High mountain glaciers and climate change

Challenges to human livelihoods and adaptation

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Challenges to human livelihoods and adaptation

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Preface

Over half of the world's population lives in watersheds of major rivers originating in mountains with glaciers and snow. A warming climate is now causing a global recession in glaciers, and some areas may lose their glaciers entirely in this century.

For millennia, these rivers have formed life lines of cultures, food production, livelihoods and biodiversity. In modern times, these rivers also provide cooling water for power stations and water supplies for industry.

This report calls for accelerating research, monitoring and modeling of glaciers, snow and their role in water supplies. But perhaps even more important, this report highlights the vulnerability and exposure of people dependent upon these rivers to floods, droughts and eventually shortages as a result of changes in the melting and freezing cycles linked with climate change and other pollution impacts.

The impact of floods was brought into sharp relief in Pakistan in August 2010. As of November 2010, over six million people were still being affected by this disaster, with many displaced and housing, livelihoods, crops and livestock lost.

Worldwide, and particularly in Asia, over a hundred million people are strongly affected by floods every year, killing tens of thousands and increasing cases of disease and ill health as cities with limited or no sewage capacity become flooded and polluted water infiltrates drinking water sources and houses.

Here lies a crucial message for all nations involved. Changes in the intensity and timing of rains, added to variable snow and glacier melt will increasingly challenge food security and the livelihoods of the most vulnerable under various climate change scenarios.

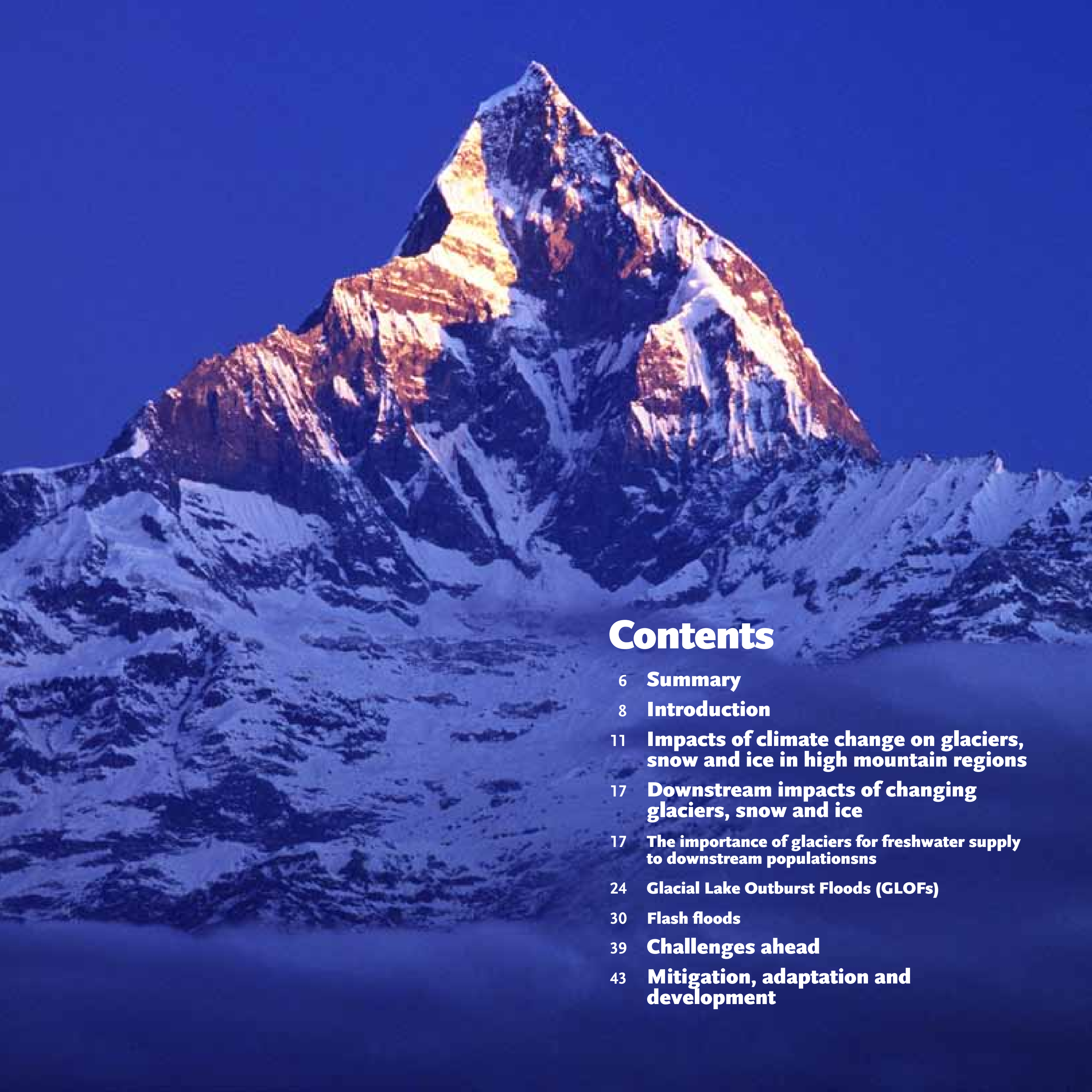
With urban populations expected to nearly double to over six billion people in 40 years, and land pressures rising in the surrounding hills, the development of strategies for adaptation is urgently needed with women often being in the center of the ability of families to cope.

