unpublished data).

component of the annual stream flow. Following this second peak, the expected exponential recession curve begins.

For individual gauged basins in the UIB, the annual hydrograph is considered a good indicator of whether monthly runoff is primarily from melting winter snow deposit or glacier melt. This is illustrated by the annual hydrographs of the Gilgit and Hunza Basins (figure 3.3). The annual hydrographs of the Gilgit Basin (solid) and the Hunza Basin (dashed), illustrate the general difference in monthly flow volumes for a predominantly snow-fed basin and a basin with runoff resulting from both snowmelt and glacier melt. The two basins are almost equal in surface area, approximately 12,000 and 13, 000 $km^2$, respectively, and differ only slightly (about 8–10 $km^3$) in total annual discharge volume. Where they are most different is in glacier area. The Hunza has about 5,800 $km^2$ of glaciers, while the Gilgit has about 1,200 $km^2$. Both hydrographs are similar in shape, with a July maximum, the primary difference being that the Gilgit Basin has slightly higher volumes in the early spring and a peak flow in July, while the Hunza has much higher flow during both July and August and a higher volume in the early fall, suggesting a source of melt water beyond the winter snow.

## Glacier Climates of the Upper Indus Basin

The literature provides several descriptions of the climates of the UIB. Thayyen and Gergan (2009) describe the geography of the hydrometeorological environments; Archer et al. (2010) describe the seasonality and altitudinal distribution of precipitation and temperature; and Hewitt (2010) provides a meteorological interpretation of the glacier climates. Glaciers can be found in all large mountain ranges, and they grow or shrink in response to the interaction between a regional climate and the topography of the mountains. The regional climate is modified by the topography of the mountains into a three-dimensional environmental mosaic, referred to as "topoclimates" (Thornthwaite 1953). The two most important topographic factors are altitude, and aspect. Altitude influences the physical properties of the air mass surrounding the mountains, primarily as a result of decreasing atmospheric density with increasing altitude. Aspect—the direction faced by mountain terrain—from a macro-slope of an entire mountain range to a cirque wall within that mountain range, influences the angle at which an air mass moving through the region intersects the mountain terrain, creating windward and leeward slopes. Aspect also is a major factor in determining the amount of solar radiation received at a surface. Solar radiation is the primary source of energy at higher altitudes in mountain ranges. There will be major differences in energy available for north- and south-facing slopes, largely unrelated to the mean air temperatures measured in adjacent valley floors.

Glaciers grow or shrink as a result of complex interactions between the processes of mass gain—in the form of snow—and energy exchange, primarily as short- and long-wave radiation and sensible heat. These interactions determine the mass balance of a glacier. The snow deposited annually, or seasonally, on the surface of a glacier represents a heat sink. When snow deposited on the glacier exceeds the amount of snow and ice that is removed by the annual amount of energy input, the mass balance is said to be positive, and over time the glacier will grow and advance. When the energy received is sufficient to melt both the annual snow deposits and the ice formed from snow deposits of previous years, the mass balance of the glacier is negative, and the glacier will retreat. Glaciers may advance or retreat from either an increase or decrease in energy availability, an increase or decrease in snow accumulation, or some combination of the two.

The average summer altitude of the 0°C isotherm, at which sufficient snowmelt and ice melt is possible to produce measureable runoff from a basin, is estimated to be approximately 5,000 m. A few valley glaciers in the Karakoram Himalaya have terminal altitudes below 3,000 m. At this altitude, ice melt is assumed to be occurring during most months of each year. This formation represents a very small fraction of the glacier cover of the UIB, however, and produces only an insignificant amount of runoff. The primary altitude of runoff volume produced by ice melt is immediately below the annual freezing level, where a combination of energy exchange and glacier surface area is maximized. In assessing the role of glacier melt in the rivers of South Asia, it is useful to remember that, presently, there are altitudes above approximately 5,000 m above which snow is deposited and never melts under present-day conditions. These glaciers exist through a range of altitudes from the lowest, where melt occurs continuously throughout the year, to the highest, where melt never occurs.

As inferred from the hydrological data, the hydrometeorology of the Karakoram tributaries to the main stem of the Indus River is dominated by a winter snowfall regime, with maximum snow-water equivalent (SWE) depths centered at approximately 4,000 meters above sea level (MASL). Between approximately 3,000 and 5,000 m, this snow melts each spring and summer and forms the bulk of the surface runoff. Following removal of the seasonal snowpack, glacier melt begins at these same altitudes and continues until all melt ceases in September. Above 5,000 m, there appears to be a rapid decrease in precipitation depth and glacier melt with altitude. Snowfall above 5,000 m is presumably redistributed by wind or avalanches into the topographic basins that form the accumulation zones of the glaciers. As a result of plastic flow, this snow is ultimately transferred to the altitude of the ablation zone of the glaciers at 3,000–5,000 MASL where it becomes the source of much of the August–September stream flow. In the western Himalaya basins of the Jhelum and Chenab Rivers, the winter snow is augmented by the summer monsoon, and, in the Chenab, by a small glacier melt component.

