



The Glaciers of the Hindu Kush-Himalayan Region

A summary of the science regarding glacier melt/
retreat in the Himalayan, Hindu Kush, Karakoram,
Pamir, and Tien Shan mountain ranges



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Mt Everest with Khumbu glacier - Sharad Joshi

NOTE

Data and information on the glaciers in the Hindu Kush-Himalayan region are sparse and often contradictory. They lack consistency, multi-temporal recording, field-validation, and peer review, and there is a particular lack of data for the higher elevation glaciers. The paper presented here was prepared by Dr Richard L Armstrong as part of a larger USAID report (see inside back cover). It is being published by ICIMOD in its full form (with some updates) as a contribution to the ongoing discussions on this highly popular and important topic. We hope that the extensive literature survey and references, as well as the comparative analysis and analytical discussion, will be a useful resource for our readers, particularly for those of you trying to critically assess and establish the actual status of the cryosphere in the high mountains of the Hindu Kush-Himalayan region. We trust also that the publication will help our efforts to assess the actual and potential impacts of a changing climate on the snow and ice resources of the region.

The Glaciers of the Hindu Kush-Himalayan Region

A summary of the science regarding glacier melt/retreat in the Himalayan, Hindu Kush, Karakoram, Pamir, and Tien Shan mountain ranges

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Background

News of glaciers retreating in the high mountains of Asia has intensified concerns about impacts of climate change on the hydrological systems of central, south, and east Asia. The overall purpose of this review is to provide a summary of the scientific knowledge about glacier melt/retreat in the high mountains of Asia. Major points of the review include the following:

- Glaciers are one of the most obvious, and seemingly simple, indicators of climate change. However, glaciers themselves are physically complex and spatially diverse.
- The dramatic statements that glaciers are smaller than they have been for over two hundred years since the Little Ice Age (LIA) are not particularly surprising or enlightening. However, the increasing rate of change raises concerns.
- Glacier data in the Himalayas and surrounding mountains are very sparse, limited mostly to terminus location data that do not comprehensively describe overall conditions of the glaciers.
- Many of the glaciers in the extended Hindu Kush-Himalayan region are retreating, but there is no spatially comprehensive or region-wide evidence that the glaciers in the region are retreating faster than glaciers in any other location in the world.
- Efforts to quantify the contribution of melting glacier ice to regional hydrology are in the early stages of development, but it is already clear that conditions vary significantly along the south-east to north-west transect of the Himalayan-Karakoram-Hindu Kush mountain ranges, extending from eastern Nepal and Bhutan to northern Afghanistan.

Glaciers as indicators of climate change

Glacier retreat provides a clear indication of a global climate that has been warming since the Little Ice Age (LIA), which occurred from approximately 1650 to 1850 (Oerlemans 2005). Throughout the world, including the Himalayan region, evidence left by glacier moraines shows the maximum extent of these glaciers during the LIA and quantifies the fact that glaciers have been retreating since this period in response to a warmer climate.

There is now clear evidence that the retreat of glaciers in many locations of the world has accelerated in recent decades (Zemp et al. 2008). However, glacier systems at the highest elevations, 4000-7000 m, have not responded to recent climate warming in the same way as glaciers that extend to lower elevations, simply because glaciers at higher elevations remain below freezing during much of the year, even in the presence of a warmer climate. Therefore, although glaciers are retreating both in the European Alps and in the Himalayan region, one cannot always make direct comparisons and extrapolations from the well-studied lower elevation glaciers to the more poorly observed higher elevations of the Himalayan region.

Glacier terminus fluctuation measurements

Perhaps the simplest method to monitor mountain glacier change is by recording the annual location of the glacier terminus, the location at which the glacier extends furthest down valley. Abundant terminus histories are available from several regions of the world, Europe in particular. In contrast, field-based measurements in remote glacierised areas such as the Himalayas are often, by necessity, limited to a few measurements and typically limited to easily accessible glaciers at the lower elevations. Therefore, the sample is biased by elevation.

In addition, it is necessary to understand that the location of a glacier's terminus is not a comprehensive assessment of total glacier condition or health. Such measurements represent nothing more than the location of the terminus at a given point in time as it responds to both the dynamics of the ice body and the current climate. For example, if a glacier is noted to be retreating, this simply means that the ice at the terminus is melting faster than the rate at which ice is being supplied to that location by movement (dynamics) of ice from further upslope in the system. It is possible that a glacier may be gaining in total mass from one year to the next, due to increasing amounts of snow arriving at the higher elevations by precipitation, wind deposition, and avalanching, while the terminus, at the lowest elevation, is retreating. Therefore, it should be understood that measurements showing short-term retreat only indicate that the recent climate does not support the extension, or even stability, of the lowermost elevation of a given glacier, and does not define the current conditions controlling the changes in volume over the entire glacier at all elevations. Certainly, however, when glaciers are observed to have been in retreat consistently over many decades, they are not in balance with the recent climate.

Glacier mass balance measurements

More direct and comprehensive methods have been developed to determine the year-to-year condition of a total glacier system through measurements of 'mass balance'. During the accumulation season (often, but not in all locations, the winter season), a glacier gains mass from accumulating snow. During the following summer melt season, some or all of that winter accumulation is lost to ablation, predominantly by melt, but it may include sublimation/evaporation as well as calving where a glacier enters a water body. The upper elevation zone where the glacier experiences an annual net gain in mass is called the accumulation area; the lower elevation zone where the glacier experiences a net mass loss is called the ablation area. The elevation contour at which these two zones meet is called the equilibrium line altitude (ELA) representing the point on the glacier where the annual net mass balance is zero (see Figure 1). The difference between the accumulation and ablation for a given year describes the annual net mass balance, which corresponds to the change in total glacier volume and mass. Methods to monitor mass balance vary but are always complex and time consuming, so only a few dozen such records in the world exist that cover significant periods of time (decades) (Zemp et al. 2008, 2009). There are currently no such long-term records for the Himalayan region (Kaser et al. 2006).