Adaptation strategies need to be wide ranging covering issues such as urban planning, improved water storage networks and improved water efficiency in sectors such as agriculture, but also the rehabilitation and restoration of critical ecosystems ranging from forests to wetlands which can enhance water supplies and act as buffers against extreme climatic events such as flooding.

Glaciers and trends in their mass and size have recently been at the centre of the climate change debate. This report confirms the work of bodies such as the World Glacial Monitoring Services: namely that the overall trend is one of loss and shrinkage and that improved monitoring in many developing country regions will improve global scientific understanding while contributing to better early warning of potentially hazardous events.

I would like to thank the authors and contributors drawn from research centres in Asia, Europe, Latin America and North America for their efforts in making this report rigorous, impartial and above all contribution towards advancing humanity's options and actions in a climate constrained world.

Achim Steiner
UN Under-Secretary General and UNEP Executive Director



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Summary

Climate change is causing significant mass loss of glaciers in high mountains worldwide. Although glacier systems show a great amount of inherent complexity and variation, there are clear overall trends indicating global glacier recession, which is likely to accelerate in coming decades. Large gaps remain in our understanding and ability to model accurately the key processes and cause-effect relationships driving glacier response to climate change. In addition, a lot of data on glacier mass changes are not available to the public due to national interests concerning water supply.

Impacts of the shrinkage and disappearance of mountain glaciers include changes in the flow characteristics of glacier-fed rivers, glacier lake outburst floods (GLOFs) in the Andes and Asia, and changing flood severity and frequency. GLOFs were observed in Patagonia in 2008 and 2009, in addition to GLOFs in the Himalayas and Andes in the past decades in areas where glaciers are receding. While such GLOFs may immediately endanger lives, infrastructure and power supply, flash floods and particularly large-scale down-river floods pose an ever greater challenge and risk. These floods are caused by extreme events of intense and high-volume monsoons or other types of rains that are often exacerbated by unsustainable land use practices killing several thousand people every year directly, and impacting over 100 million people annually, including through loss of crops and eruption of diseases associated with flooding of sewage or contamination of drinking water supplies.

The glacial contribution to river flow varies greatly, both annually and within and between catchments. The hydrological significance of glacier runoff also depends on other components of the hydrological cycle, such as precipitation, evapo-transpiration, and groundwater flow. In consequence, the impacts of glacier mass loss will be highly variable both locally and worldwide. Some regions will undoubtedly be affected by water shortage, whereas others are unlikely to be significantly affected by glacial melt. Much detailed work remains to be done to adequately predict regional and local hydrological responses to climate change. Flood risks are expected to increase in some regions, including increased frequencies of GLOFs and weather-related flash floods in both the Hindu Kush Himalayas and in the Andes. Melting of glaciers and ice caps will also have global effects on sea level rise. It is currently estimated that they will contribute approximately 40 to 150 mm (depending upon the greenhouse gas scenario and climate model used) to sea level rise by 2100.