## Distributed Process Models of Glaciers and Total Basin Runoff

The approach described here uses a very simple physical distributed process model, which is based on the assumption that, as a useful first approximation, the most important controls on the water budget of a mountain basin in the Hindu Kush-Himalayan Mountains are the altitudinal range occupied by the basin and the distribution of surface area within the basin. Altitude is used as a proxy for all major topographic variables—altitude, aspect, and slope—and temperature for both sensible heat and radiation, as exemplified by the use of the "degree-day" index (Ohmura 2001). Surface area is necessary to convert the specific values to total volumes. The areal distribution of runoff may be derived as the product of the area-altitude hypsometry of an entire catchment basin, or of selected portions such as the glacierized area of the basin, and the altitudinal gradient of the water budget over that portion of the basin. Much of the procedure is based on the application of traditional budget analysis procedures from hydrology or glaciology. Ideally, the basin should have a gauging station at its outlet, to provide an empirical test of the volume and timing estimates.

### *The Catchment Basins*

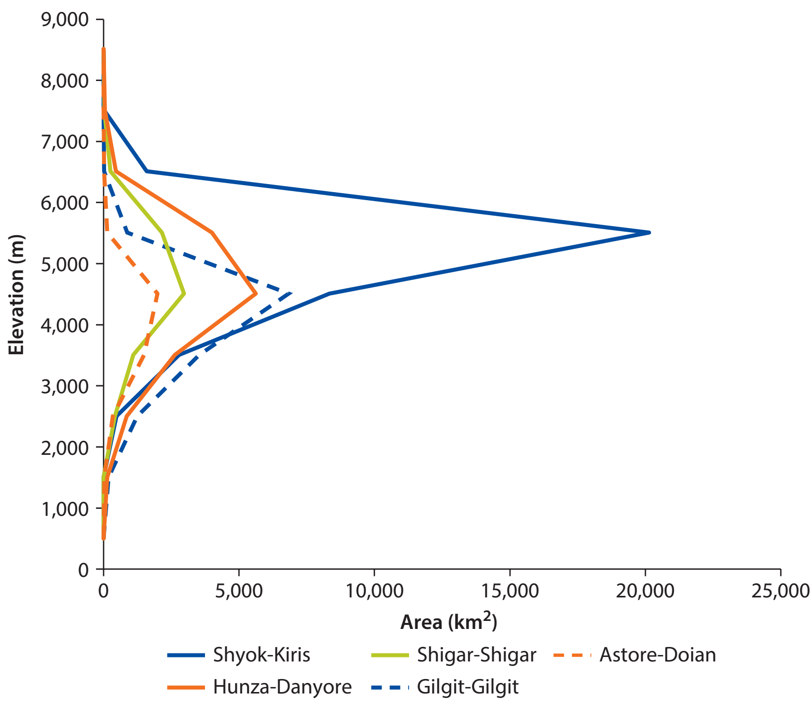
A digital elevation model (DEM) was produced of the entire region occupied by the UIB from Shuttle Radar Topography Mission (SRTM) 90 m data. The perimeter of the entire basin to be included was determined, together with each of the individual gauged sub-basins within this basin. Catchment basins were defined as the drainage area upstream from a hydrometric gauging station. Basin boundaries above the stations were defined using the Watershed tool in the Hydrology toolset of Spatial Analyst Tools in ArcGIS 9.3.1 to define basin boundaries. The rasters were converted to polygon shape files, combining the basins and sub-basins, and the basin surface areas calculated (in km$^2$). The results for all the basins included in this study are shown in table 3.1 and figure 3.4.

Table 3.1 illustrates the concentration of surface area at altitudes 4,000–6,000 MASL for many basins. The primary importance of this concentration of