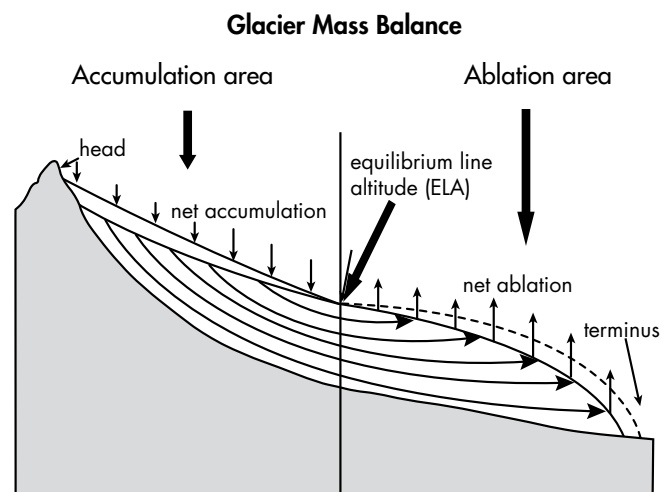


Figure 1: Glacier accumulation and ablation areas, and equilibrium line altitude (ELA)

Figure 2: Mountain ranges and river systems of High Asia



Glacier dynamics

An understanding of the response of glaciers to climate change must include basic concepts of ice dynamics. Glaciers continually move, carrying mass downhill somewhat like a conveyor belt. If the combination of climate (principally precipitation and temperature) and ice dynamics (internal deformation of the ice and sliding at the base in response to the force of gravity) determines that the glacier is extending further down slope with time, this advance of the terminus will increase the glacier length and total area. Because glaciers move slowly, however, a significant time lag occurs between the changing climatic conditions and the resulting glacier advance or retreat. This response time may last several decades or longer for most mountain glaciers, determined by complicated processes that control how fast the glacier moves; that is, how quickly a glacier transfers mass from the higher elevations of the accumulation zone to the lower elevations of the ablation zone. Therefore, year-to-year glacier terminus fluctuations may be a response to climatic events that occurred several decades or more in the past.

Response times for the majority of Himalayan glaciers are most likely decades to centuries, appropriate for glaciers whose movement results mainly from internal ice deformation (i.e. in contrast to surging or dramatic basal sliding examples). Rough estimates of glacier response time can be based on size and slope. Large low-slope glaciers may have response times of the order of centuries. Length changes of such glaciers, especially if debris-covered, can not, therefore, be used as indicators of recent (decadal) climate change. Such decadal changes are much better reflected by smaller/steeper glaciers. Response time scales have been described by Raper and Braithwaite (2009), Adhikari et al. (2009), McClung and Armstrong (1994), and Johannesson et al. (1989).

Geographic extent of the review

The focus of this review is on those regions of 'High Asia' (Figure 2) sometimes referred to as the Hindu Kush-Himalayan or greater Himalayan region, and including the Himalayan, Hindu Kush, Karakoram, Pamir, and Tien Shan mountain ranges, where there is currently glacier coverage. Note that this is a somewhat wider coverage than usually included in ICIMOD's use of 'Hindu Kush-Himalayan', which is limited to areas within its eight regional member countries and does not include the Tien Shan range or all of the Pamirs.

The east-west glacier/climate pattern of the greater Himalayan region

It is not appropriate to treat the Hindu Kush-Himalayas as a single region: the eastern Himalayas are separated from the Karakoram-Hindu Kush mountains by approximately 2,000 kilometres. These two areas, east and west, differ in climate, especially in sources and types of precipitation, and in glacier behaviour and dynamics. Moreover, there is no sharp dividing line between east and west; rather, conditions change gradually across the region.

Climate

Precipitation and basin runoff generally decrease from the east to west as a direct result of the weakening of the summer monsoon as it moves westward along the Himalayan range. In the east, summer monsoon precipitation dominates, while in the west, westerly circulation and cyclonic storms contribute about two-thirds of the annual precipitation as high altitude snowfall during winter, with the remaining one-third resulting from summer precipitation mainly due to monsoon circulation (Wake 1989). Hewitt and Young (1993) note that a very significant source of nourishment for many Himalayan glaciers is avalanche snow from the surrounding slopes.

Reported trends in air temperature over recent decades vary across the region. In the central/eastern Himalayas, Shrestha et al. (1999) reported increasing temperature trends ranging from 0.06 to 0.12°C /yr in most of the regions of the Nepal Himalayas. Bhutiyani and others (2007) report a significant rise in air temperature in the northwestern Himalayas in the last century. An increase in maximum and minimum temperatures of 1.0 and 3.4°C was found across the Himalayan region during the period 1988–2008 (Shekhar 2010). The increase in temperature was accompanied by decreasing trends in precipitation, and a reduction in total seasonal snowfall (Dimri and Kumar 2008; Shekhar 2010). In contrast, the Karakoram range has experienced a decreasing trend in maximum and minimum temperatures of 1.6 and 3.0°C, respectively (Shekhar 2010), together with an increase in winter precipitation (Fowler and Archer 2006). These downward trends in summer temperature in the Karakoram are consistent with the observed advances and thickening trends of some Karakoram glaciers reported in recent studies, for example, Schmidt and Nusser (2009).

The orographic runoff gradients (variation in runoff with elevation) are also very different between east and west. While data from Nepal show the maximum runoff being generated at approximately 3,000 m with decreasing amounts at both lower and higher elevations (Alford 1992), data from regions further to the west indicate more linear gradients of steadily increasing values up to a maximum at 5,000 m to 6,000 m (Hewitt and Young 1993). This results in a gradual shift upwards in the altitude of the zone of maximum runoff from east to west. This high-altitude runoff would indicate that glaciers in the western Himalayas, Karakoram, and Hindu Kush mountain ranges are an increasingly important source of streamflow volume. However, the total runoff in the western mountains is considerably less than that in the east at all altitudes – an expected condition given the relative aridity of the western mountains. Moreover, throughout the greater Himalayan region, most available precipitation data come from lower elevation stations, generally below 2,000 m, and a very significant increase in precipitation can occur between those lower elevations and the accumulation zones of glaciers (Alford 1992).

Glaciers

The glacier accumulation and ablation patterns are distinctly different, seasonally and spatially, across the region. In the east, the summer season typically includes both maximum accumulation and maximum melt (accumulation at the highest elevations with melt below), while in the west there is a general pattern of summer melt and winter accumulation, similar to North America and Europe. Glacier termini extend to lower elevations, approximately 2,500 m, in the west, compared to approximately 3,500 m to 4,500 m in the east, due primarily to the lower temperatures at the higher latitudes of the more western mountain ranges.