Changes in glacier regimes and runoff from snow and ice, combined with changes in precipitation timing and intensity will most likely increase human vulnerability in many areas. Livelihoods are affected as climate variability and water stress affect agriculture, forestry, health conditions and tourism. Future challenges for the management of impacts of climate change include filling data gaps, improving regional cooperation in observation networks and developing comprehensive databases, improving modeling of glacier mass balance and runoff, strengthening regional cooperation and developing adaptive strategies that are cultural and context specific, and ensuring sufficient irrigation capacity to uphold higher levels of food production.

One of the chief challenges in the coming decades will be to capture and store excess water during periods of high water availability. We are likely to experience more extreme melting, as well as extreme events of rainfall. With great land-use pressures in many mountain regions, including deforestation and heavy grazing combined with extreme rainfall, flash-floods and flooding will likely increase. New and more effective systems in both capturing and storing water will become essential in the future. This includes both installation of new water capture and storage methods, as well as re-introduction of some of the ancient traditional irrigation systems, such as the qanat, foggara, karez or falaj systems known from desert regions, and the zabo, pokhari, johad and pyne systems known from hilly regions.

Irrespective of the variation in glacial and snow melt, which normally contributes only a smaller share of the total river flow, future variability in timing and intensity of precipitation will contribute substantially to down-river impacts. Indeed, continuing land pressures, rapid urban development and settlement of the impoverished in exposed low-lying areas greatly influence flood risks, health and livelihoods. More than 40% of the world's floods takes place in Asia, and have affected near a billion people 1999–2008, and causing an estimated 20–25% of all deaths associated with natural disasters. In 2009, more than 56 million people were severely impacted by floods and over 1 million people by the smaller, but often dangerous flash floods.

Down-river regions also comprise critical food production centres. The combined actions of changes in timing and intensity in monsoons, other precipitation and land use will continue to often over-rule changes in glacial melt for downstream population centres, and provide major impacts not only on drought and flood risk and subsequent human exposure, but also on food security. This is particularly true for the Hindu-Kush Himalayas, Central Asia and parts of the Andes where large populations depend upon the mountains and predictable climate for food production and livelihoods.

Irrigation systems and pipelines from major rivers should also be developed, maintained and improved, also because deforestation frequently increases the rate and speed of the flow of water into major channels. Necessary training, revival of old knowledge and implementation of new greener irrigation technology will require funds and programmes directed towards adaptation. Storing excess water, adapting to floods and developing and implementing more effective irrigation systems will become crucial to future food security in regions dependent upon mountains for their water supply.

Glacier melt inputs to rivers can affect the ecosystems in a number of ways, including habitat changes such as stream temperatures, sediment concentrations, water chemistry and nutrient availability, or through the release of pollutants deposited and stored in the glaciers over many years, impacting fish and other organisms in glacier-fed systems.

Adaptation, mitigation and development should be seen as a continuum. Livelihood diversification will require significant policy and institutional support, and strategies must be sensitive to cultural contexts, norms and differences. Good governance and planning need to take climate change into account in order for infrastructure development to support water security.

Recommendations:

- Strengthen glacial research and trans-national collaboration with emphasis on mass calculation, monitoring and particularly the effects of glacial recession on water resources, biodiversity and availability downstream.
- Improve modeling on precipitation patterns and effects on water availability in particular in mountain regions of Asia and Latin America.
- Prioritize support to and development of adaptation to water-related disasters.
- Prioritize programmes and support to development and implementation of adaptation strategies for too much and too little water including strengthening the role of women.
- Urgently support the implementation and improvement of both small and large-scale water capture and storage systems and improve efficiency of current irrigation systems through the use of green technology and agricultural knowledge.