**Table 3.1 UIB Catchment Basins with Total Areas and Area-Altitude Distribution**
*1,000 m increments, km²*

| *Station* | *0–1 k* | *1–2 k* | *2–3 k* | *3–4 k* | *4–5 k* | *5–6 k* | *6–7 k* | *7–8 k* | *8–9 k* | *Total* |
|---|---|---|---|---|---|---|---|---|---|---|
| Thakot | 240 | 3,305 | 9,443 | 26,110 | 68,278 | 56,493 | 2,726 | 111 | 1 | 166,707 |
| Besham | 172 | 3,083 | 9,212 | 26,028 | 68,274 | 56,490 | 2,725 | 111 | 1 | 166,096 |
| Partab | 0 | 644 | 4,809 | 19,150 | 62,015 | 56,224 | 2,677 | 99 | 1 | 145,618 |
| Kachura | 0 | 0 | 1,947 | 11,752 | 48,337 | 51,046 | 2,153 | 52 | 1 | 115,289 |
| Kiris | 0 | 0 | 477 | 2,785 | 8,337 | 20,141 | 1,588 | 22 | 0 | 33,350 |
| Shigar | 0 | 0 | 417 | 1,094 | 2,968 | 2,157 | 254 | 31 | 1 | 6,922 |
| Danyore | 0 | 138 | 848 | 2,632 | 5,620 | 3,997 | 454 | 44 | 0 | 13,732 |
| Gilgit | 0 | 179 | 1,246 | 3,534 | 6,832 | 875 | 15 | 0 | 0 | 12,680 |
| Doian | 0 | 23 | 336 | 1,489 | 1,985 | 134 | 18 | 3 | 0 | 3,988 |
| Dhangalli | 1,182 | 8,085 | 7,632 | 7,217 | 2,986 | 20 | 0 | 0 | 0 | 27,122 |
| Aknoor | 874 | 2,718 | 4,078 | 4,935 | 6,719 | 3,162 | 19 | 0 | 0 | 22,504 |
| Chitral | 0 | 156 | 1,505 | 3,490 | 5,398 | 1,769 | 173 | 14 | 0 | 12,505 |
| Total | 2,468 | 18,331 | 41,950 | 110,216 | 287,749 | 252,508 | 12,802 | 487 | 5 | 726,513 |

**Figure 3.4 Upper Indus Basin Hypsometries of Table 3.1**




surface area at these altitudes is that it provides an extensive platform for the deposition of the winter snowfall. Beginning in the early spring, the freezing level gradually rises to the upper portion of this altitudinal belt, providing a large fraction of the summer-season stream flow volume. The area-altitude distribution of the hydrologic characteristics of the UIB is fundamental to a realistic assessment of the potential effects of climate change on the volume and timing of stream flow from the basin. While most gauged basins have a concentration of surface at 5,000 MASL, the Shyok Basin has a maximum concentration at 6,000 MASL. This suggests that the Shyok Basin, including a portion of the Baltoro Mustagh, may have an ice balance that is slightly more positive.

### *The Orographic Runoff Gradient*

The gradient of total basin water budget with altitude was estimated from the relationship between the measured mean specific annual runoff (mm) and the mean altitude of the gauged basin (m). A curvilinear relationship between specific runoff and mean basin altitude is observed, with a maximum at 3,000–4,000 m and a minimum at the highest and lowest altitudes. It is assumed this distribution is produced by monsoon rain, as the encroaching summer monsoon is forced to rise over the Himalayan wall. Variation in the curvature of the gradient is assumed to be a result of a weakening of the summer monsoon as it moves from east to west along the Himalayan front. Estimating the orographic runoff gradient for the Karakoram Himalaya, in the UIB is more difficult. There are far fewer gauged basins in the Karakoram than in the Nepal Himalaya, and the range of mean altitudes of those basins is much narrower. To define the general form of the orographic gradient for the western Himalaya and Karakoram, specific runoff values and mean altitudes shown in table 3.2 were combined with similar data from winter snowpack SWE (from Forsythe et al. 2010) and the Karnali Basin, from western Nepal. The result is shown in figure 3.5. The data from snowpack SWE data from Forsythe et al. (2010). are shown in white, the Karnali Basin in eastern Nepal in gray, and the Karakoram basins and the western Himalaya tributaries to the UIB are in black. This data suggests that above 5,000 m there is negligible runoff being produced.

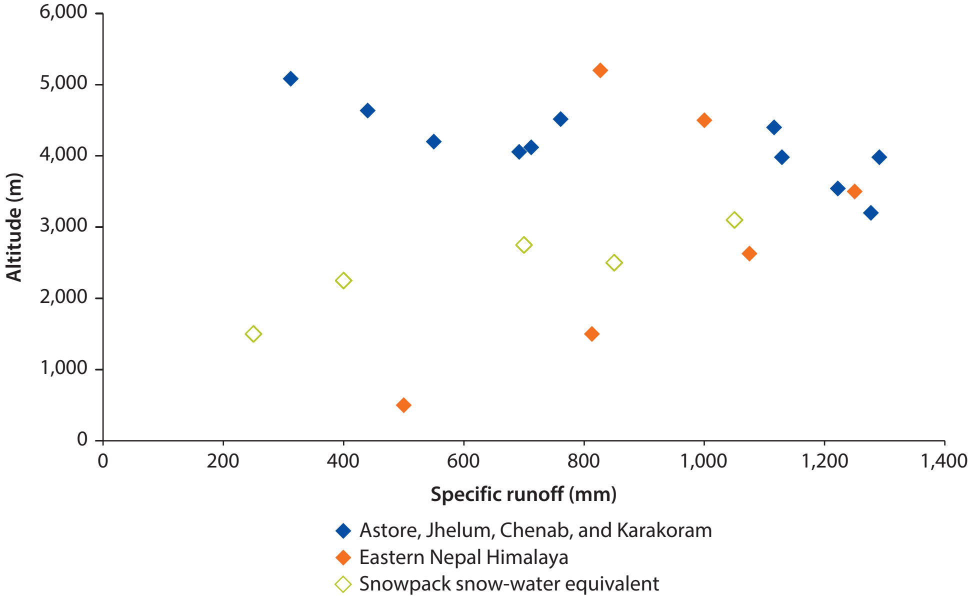
### *Glacier Melt and the Ablation Gradient*