Although there are reports of widespread glacier retreat in the east (e.g. Bajracharya et al. 2007; Kayastha and Harrison 2008), in the west, Hewitt (2005) and Immerzeel et al. (2009), for example, report that there has been expansion and thickening of the larger glaciers in the central Karakoram since the 1990s, accompanied by an exceptional number of glacier surges (i.e., rapid advances). This may result from the high elevation combined with a possible increase in orographic precipitation leading to accelerated accumulation. Other studies show positive mass balance anomalies in the Karakoram for the same period, such as those based on multi-sensor remote sensing analysis and gravity data from the Gravity Recovery and Climate Experiment (GRACE) (Bishop et al. 2008). Some Karakoram weather-station records, and

gauging station data that show reduced runoff from the heavily glacierised Hunza basin, indicate that a general shift to a positive mass balance regime may be taking place (Fowler and Archer 2006).

The comprehensive scientific understanding of the glaciers of the Karakoram has been slow in developing due to the complex topography and related lack of systematic or long-term field measurements. However, certain valuable field observations have been undertaken over the past several decades, localised and limited as they might be. These earlier studies (1970s – 1980s) are described in a recent USGS publication (Shroder and Bishop 2010).

In summary, the west appears to show slower rates of retreat, less formation of pro-glacier lakes associated with flood hazard (described below), and frequent observations of advancing glaciers, in contrast to the eastern region.

The areal extent of glacier coverage across the mountain ranges of the study area

The major concentrations of glaciers are spread across about 12 mountain ranges forming the headwaters of almost all the major rivers in the central, south, and southeast Asia mainland. Although there are currently no complete glacier inventories, there is some general agreement on the area of the glaciers in High Asia. The total glacier coverage is estimated to exceed 110,000 sq.km, with the number of identifiable glaciers exceeding about 50,000 (Dyrgerov and Meier 2005). However, given the incomplete inventories, area estimates may differ, such as those of Cogley (2003) who is of the opinion that for some Asian basins (Brahmaputra, Ganges, and Indus, for example) the generally accepted area values may be considerably underestimated.

The World Glacier Monitoring Service (WGMS) in 'Global glacier changes: Facts and figures' (Zemp et al. 2008) states that the total glacier coverage for the 'greater Himalayan region', is 114,800 sq.km, with 33,050 sq.km in the central Himalayan range. The International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, reports that there are 32,182 sq.km of glaciated area the central Himalayan region, within the mountain catchments feeding the Ganges, Brahmaputra, and Indus river basins (the central Himalayan region) (Eriksson et al. 2009 citing Qin 1999).

In the upper Indus and Yarkand basins, glacier coverage is approximately 21,000 sq.km, with the largest fraction, about 16,500 sq.km, in the Karakoram. There are more than 5,000 glaciers in this region, but 12 make up almost 50% of the total area (Hewitt 2010). Other mountain glacier coverage amounts to 15,417 sq.km for the Tien Shan, 12,260 sq.km for the Kunlun Shan, and approximately 12,200 sq.km for the Pamir (Dyrgerov and Meier 2005).

Glacier melt and area/mass changes

Glacier melt (but not necessarily negative mass balance) is occurring in the Asia Region. This is a normal warm season phenomenon, more or less a continuous process since the LIA, at the lower elevations of virtually all glaciers. The amount of melt generally depends on elevation, aspect, and local climate of the glacier.

Glacier terminus and area measurements

Estimated rates of terminus retreat, typically measured from the point of furthest down-valley extent of a glacier, vary from approximately 2 to 20% over the past 40 years, averaging about 0.4% per year (Kulkarni et al. 2007). ICIMOD reports that glaciers are retreating at rates of 10 m to 60 m per year and many small glaciers (<0.2 sq.km) have already disappeared (Bajracharya et al. 2007). Vertical shifts as great as 100 m in terminus elevation have been recorded during the past 50 years and retreat rates of 30 m per year are common. Change detection of total glacier area can involve the use of historic paper maps, ground or air photography, or satellite imagery. For a review of the methods, and challenges, associated with mapping glaciers using satellite imagery, see Racoviteanu et al. (2008b and 2009).

Bolch et al. (2008) show a decrease in the overall ice-covered area in the Khumbu Himalayas (Mt. Everest area) of approximately 0.12% per year between 1962 and 2005. The highest area loss occurred from 1992 to 2001, 0.25% per year, and the lowest between 1962 and 1992, 0.09% per year. The Khumbu Glacier itself has experienced very limited retreat since 1956 as indicated by the repeat photography of Byers (2007). However, it should be noted that the terminus of the Khumbu Glacier is covered with very thick debris which insulates the ice from the influence of above freezing temperatures. Byers (2007) does note that numerous lower elevation small glaciers of less than 0.5 sq.km, have completely disappeared since 1956.

Kääb et al. (2010) found retreat rates in the high elevation northwestern basins of the Brahmaputra and Lhasa rivers in Tibet AR to average less than 1% per year over the last 20-30 years, and they noted that their results were in good agreement with area changes reported from other studies in the region. These rates of retreat do not differ to any significant extent from retreat rates measured at other locations throughout the world, and in many cases the measured retreat is less than the global average.

While there is evidence in the eastern Himalayas of increasing rates of retreat during recent decades, a contrasting picture often emerges from the western Himalayas where decreasing rates of retreat are reported, such as that from observations on the Gangotri glacier (Kumar et al. 2008) and other locations further to the west in the Karakoram (Hewitt 2005). Mayer et al. (2006) report that over the past 50 years the Baltoro glacier, located on the south side of the Karakoram and one of the largest in the Karakoram, and the world (approx. 1500 sq.km in area and more than 60 km in length) has apparently retreated only about 200 m. They also refer to an unpublished photograph from 1929 where the glacier snout looks almost identical to the modern one.

Scherler et al. (2010) report terminus changes from more than 250 glaciers across the Himalayan region between 2000 and 2008 using satellite data. They note that debris-free glaciers in regions of low relief have been mainly retreating, while debris-covered glaciers in high-relief areas were mostly stagnating and in-situ down wasting, but not always retreating. For example, the debris-covered Karakoram glaciers in the sample showed no signs of appreciable retreat. Thus their study demonstrated that regional differences in topographic relief and related debris cover should be considered when comparing glacier retreat rates. They also note that predictions of future water availability have typically neglected the effect of debris cover on glacier melt rates and thus likely overestimate the rate of glacier meltdown in steep mountain ranges such as the Himalayas where debris-covered glaciers are common.

Naz et al. (2010) determined that across the Upper Indus Basin in general, during the period 1977 to 2006, the snow-covered area on the glaciers (accumulation zones) increased, while the ice-covered area (ablation zones) decreased, caused primarily by the increased snow area, but in particular locations by increased debris covered area, as well as simply due to localised glacier retreat. This analysis, derived from Landsat satellite images, also indicated a pattern of decreasing equilibrium line altitude (ELA) and an associated positive glacier mass balance pattern over the study period. In addition, the authors ran a climate model (VIC) using daily maximum and minimum temperatures increased by 5°C (A2 scenario) which led to a decrease in the seasonal snow cover at the lower elevations, but no comparable decrease at the elevations in the basins where the glaciers were located.