Introduction

There is increasing concern about impacts of climate change on high mountain glaciers and snow ablation, and the effects of glacier recession on sea-level rise, natural hazards and water resources. The conference "High mountain glaciers and challenges caused by climate change" was held in Tromsø on 8–10 June 2009, initiated by the Norwegian Ministry of the Environment in cooperation with the United Nations Environmental Programme (UNEP), and hosted by the Norwegian Polar Institute. The conference gathered leading scientists from glaciology, geography, resource management and related fields to discuss the latest research on high-mountain glacier meltings and the consequent effects on downstream regions.

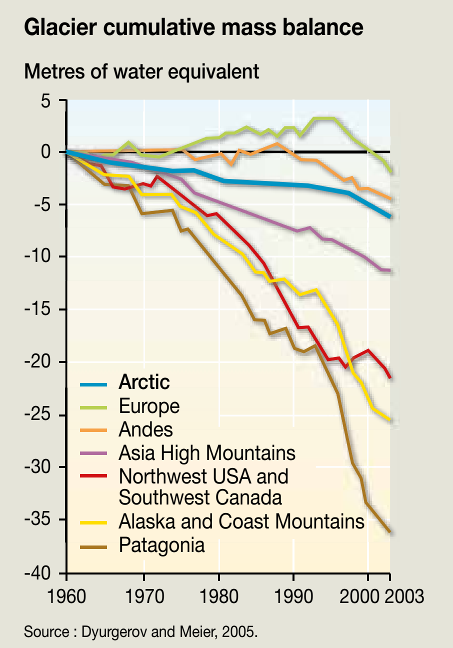
This report presents an update based on presentations and working group discussions at the conference, combined with recent compilations on issues of food security, disaster management and the need for adaptation, including from the Himalayas Climate Impact Assessment pilot study (ICIMODa-b, 2009; UNEP, 2009; 2010b). It outlines status and trends of high mountain glaciers in relation to climate change, identifies challenges and knowledge gaps, and finally makes recommendations for adaptation, research and policy.

Impacts of climate change on glaciers, snow and ice in high mountain regions

The majority of mountain glaciers are losing mass in response to climate change. Most glaciers have been shrinking since the end of the Little Ice Age around 150 years ago. However, since the beginning of the 1980s the rate of ice loss increased substantially in many regions, concurrent with an increase in global mean air temperatures. Glaciers might disappear from some mountain regions by the end of the 21st century given the current melting rate. At the same time, some glaciers have increased in size since the 1980s. This is consistent with regionally increased precipitation in a warming world.

Glaciers originate from accumulations of snow and ice and flow down the slope in response to gravitational forces, and grow or shrink as a result of exchanges of mass and energy. Glaciers gain mass mainly by snowfall, and lose mass mainly by melting in their lower reaches. Where glaciers terminate in lakes or the sea, significant mass losses can occur by iceberg calving. The difference between mass gains and losses, measured over one year, is known as the *annual mass balance*. Measuring mass balance is the primary quantitative way of measuring the effects of climate change on glaciers. Prior to 1976, however, such measurements are only available for the Northern Hemisphere with emphasis on Europe. Length change measurements provide an important supplement to mass balance measurements, showing intermittent periods of re-advancing glaciers but an overall global and centennial negative trend (Fig 1.)