Haefeli (1962) postulated the existence of an "ablation gradient" to summarize the trend of melt from all processes with altitude over the ablation zone of a glacier (figure 3.6). In plotting data from reports in the literature, the author

**Table 3.2 Basic Descriptive Statistics of the Basins in This Study**

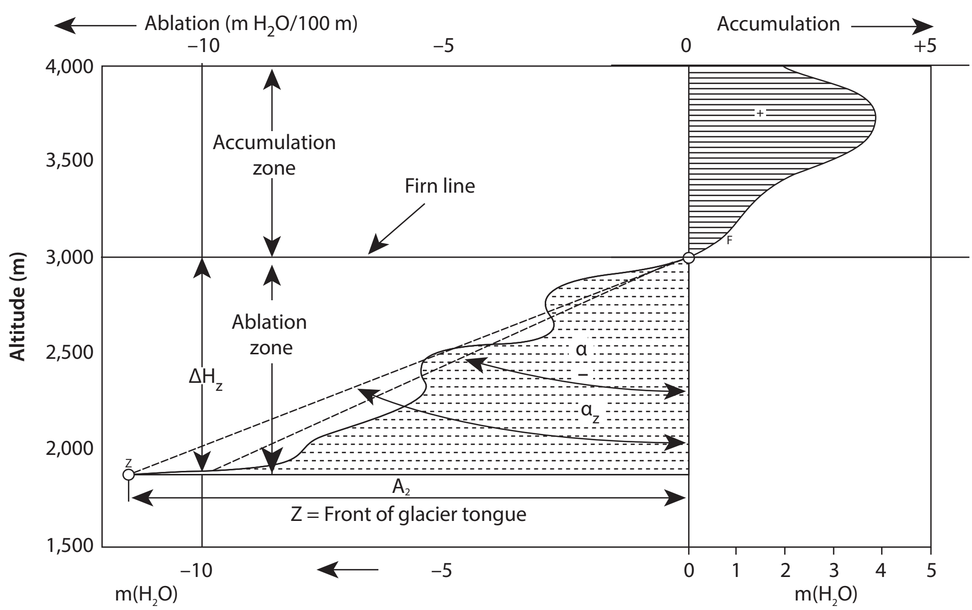
| *River* | *Sub-basin* | *Gauge site* | *Specific runoff (m)* | *Average altitude (m)* |
|---|---|---|---|---|
| Indus | Astore | Doyan | 1.29 | 3,981 |
| | Gilgit | Gilgit | 0.62 | 4,056 |
| | Hunza | Danyore | 0.76 | 4,516 |
| | Shigar | Shigar | 0.98 | 4,611 |
| | Shyok | Kiris | 0.32 | 5,083 |
| | Indus | Besham | 0.44 | 4,536 |
| | Chitral | Chitral | 0.71 | 4,120 |
| Jhelum | | Dhangalli | 1.08 | 2,628 |
| Chenab | | Aknoor | 1.22 | 3,542 |

**Figure 3.5 Orographic Runoff Gradient for the Western Himalaya and Karakoram Sub-Basins**




*Source:* Based on data from sub-basins in the Astore, Jhelum, Chenab, and Karakoram, the eastern Nepal Himalaya, and snowpack SWE values from Forsythe et al. 2010.

**Figure 3.6 The Ablation Gradient**



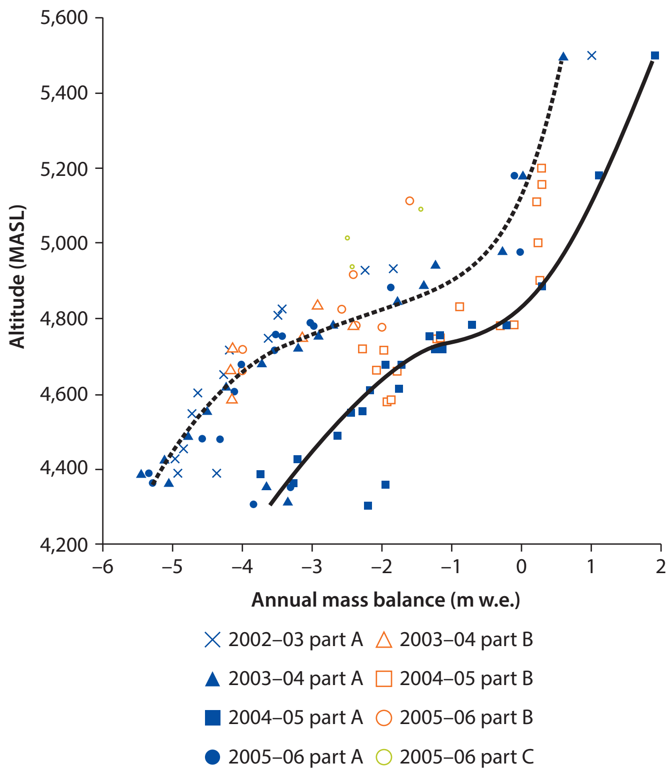

*Source:* © International Association of Hydrological Sciences (IAHS). Reproduced, with permission, from Haefeli 1962; further permission required for reuse.