Temperature data from the Hindu Kush and Karakoram mountains of the Upper Indus Basin show a variable pattern, but one that would support the stability, if not growth, of glaciers in the region. Since 1961, summer mean and minimum temperatures show a consistent decline while winter mean and maximum temperatures show significant increases, although still remaining well below the freezing level at the elevation of the glaciers (Fowler and Archer 2006). Decreases of approximately 20% in summer runoff of the Hunza and Shyok rivers are estimated to have resulted from the observed 1°C decrease in mean summer temperatures, a pattern consistent with the observed thickening and expansion of some Karakoram glaciers (Fowler and Archer 2006; Hewitt 2005).

Several relatively recent studies have evaluated glacier retreat in the Akshirak and Ala Archa mountain ranges of the Tien Shan. Khromova et al. (2003) used air photo mapping surveys from 1943 and 1977 with ASTER satellite imagery from 2001. They determined a small shrinkage of only a few percent between 1943 and 1977 in contrast to a major shrinkage of more than 20% between 1977 and 2001. The reasons presented for this large reduction in glacier area include increases in annual and summer temperatures, decreases in precipitation, and a decrease in the summer/winter precipitation ratio – less snowfall at the higher elevations on the glaciers during summer results in a lower albedo (reflectivity) and higher melt rates. Another study in the same region by Aizen et al. (2006), using similar input data, found lesser amounts of glacier shrinkage over the later period of 1977 to 2003, 8.7% and 10.6% respectively for the Akshirak and Ala Archa mountains. A third study (Bolch 2007) determined that for the Northern Tien Shan (Kazakhstan/Kyrgyzstan) the average decrease in glacier extent was more than 32% between 1955 and 1999 in the valleys of Zailiyskiy and Kungey Alatau. A recent study by Aizen et al. (2010) provides a comprehensive assessment of glacier-climate responses across the Tien Shan using extensive satellite and surface station data. For the period 1973 to 2008, the total glacier area lost for the region was 8.5%, with the largest losses, 14.3%, in the northern Tien Shan where the annual precipitation had decreased

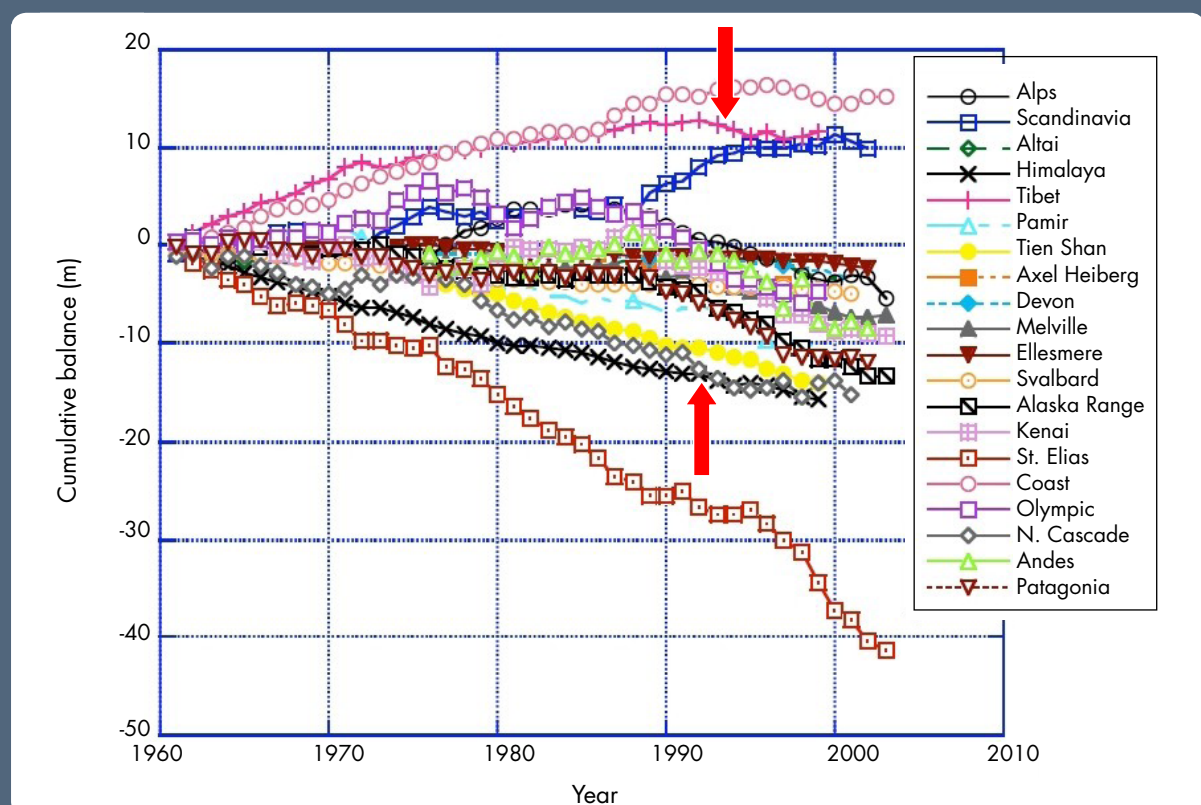
and summer air temperatures had increased. In Central Asia in general, Kotlyakov and Severskiy (2009) report that during the period 1956 to 1990 glaciers receded by more than one-third, and that the current rate of recession is thought to be approximately 0.6 - 0.8% per year.

Glaciers in the Muztag Ata and Konggur mountains of the eastern Pamir plateau, northwestern China, have been monitored by applying aerial photo stereo models (1962/1966) and Landsat TM (1990) and ETM+ (1999) images, which were compared in order to detect areal and frontal changes through the past four decades (Shangguan et al. 2006). Glaciers in the Muztag Ata and Konggur mountains retreated 6.0 m per year between 1962/66 and 1990, increasing to 11.2 m per year between 1990 and 1999, with an overall glacier length reduction of 9.9% for the whole study period. The glacier area has decreased by 7.9%, mainly due to changes observed in the most recent period (1990-99), when the annual area loss almost tripled.