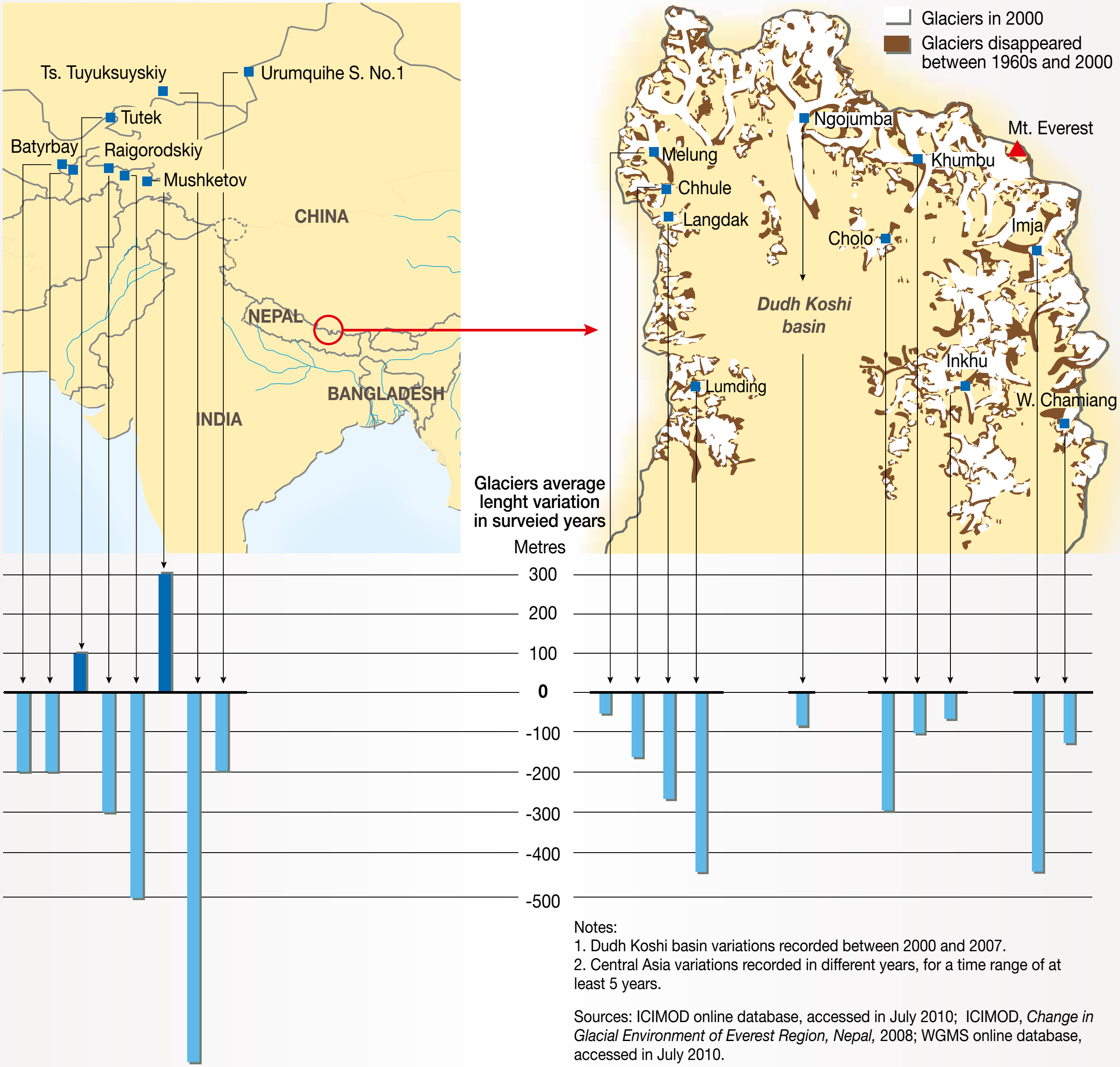
Compilation of available data (Fig. 1) shows that most mountain glaciers are losing mass, and that the overall rate of mass loss has increased in the last decade. For the last decade the highest mass loss per unit area has been observed in the European Alps, Patagonia, Alaska, and north-western USA/south-western Canada (Kaser *et al.*, 2006, Lemke *et al.*, 2007, Arendt *et al.*, 2009).



Source : Dyurgerov and Meier, 2005.

➔ **Figure 1:** Cumulative glacier mass balances for seven mountainous regions. Modified from Kaser *et al.* (2006) and Lemke *et al.* (2007).

Glacier recession and expansion in Hindu Kush-Himalayas and Central Asia



Notes:
1. Dudh Koshi basin variations recorded between 2000 and 2007.
2. Central Asia variations recorded in different years, for a time range of at least 5 years.

Sources: ICIMOD online database, accessed in July 2010; ICIMOD, *Change in Glacial Environment of Everest Region, Nepal,* 2008; WGMS online database, accessed in July 2010.