found an inverse correlation in the slope of the ablation gradient with latitude, progressing from values of 0.2 m/100 m for glaciers in the high arctic to approximately 1 m/100 m at the latitude of the Karakoram Himalaya. According to Haefeli, "The ablation gradient is analogous to the well-known gradient of the average annual temperature of the air. The analogous phenomenon in the ablation would mean that the ablation gradient for a given glacier within a given climatic period remains approximately independent of the yearly fluctuations of the firn line" (50).

For the present study, an ablation gradient of 1m/100 m was assumed, based on studies of glaciers in the western Himalaya and Karakoram by Mayer et al. (2006) and Wagnon et al. (2007) (figure 3.7). Hewitt et al. (1989) estimated an ablation gradient of 0.5 m/100 m for the middle portion of the ablation zone on the Biafo glacier but did not present actual measurements.

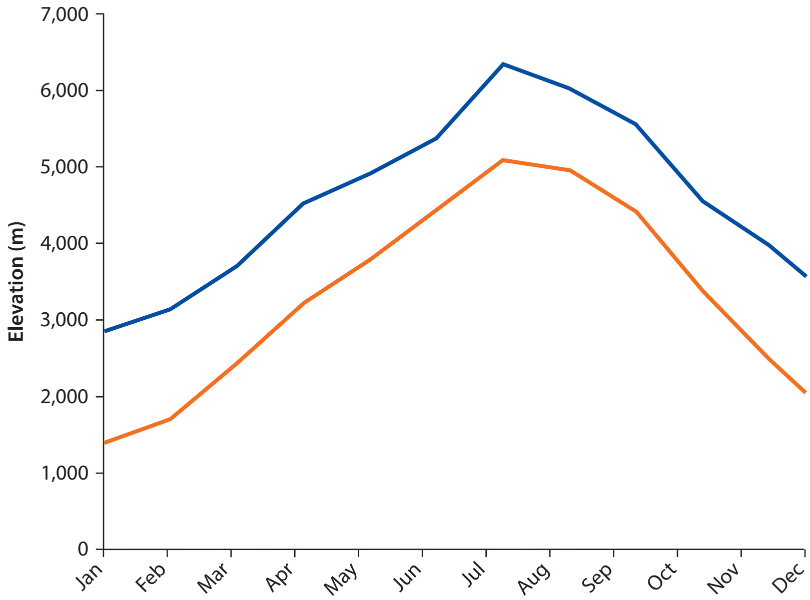
The use of the ablation gradient concept requires that an altitude above which no ablation and runoff occurs be defined. For this study, this altitude is defined as the mean summer-season altitude of the 0°C isotherm. The mean altitude of the 0°C isotherm will be located at some intermediate altitude between that of

**Figure 3.7 Four Years of Mass Budget Variation with Altitude, Chhota Shigri Glacier, Chenab Basin, Western Himalaya**




*Source:* © International Glaciological Society. Reproduced, with permission, from Wagnon et al. 2007; further permission required for reuse.
*Note:* MASL = meters above sea level, m w.e. = meters water equivalent.

**Figure 3.8 Elevation of the Freezing Level for Monthly Maximum and Minimum Temperatures, Karakoram Himalaya**




*Source:* © Archer and Fowler. Reproduced, with permission, from Archer and Fowler 2004; further permission required for reuse.

the minimum and maximum temperatures, as shown in figure 3.8. The estimates of glacier melt volume in this report are based on a summer-season freezing level of 5,000 m, above which some melt may occur but there is no measureable runoff. This level may be somewhat higher, on average, or may vary with location within the UIB. Any change in the altitude of the freezing level will have a considerable impact on the calculated volume of glacier melt and runoff, since the altitude of the freezing level is also the altitude of the maximum surface area belt of the glaciers.