Yao et al. (2009) describe how the percentage of retreating glaciers within China has increased from about 50% of all glaciers during the period 1950-1970 to more than 90% since 1990. The least amount of retreat has occurred at the higher elevations of the Tibetan Plateau with increasing amounts of retreat toward the lower elevations of the south-east edge of the Plateau and the lower elevations of the Karakoram mountains. This general situation is reflected in Figure 3, where the mass of the glaciers at the higher elevations of the 'Tibet' region is shown to be decreasing at a slower rate than glacier mass in the more extensive 'Himalayan' region, which includes glaciers found at much lower elevations.

In summary, the rate of retreat and/or down-wasting depends on several factors. These include elevation, topographic slope and aspect, debris cover, and ice thickness, and not all investigators consider these variables when they report retreat rates. Clearly, the greatest retreat and or down-wasting is associated with those glaciers located at the lowest altitudes on gentle slopes, with thin ice near the terminus, and a debris-cover thickness that enhances rather than retards melt. Smaller glaciers at the lowest elevations with a southerly aspect, and those 'hanging glaciers' cut off from a substantial accumulation area, will be the first to disappear.

Figure 3: **Cumulative mass balances (m) for selected glacier systems compiled from individual glacier time series** (from Dyurgerov and Meier 2005, details in reference list; upper red arrow, 'Tibet' region, lower red arrow, 'Himalaya' region)



Mass balance measurements

WGMS (Zemp et al. 2008) reports an average global annual ice loss of almost 0.75 m of water equivalent since 1997 (average thickness across total global glacier ice area), twice as much as in the decade before, 1988-1997, and three to four times as much as the time period 1978-1987. However, a key fact to note here is that virtually all of the glaciers in this global sample exist within an elevation range that is well below the average elevation of the Himalayan glaciers. For a review of mass balance monitoring of the past six decades, see the recent publications by Zemp et al. (2009) and Lemke and Ren (2007).

Mass balance records from Himalayan glaciers are extremely rare and of short duration (Zemp et al. 2009). Only records of ten or more years are relevant for climate and hydrological variability and trend studies, and only two glaciers barely meet this threshold. Most glaciers studied are also very small in size and altitude range and as such are not representative of all Himalaya glaciers.

Mass balance data from the higher elevation Langtang (Nepal) and Chhota Shigri (India) glaciers indicate consistently negative mass balance values, but the extent to which they can be considered regionally representative is not known. The glacier AX010 in Nepal has been predicted to disappear by the year 2060 if conditions represented by the period 1992-1996 remain unchanged (Kadota 1997). This could be considered a reasonable prediction, given that the size of this glacier was only 0.57 sq.km. The uppermost altitude of AX010 is 5360 m, while approximately 50% of the surface area of all Nepal glaciers exists at altitudes above approximately 5400 m (Alford et al. 2010). Therefore, AX010 can only be considered representative of the lower elevation glaciers. On the Yala glacier, in Nepal, at a higher elevation than the Langtang, Fujita et al. (2006) have constructed a 30-year mass balance history from ice cores and the inspection of crevasse layers. They determined that the mass balance on the Yala glacier at 5,380 m shows a positive balance, about 0.2 to 0.8 m, during the period 1960 to 2000, tending towards zero in the mid-1990s. Only a limited amount of melt was observed at 5,380 m on the Yala glacier. This observation would be in agreement with the estimates of Alford et al. (2010) that no significant melt occurs on the glaciers of Nepal under current climate conditions above approximately 5,400 m, as described in below.

Individual glaciers can respond with great variability to a changing climate. Therefore, it is important to involve more regional-scale estimates in the analysis of Himalayan glacier mass balance. Berthier et al. (2007) compared elevation data from 2000 Shuttle Radar Topography Mission (SRTM) data with a 2004 digital elevation model (DEM) derived from SPOT5 (Satellite Pour l'Observation de la Terre) imagery in the Himachal Pradesh region of northwest India. Results indicated an average mass balance of - 0.7 to - 0.85 m per year of water equivalent over a total glacier area of 915 sq.km. Such values are comparable to the global average (Zemp et al. 2008).

Naz et al. (2008) calculated recent thickness changes on glaciers in the Upper Indus Basin of the Western Karakoram by subtracting SRTM elevation data from Ice, Cloud, and land Elevation Satellite (ICESat) data for the period 2004 to 2008. Preliminary results indicated the average thickness change over glaciers in the Hunza Valley to be approximately + 0.10 m/year in the ablation zone and approximately + 0.64 m/year in the accumulation zone, implying a recent mass balance regime that is positive.

Only one time-series set of mass balance measurements has ever been made in the Karakoram. Bhutiyani (1999) used the hydrological (water-balance) method to compute the mass balance of the Siachen glacier in the Nubra Valley, eastern Karakoram range, India, the largest glacier in the Himalayas (1142 sq.km), for the period 1986-1991. The average mass-balance was negative, the lowest being in 1990-91 (-1.08 m). A positive mass balance was calculated for 1988-89 (+ 0.35 m) and was attributed to comparatively heavy winter snowfall amounts and low temperatures during the ablation season. Significantly lower runoff was measured during this season. The most negative values of 1989-1990 and 1990-1991 are thought to be the result of comparatively dry winters and warm ablation periods, with monthly mean air temperatures 1.4 to 5.1°C higher at the beginning of the ablation season, June and July, than the mean of the five years.