Averaged over their entire areas, within the period 1960–2003 glaciers in Patagonia and Alaska have thinned by approximately 35 m and 25 m, respectively, whereas high mountain glaciers in Asia have thinned by over 10 m. Data for Patagonia and Alaska are computed from glacier surface elevations for dozens of glaciers. In many other high mountain environments such as the Himalayas and the high Andes, where data are limited due to both difficult access to the high-altitude regions and for political reasons, the exact amount of regional mass loss remains subject to some uncertainty (Fig. 2). This makes it difficult to compare rates of change with other regions. Recent satellite observations, however, have confirmed that glaciers in many mountain regions are thinning (e.g. Berthier *et al.*, 2007; Paul *et al.*, 2007; Bolch *et al.*, 2008a, b), conclusively showing that the majority of mountain glaciers are losing mass in response to climate changes.

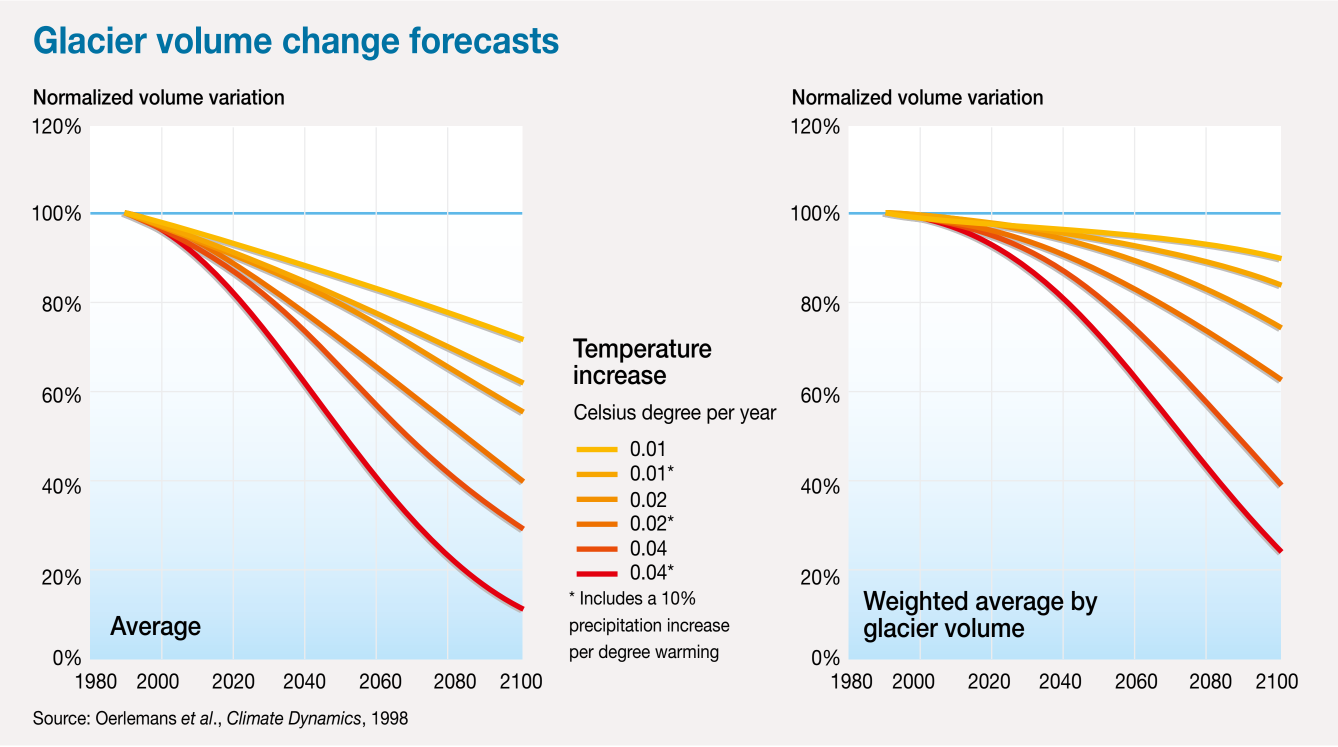
In a few areas, mountain glaciers have undergone periods of growth in recent decades. For example, glaciers in western Norway and the South Island of New Zealand advanced in the 1990s, glaciers on the southwestern sector of Cordillera Darwin, Tierra del Fuego, are presently advancing (Chinn *et al.*, 2005), while in the Karakoram mountains some glaciers have over-ridden areas that have been ice-free for 50 years or more (Hewitt, 2005), opposed to further north and east where glaciers are declining. In northern Karakoram in China, glaciers are receding and have resulted in increased number of glacial lake outburst floods (Chen *et al.*, 2010). These exceptions to the global trend of recession in ice mass can be partly explained in terms of regionally increased precipitation in a more energetic climate system, which locally offset the effects of temperature increase. In Norway and New Zealand, however, the recent glacier advances appear to be short-lived events superimposed on a longer-term trend of glacier recession. Frequently also the actual number of glaciers increase locally as larger glaciers melt down into several smaller glaciers, while the total ice mass obviously declines.