### *The Estimated Glacier Component of Stream Flow*

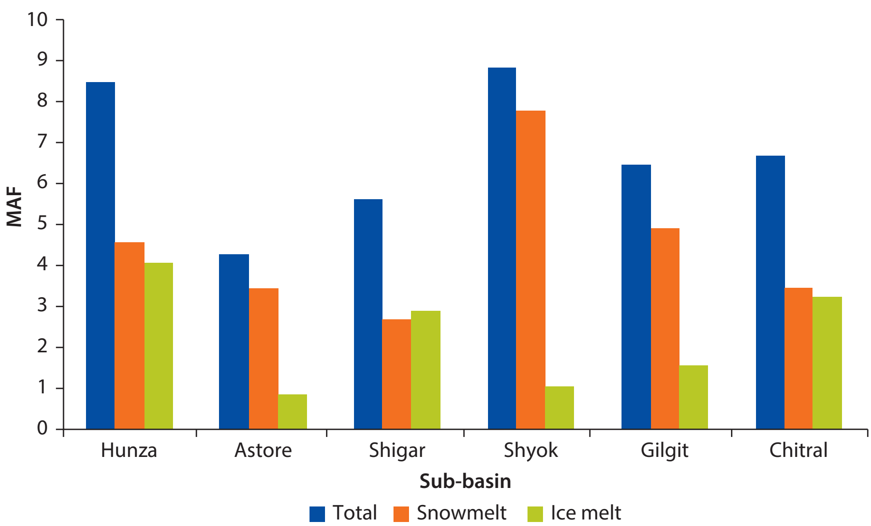
Values for each 100 m belt were determined from the ablation gradient, and the total ice melt was calculated as the sum of the product of the surface area of the respective belt and estimated ablation at that altitudinal interval. These values, summed for all the altitudinal belts on the ablating portion of the glaciers, were assumed to represent the annual ablation balance for the combined glaciers of each catchment basin. An assumed summer-season freezing level of 5,000 m and an ablation gradient of 1 m/100 m are used. The estimate of glacier melt to total stream flow in the UIB is based on a corrected surface area derived from an initial measurement of glacier surface area prepared by the National Snow and Ice Data Center (NSIDC) at the University of Colorado. This approach allows the calculation of the relative contribution of glacier melt and snowmelt as components in the annual flow of the UIB (table 3.3, figure 3.9). Results show that glacier

**Table 3.3 Estimated Contribution of Glacier Melt and Snowmelt to Total Runoff for UIB Sub-Basins**

| *Basin* | *Area, (km²)* | *Glacier, (km²)* | *q (mm)* | *Q (MAF)* | *Ice melt (MAF)* | *Snowmelt (MAF)* |
|---|---|---|---|---|---|---|
| Hunza | 13,734 | 4,339 | 0.76 | 8.5 | 4.0 | 4.5 |
| Astore | 3,988 | 450 | 1.29 | 4.2 | 0.8 | 3.4 |
| Shigar | 6,922 | 2,885 | 0.98 | 5.5 | 2.9 | 2.7 |
| Shyok | 33,350 | 6,221 | 0.32 | 8.7 | 4.9 | 3.8 |
| Gilgit | 12,682 | 994 | 0.62 | 6.4 | 1.5 | 4.8 |
| Kachura (estimated) | 75,000 | n.a. | 0.21 | 12.9 | n.a. | 12.9 |
| Ungauged (estimated) | 20,000 | n.a. | 0.72 | 11.8 | n.a. | n.a. |
| Besham[a] | 166,096 | 14,889 | 0.44 | 58.0 | 14.1 | 32.0 |
| Chitral | 11,396 | 2,718 | 0.71 | 6.6 | 3.2 | 3.4 |
| Chenab | 22,503 | 2,708 | 1.22 | 22.2 | 2.3 | 19.9 |
| Jhelum | 27,122 | 0 | 1.08 | 23.6 | 0 | 23.6 |
| Total[b] | 199,995 | 20,315 | | 110.4 | 19.6 | 79.0 |

*Note:* n.a. = not applicable, MAF = million acre feet.
a. Ice melt and snowmelt contributions do not sum to the total flow (Q) because of unknown contributions from a 20,000 km² area. No glaciers are observed in this area, so it is likely that the remainder flow will be from either snow or the monsoon.
b. Total represents the sum of the Besham, Chitral, Chenab, and Jhelum basins.

**Figure 3.9 Estimated Stream Flow Sources for the UIB Primary Glacierized Sub-Basins**




*Note:* MAF = million acre-feet.

runoff contributes approximately 19.6 MAF to the total flow of the UIB: 14.1 MAF from the Karakoram Himalaya, 2.3 MAF from the western Himalaya, and 3.2 MAF from the Hindu Kush. This represents an estimated 18 percent of the total flow of 110 MAF from the mountain headwaters of the Indus River. The most probable source for a majority of the remaining 82 percent is melt water from the winter snowpack.