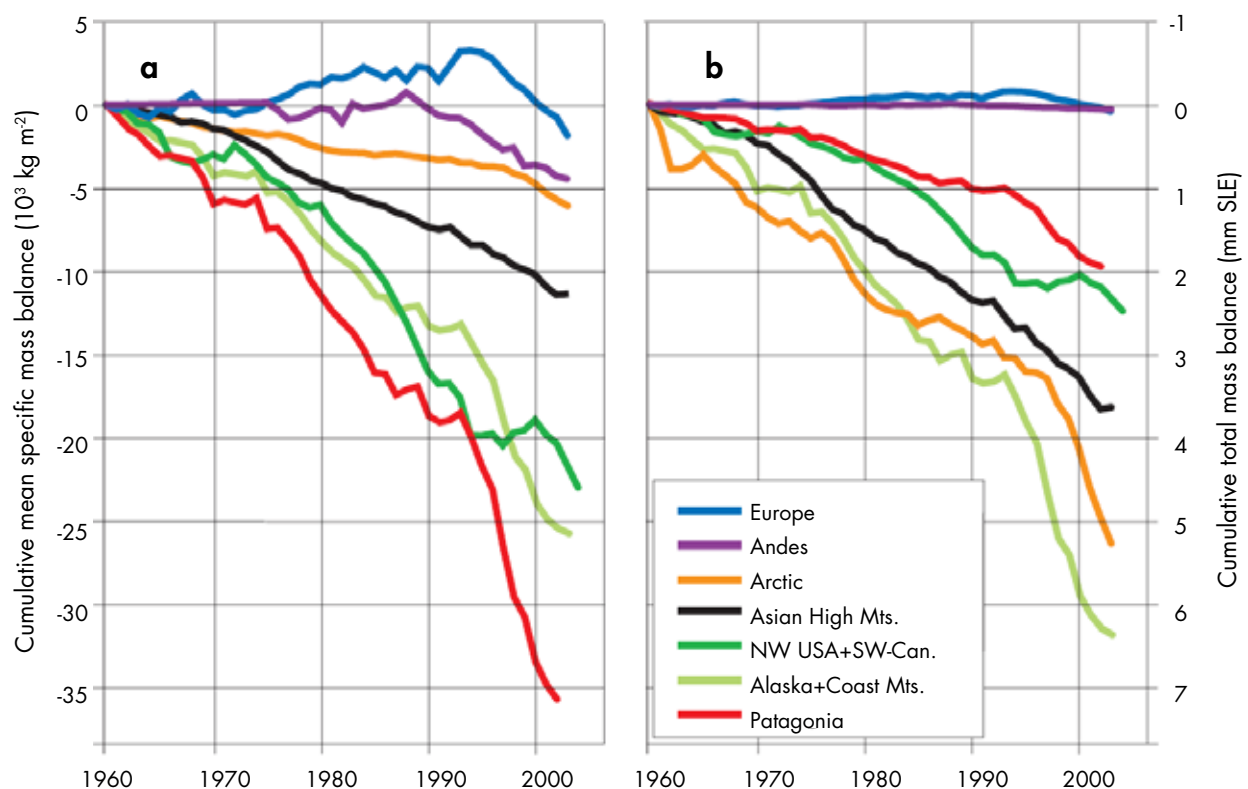
One of the very few examples of systematic direct measurement of melt in the ablation zone of a Karakoram glacier has been reported by Mayer et al. (2006) and Mihalcea et al. (2006). They measured melt on the Baltoro glacier using a

network of ablation stakes along a transect from 4100 to 4800 m. They estimated the equilibrium line altitude (ELA) for the Baltoro to be between 5300 m and 5500 m. Above this elevation, they noted that in almost all cases precipitation is deposited as snow. Below this elevation, a significant portion of the surface area is debris-covered, increasing in thickness down glacier to reach a maximum exceeding 1 m near the terminus. This debris cover considerably reduces the rate of ice melt. The variation of ablation rate with changing debris thickness and local surface conditions was observed to be larger than the effect of elevation. Between the elevations of 4537 m and 4649 m total ablation was between 0.5 m and 0.8 m. Ablation below 3900 m was not considered because the large debris cover made it very difficult to estimate melt rates. Good agreement was found between the measured ablation and the cumulated positive degree days using the method of Kayastha et al. (2000).

Projected extent of glacier melt in the next 15 to 20 years

One assessment of future glacier melt in the Himalaya recently receiving widespread attention was published in the 2007 Intergovernmental Panel on Climate Change (IPCC) Working Group (WG) II report (Cruz et al. 2007), "Glaciers in the Himalayas are receding faster than in any other part of the world and, if the present rate continues, the likelihood of them disappearing by the year 2035 and perhaps sooner is very high if the Earth keeps warming at the current rate." This statement has subsequently been acknowledged as not being correct by the IPCC. No evidence was presented that Himalayan glaciers are receding faster than those in other parts of the world, as only rates of retreat for the Himalayas were presented. In contrast, 2007 IPCC WG I authors of 'Changes in Glaciers and Ice Caps' correctly noted that "the glaciers of High-Mountain Asia have generally shrunk at varying rates and that several Karakoram glaciers are reported to have advanced and/or thickened" (Lemke and Ren 2007). The cumulative glacier mass balance data from the high mountains of Asia show values that are in fact approximately mid-way between the global extremes (see Figure 4a). A comparison of the rates of decrease of glacier area in various parts of the world can be found in Racoviteanu et al. (2008a) where it is also shown that retreat rates in the Himalayas are typical.

Figure 4: Cumulative glacier mass balance (10^3 kg m^{-2}) for selected glacier systems (a), and cumulative contribution (mm) to sea level (b) (from Lemke and Ren 2007, details in reference list)



In one recent study involving prediction, Ren et al. (2007) applied three GCMs (global circulation models), with warming effects based on a high emissions scenario, over the 30-year period of 2001–30, across the greater Himalayan region. Despite certain regional differences, all three GCMs indicated a spatially averaged glacier thickness reduction of approximately 2 m for the period 2001–30, but only for those areas located below 4000 m.

Rees and Collins (2006) have applied a temperature-index-based hydro-glaciological model in which glacier dimensions are allowed to decline with time to determine by how much and when climate warming will reduce Himalayan glacier dimensions and affect downstream river flows. Two hypothetical glaciers, of equal dimensions and initial geometries, were located within two hypothetical catchments representing the contrasting east and west climates of the Himalayan region. The model was applied from a start date of 1990 for 150 years with a uniform warming scenario of 0.06°C per year. Flows for these glacierised catchments attain peaks of 150% and 170% of initial flow at around 2050 and 2070 in the west and east respectively, before declining until the respective hypothetical glaciers disappear in 2086 and 2109. The general modelling approach is appropriate here but model inputs and glacier geometries are hypothetical, and it is assumed that melt is uniform over the total glacier surface with no distinction between specific ablation and accumulation zones. Therefore, the accuracy of results is uncertain.

In summary, where consistent results exist across various modelling efforts, they indicate little potential loss in total meltwater available from glaciers over the next few decades. This is because increased temperatures could be compensated by increased precipitation falling as snow at the higher elevations, above approximately 5,000m, as a possible result of a strengthened Indian monsoon (Sreelata 2006).

The role of black carbon in accelerating glacier melt

Black carbon emissions originate from a variety of sources, including biomass burning, residential burning, transportation, and industry/power production with relative amounts dependent on region (USAID-Asia 2010). Black carbon is a strong absorber of solar radiation and is thought to be the second-largest contributor to global excess radiative forcing after CO₂ (Ramanathan and Carmichael 2008) and, with other aerosols in atmospheric brown clouds (ABCs), a substantial contributor to atmospheric warming trends in Asia (Ramanathan et al. 2007). Where black carbon accumulates over a snow or glacier surface, the impact on melt rate may be significant and can be quantified where amount and type of soot/black carbon are known. Kandlikar et al. (2009) point out that black carbon particles that fall on bright snow or ice surfaces may potentially contribute to several extra months of warming each year. At this time, however, very few in situ measurements are available, although appropriate measurements can be expected to increase in the future.¹

A recent paper by Xu et al. (2009) describes measurements of black soot in ice cores from Tibetan glaciers and speculates on the melt rate impact. They show that the black soot content is sufficient to affect the surface reflectivity of the glaciers and that the black soot amount has increased rapidly since the 1990s, coincidentally with the accelerating glacier retreat and increasing industrial activity in South and East Asia. They suggest that a successful strategy to retain the fresh water benefits of Himalayan glaciers will require the reduction of black soot emissions so as to restore more pristine high-reflectivity snow and ice surfaces. They noted that black carbon concentrations of 10 ng g⁻¹ significantly alter the albedo (reflectivity) of a snow layer. The visible albedo of fresh snow, about 0.90–0.97, is decreased by 0.01–0.04 by a black carbon amount of 10 ng g⁻¹, thus increasing absorption (1 minus albedo) of visible radiation by 10–100%, depending on the size and shape of snow crystals and on whether the soot is incorporated within snow crystals or externally mixed (Hansen and Nazarenko 2004). The impact of the albedo change is magnified in the spring at the start of the melt season, because it allows melt to begin earlier.

In November 2009, a French research team (IRD) began work on Kongma La glacier, a very small and debris-free glacier, located close to Pokalde summit, near the Khumbu glacier, Everest region, in collaboration with the Ev-K2-CNR project. This glacier, close to the Ev-K2-CNR Pyramid laboratory, will be used for studying the impact of aerosols and black carbon on glacier melting. This is part of a project (PAPRIKA) funded by the French National Research Foundation.

¹ See Lau, W et al. (2009) *Will black carbon siphon Asia's drinking water away?* AGU Annual Fall Meeting 2009, <http://www.nasa.gov/topics/earth/features/carbon-pole-briefing.html>; and proceedings of the UNEP sponsored international expert workshop, 'Emerging issues in climate change: State of tropospheric temperature, pollution, snow, melting glaciers and potential impact on monsoon in the Himalayas-Tibetan Plateau,' held 28-29 December 2009, New Delhi, India

Impacts on water resources

While the mass balance measurements described above do represent the measure of the health of a glacier and its ability to maintain its mass from one year to the next, the values do not reveal per se anything explicit about the hydrology of the basin containing the glacier. If the mass balance is approximately zero, we know the glacier is in balance with the current climate, but we have no direct quantitative measurement of how much glacier meltwater is being contributed to the river system leaving the basin containing the glaciers.

Previous assessments of the glacier melt impact on surface water supply have been primarily either highly qualitative or local in scale, and in some cases, appear to be simply incorrect. For example, values reported in Singh and Bengtson (2004) and Barnett et al. (2005) appear to be far too large. Barnett et al. (2005) stated that "There is little doubt that melting glaciers provide a key source of water for the Himalayan region in the summer months: as much as 70% of the summer flow in the Ganges and 50–60% of the flow in other major rivers." Direct evidence is lacking to support such high values for the contribution of glacier ice melt to total river flow volume, although it is accepted that the percentage increases from east to west across the Hindu Kush-Himalayan region.

Rees and Collins (2006) believe that if all Himalayan glaciers were to disappear, there would be a much greater impact on the water resources of the west than the east, with reduction in annual mean flow of about 33% in the west, but only about 4–18% in the east, compared to 1990 levels, because of the climatic differences between the drier western and monsoonal eastern ends of the region. They note that high discharge from glacier ice melt often dominates flow for considerable distances downstream, particularly where other sources of runoff are limited. They also speculate that, should Himalayan glaciers continue to retreat rapidly, water shortages might be widespread within a few decades.

A study by Alford et al. (2010) indicates that in Nepal the glacier contribution to sub-basin stream flow varies from approximately 20% in the Budhi Gandaki basin to approximately 2% in the Likhu Khola basin, averaging approximately 10% across nine basins. This discharge volume represents approximately 4% of the total mean annual estimated volume of 200,000 million cubic metres for the rivers flowing out of Nepal. Under current climate conditions, results indicated that the glaciers of Nepal experience no significant melt over approximately 50% of their surface area at any time of the year. This is in sharp contrast to lower elevation glaciers of the world that melt over their entire surface during the summer months, often resulting in significant mass loss.

For the upper Indus basin, Immerzeel et al. (2009) found that glacier melt contributed substantially to streamflow, 32% in a reference situation and peaking in July, with snow melt providing 40% of the total with a peak in June, and rain comprising 28% with a peak in July. The removal of all glaciers, with an accompanying increase in the winter and summer temperatures of 4.8°C and 4.5°C, respectively, and precipitation increases of 19.7% and 15.7% (climate model scenario for 2071-2100) indicated a reduction in summer maximum flow of approximately 30%, and a reduction in the percentage of total precipitation falling as snow from 60% to 48%. In these types of projections there is typically an increase in total precipitation, summer and winter, with melt from snow cover remaining about the same and peak discharge appearing approximately one month earlier than present conditions. Patterns of increased total precipitation and earlier snow melt could actually be beneficial for agriculture, as this pattern would provide more water for local irrigation and increased input to reservoirs when they are most empty at the beginning of the growing season.

Immerzeel et al. (2010) have recently applied their modelling approach across the greater Himalayan region and conclude that glacier melt water is extremely important in the Indus Basin, reasonably important for the Brahmaputra, but only plays a modest role for the Ganges, Yangtze, and Yellow rivers. Preliminary results indicate that the snow and glacier melt contribution, compared to total runoff generated below 2,000 m, is as follows: Indus 151%; Brahmaputra 27%; Ganges 10%; Yangtze 8%; and Yellow 8%. This recent work of Immerzeel et al. represents an important step forward in understanding the regional hydrology of the greater Himalayas.

In Central Asia, Severskiy (2009) reports that glaciers lost volume at about 1% per year during the last 35-40 years of the 20th Century. Such losses will result in significant changes in the hydrological cycle as glacier runoff is responsible for 40-50% of discharge in the Tarim and Balkhash basins (from Dolgushin and Osipova 1989, referenced in Kotlyakov and Severskiy 2009). For the whole Tien Shan, the annual and summer fractions of glacier runoff are approximately 20 and 35% respectively (Aizen et al. 2006).