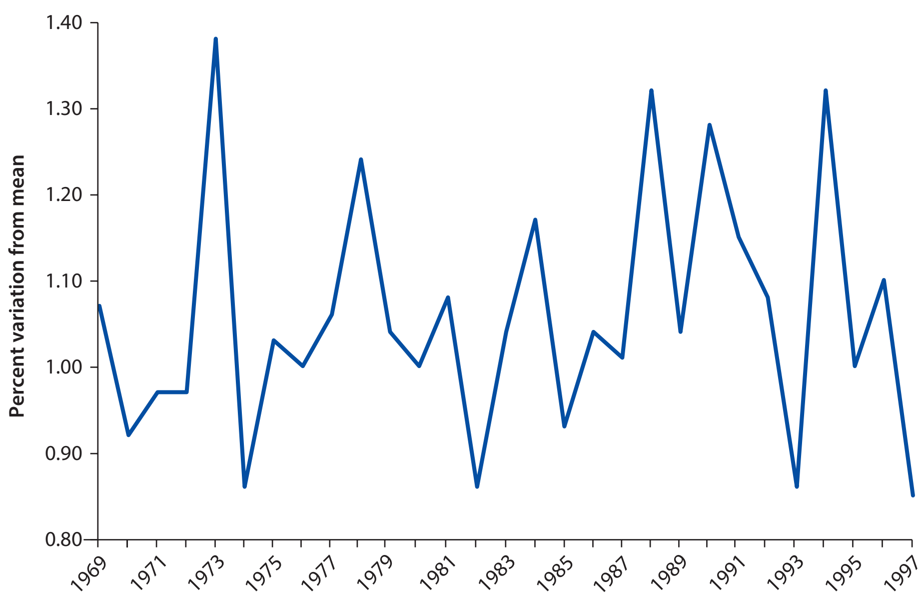
## Climate and Stream Flow Variability in the Upper Indus Basin

A reasonable concern is how much will a changing climate cause changes in the volume or timing of stream flow in the Indus River. Most scenarios of the impact of climate change on the hydrology of glacierized mountains have been based on the assumption that increasing air temperatures will produce an initial period of flooding, followed by an increasing drought as the glaciers retreat (Rees and Collins 2004). At least implicitly, such scenarios assume that current annual discharge volumes are relatively constant from year to year and that stream flow volume is primarily a result of glacier melt. The findings of this analysis based on analyses of the hydrographs from both glacierized and non-glacierized basins in the UIB do not provide support for either of the assumptions. This chapter demonstrates that snowmelt is the main source of annual stream flow to the UIB. Moreover, interannual variability may be determined, in part, by year-to-year fluctuations in both winter precipitation, as snow, and summer-season snowmelt and ice melt, as a result of fluctuations in energy availability. Some insight may be provided by an analysis of the variability of stream flow in the river under existing climate conditions.

The annual variation in stream flow in the main stem of the UIB (where roughly 80 percent of the glaciers of the entire basin are located) ranges from 140 to 80 percent of the mean. The variation is not symmetrical with respect to the long-term average volume (figure 3.10).

Approximately 70 percent of the annual flow from the sub-basins of the UIB occurs during July and August each year. These are months of maximum snowmelt (July) and glacier melt (August), as discussed earlier. An inspection

**Figure 3.10 Percent Variation from Mean Annual Stream Flow at Besham, 1969–97**



of the period-of-record summer-season runoff shows that the peak flow month varies from year to year, the frequency of this shift varying among basins, presumably as a result of variations from wet-cold to dry-warm conditions, increasing or decreasing the relative contribution of either snow-melt or glacier melt.

The peak annual flow times for several UIB sub-basins are as follows:

- For Besham, a basin with approximately a 15 percent glacier-covered area, the annual peak flow has occurred 75 percent of the time in July, and 25 percent of the time in August during the period of record (figure 3.11).
- For the Hunza Basin, with a glacier covered area of approximately 50 percent, the peak annual flow has occurred 60 percent of the time during August (figure 3.12).
- The annual peak flow from the Astore Basin, with approximately 10 percent glacier covered area, is consistently in July (figure 3.13).

These basins exemplify conditions in all gauged basins in the main stem of the UIB, illustrating the differences between the maximum and minimum glacierized areas in these basins. With a warming climate, it is assumed that there would be a shift to an increasing number of peak flows occurring in August; with a shift to a cooler-wetter climate, the July peak would become dominant.

For assessing the potential impact of climate change scenarios on stream flow in the UIB, it is useful to distinguish between those changes that could result from variations in precipitation from those related to changes in temperature. The volume of runoff from winter snow-melt will be determined primarily by variations in winter precipitation, since in all cases sufficient energy should be available during normal melt seasons to remove any realistic increases. On the other hand, glacier melt-water production will vary with the energy availability (change in temperature) during the melt season at the glacier surface. This also might not necessarily result from an increase or decrease in air temperature,