In summary, a highly accurate assessment of the significance of snow and glacier melt in the overall Asian river hydrology remains largely unaccomplished. There is reasonable confidence in stating that the contribution of glacier ice melt to the total downstream hydrology is small in the east, and not expected to change in the next few decades. Contribution is considerably larger in the west, but total volume from glacier melt is still relatively small and there is no apparent reason to think that it would change significantly in the next few decades. It should be noted that while the contribution from melting glacier ice to the hydrology of the lower reaches of mountain rivers is relatively small, melt water increases in significance when moving upward in the basin towards the source of that melt water. However, societies that have adjusted to this current minimal volume of melt water from glaciers are not likely to be in for any great surprises over the next few decades.

Environmental impacts of glacier melt

A misconception sometimes found in the popular literature expresses the concern that the rapid melting of glaciers will lead directly to catastrophic flooding downstream. Flooding from glacier ice melt alone is not physically possible. Glacier ice melt rate under any reasonable warming scenario is relatively slow, and thus cannot, per se, cause floods. The actual environmental impacts come in the form of hazards associated with two distinct types of glacier lake outburst floods (GLOFs). Interestingly, these types of floods can result from both retreating and advancing glaciers. One, a moraine-dammed outburst flood, occurs when large volumes of water build up behind the terminal moraine of a rapidly melting, retreating glacier and the moraine dam fails. For example, in 1985 a glacial lake, Dig Tsho in the Khumbu region of Nepal, burst and the flood waters completely destroyed a nearly completed hydro-electric power station at Thame, some 12 km below Dig Tsho that was being built with the assistance of the Austrian government. Thirty houses, many hectares of scarce agricultural land, and 14 bridges were also destroyed (Ives 2006).

Results from a 20-year study of the moraine-dammed glacier lake at the Imja glacier in the Khumbu Himal, located a few kilometres south of Mt Everest and often characterised as one of the most potentially dangerous in the Himalayan region, show that it is relatively stable (Watanabe et al. 2009, Fujita et al. 2009). Efforts to identify which lakes are actually the most dangerous are currently underway (Bajracharya et al. 2007, Ives et al. 2010). Bajracharya and Mool (2009) report that during the past decade the overall area of moraine-dammed lakes has increased, although the number of lakes above the elevation of 3,500 m has decreased.

Past records show that at least one GLOF event occurs every 3 to 10 years in the Himalayan region (Bajracharya et al., 2008). Although this type of GLOF did become more frequent during the second half of the 20th century (WHO 2005), only a small number of the total moraine-dammed lakes are actually dangerous at the present time. However, with rising temperatures the frequency and size of moraine-dammed lakes is expected to increase in the coming years, along with the associated potential for outburst floods, and thus the hazard represented by those moraine-dammed lakes that are upstream from inhabited and heavily travelled areas is considerable.

The second type of outburst flood, which is associated with advancing glaciers, occurs when a glacier tongue reaches the location where a tributary river or stream converges with the advancing glacier and is dammed by the advancing ice tongue. In this case an outburst flood may occur when the glacier subsequently retreats or breaks up. These glacier outburst floods are often referred to by the Icelandic name of 'jökulhlaups' (Ives 1986).

Hewitt (2010) notes that in the Karakoram, there is a greater prevalence of ice-dammed lakes or 'jökulhlaups' formed by advancing glaciers (typically short-lived and unstable), in contrast to moraine-dammed lakes, which are more typical in the east and associated with greater rates of melt. The only types of damaging outburst floods reported from the upper Indus Basin in recent decades have included debris flows (conversion from water flood to debris flow). According to Hewitt (2010), regions where advancing glaciers may possibly soon impound rivers are the Shaks gam, upper Shyok, and Shimshal valleys. In 2009, satellite imagery revealed a sudden advance of the Chong Khumdan glacier into the Shyok river. Previously, between 1926 and 1932, this glacier formed a series of large ice dams and at least four outburst floods were reported that resulted in a measurable rise in the river 1,100 km away at the Attock gauging station.

Conclusions

Glaciers can be thought of as long-term reservoirs, storing water in one place over many decades – unlike rain, or even seasonal snow melt, that typically reach the stream flow within days to months. This glacier storage acts like a large-volume water tank on the mountain side with new water coming in the top throughout much of the year, and some of the older water running out the bottom during the melt season. The annual balance question involves whether more water runs out from the bottom during melt than arrives at the top during a given year – and of course it is the long term that is ultimately more important than the annual or short term – that is, the climate versus the weather.

While the glaciers of the Himalayan region do provide a certain amount of the runoff to the 1.5 billion people living downstream, perhaps the smallest amounts correspond to the regions of the highest population: China, India, and the Southeast Asia mainland. In the eastern Himalayas the contribution of melting glacier ice to the downstream river flow is most likely less than about 5%. In the western Himalayas, and specifically the Indus basin, the contribution of melting glacier ice to the rivers is considerably larger. However, it is also thought that the glaciers in the western Himalayas are more in equilibrium with the current climate and may be retreating at a slower rate than those in the east, and in some cases advancing. Glacier melt water is estimated to comprise approximately one-third of the flow of the Indus river, with snow and ice together providing perhaps over two-thirds. It has perhaps the largest ratio of melt water to population of any river system anywhere in the world (Hewitt 2005; Immerzeel et al. 2010; Kaser et al. 2010).

More realistic, accurate and comprehensive assessments of the future availability of water resources in the Himalaya region in the context of glacier retreat are not possible until the existing hydrological regime of these mountains is better defined, the current relationship between glaciers and streamflow is evaluated in quantitative terms, and the contribution from other sources of streamflow is examined.

For the populations relying on the water resources provided by the Himalayan drainages, primary measures should involve well-planned management, conservation, and efficient use of the water that is currently available to them. The potential for rapidly increasing consumption or mismanagement of existing water resources should perhaps be of much greater concern than the relatively small changes that may occur in either the climate or hydrology in the coming decades. Finally, although glaciers across the Himalayan region may not be disappearing at as rapid a rate as had been previously thought, the need remains for mitigation and adaptation to the response of these glacier systems to climate change, as well as for the continued development of accurate estimates of the potential impact of melting glaciers on downstream water resources.

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The review is intended to be a reasonably comprehensive summary of the topic, given the length limits of the manuscript. It is acknowledged that the review cannot have covered each and every example of published results from glacier research in South and Central Asia, but does provide a systematic cross-section of such results with a focus on the most recent peer-reviewed publications

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