**Figure 3.11 Summer Season and Annual Stream Flow in Besham Basin, 1970–95**

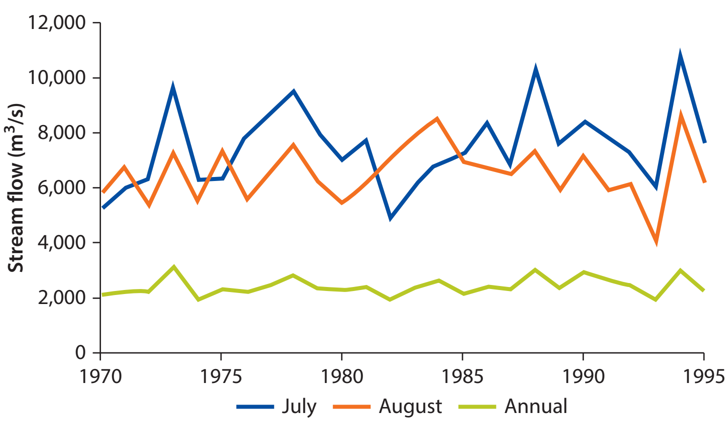


**Figure 3.12 Summer Season Stream Flow in Hunza Basin (Significant Glacier Cover), 1966–96**

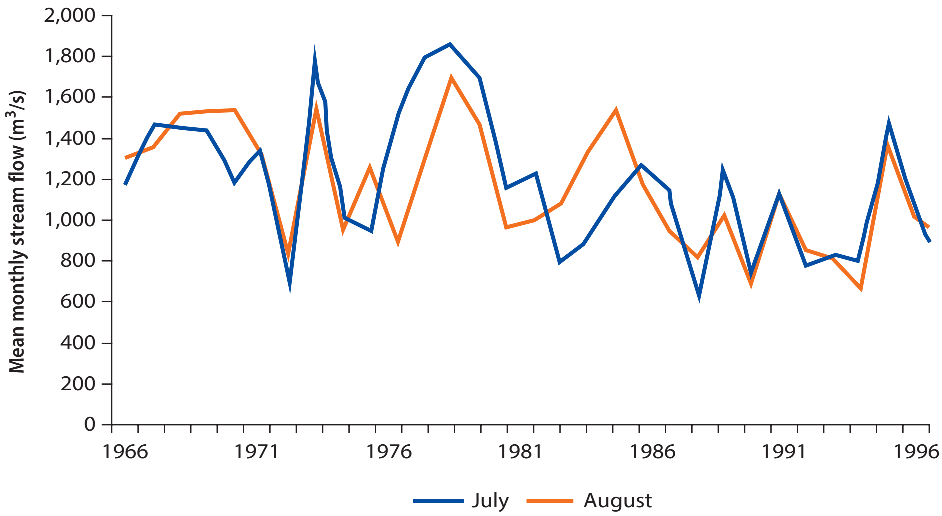
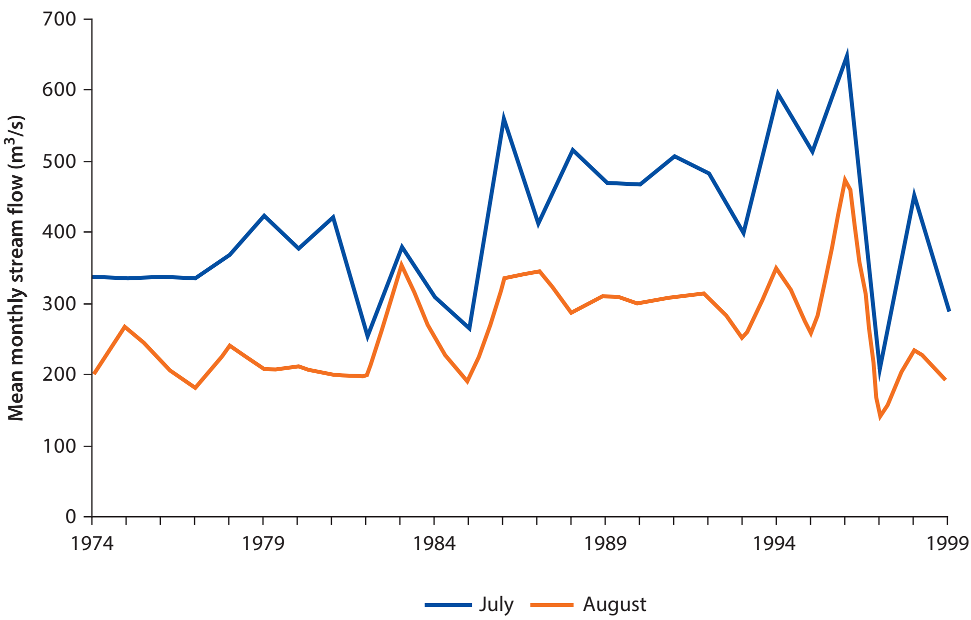



**Figure 3.13 Summer Season Stream Flow in Astore Basin (Limited Glacier Cover), 1974–99**




but could result from changes in summer cloudiness that increase or decrease receipt of shortwave radiation, or from the frequency of minor summer snow storms at the altitude of the glaciers that alter the albedo of the glacier surface.

Thus, the major challenge in predicting the impact of climate change on overall water resource availability in the UIB is to be able to make accurate predictions of changes (magnitude and direction) in winter precipitation and summer temperatures. This analysis also demonstrates that, since the large majority of total flow originates from snow, predictions of future precipitation change would be the top priority. Additional scientific studies, as well as major investment in snow and ice hydrology monitoring stations, will help to improve the hydrologic understanding of the UIB and future projections.

## Note

1. The gauging station for the Shigar Basin has reportedly been discontinued (personal communication, D. Archer et al. 2010).

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