← **Figure 2: Glacier recession and expansion in Hindu Kush-Himalayas (HKH) and Central Asia.** Notice that while some glaciers, especially in the Karakoram, have increased, the majority of the glaciers in the HKH region and on the Tibetan plateau are receding.

Predicting the future response of mountain glaciers is fraught with difficulty. The world's mountain ranges encompass a huge range of topographic and climatic environments, and each glacier has a unique relationship with local terrain and microclimate. Indeed, local variation is so great that it is impossible to make general statements about glacier response even within single mountain ranges. For example, glaciers in the Himalayan region include large, winter-accumulation type glaciers in the high-altitude Karakoram, steep, summer-accumulation type glaciers on monsoonal southern slope of the mountains in Nepal, and small, cold-based cirque glaciers on the arid northern slope, each of which will exhibit different responses to local climate changes, demonstrated by the increase in some glaciers in western and southern Karakoram and recession in some in north-eastern (Chen *et al.*, 2010). Within each of these regions, glaciers occur across a considerable range of elevations. *In general, the most vulnerable glaciers are at relatively low elevations, whereas glaciers at high altitudes are more robust.*

Glaciologists have adopted a range of strategies to deal with this complexity. One common approach is to model the response of a small sample of glaciers, and then extrapolate the results to wider regions. Two basic types of models have been employed. First, static models compute how snow and ice melt rates will change under different climatic scenarios, but do not consider changes in glacier geometry (e.g. Radic and Hock, 2006). Second, dynamic models allow glacier dimensions and geometry to evolve through time, and can therefore include feedbacks between melt rates and glacier characteristics (e.g. Oerlemans *et al.*, 1998; Schneeberger *et al.*, 2003). While the second approach yields more robust results, dynamic models must be tailored to individual glaciers and are very time-consuming to implement. Consequently, dynamic models have been run for very few of the world's glaciers and most predictions are based on static models with a tendency to overestimate mass loss (e.g. ACIA, 2005). Undoubtedly, there is great need for more glacial research, monitoring and inventories (Braithwaite, 2009; Shi *et al.*, 2009).

Oerlemans *et al.* (1998) conducted modelling experiments for a sample of 12 glaciers and ice caps, to determine volume changes under a range of temperature and precipitation forcings (Fig. 3). The range of glacier response is very wide, so a key issue is finding ways to upscale the results of modelling this tiny sample of glaciers to large regions. Figure 2 shows the results of two alternative weighting procedures. Although the absolute values of volume change differ, the results imply



Source: Oerlemans *et al.*, *Climate Dynamics*, 1998

Figure 3: Scaled glacier volume changes for a range of climate scenarios. Labels are in degrees C yr^{-1}, and + indicates a 10% increase in precipitation per degree warming. The left-hand panel ($<V_{SC}>$) shows the average of all model results, and the right-hand panel ($<V>_{SC}$) shows results weighted by glacier volume. (From Oerlemans *et al.*, 1998: Climate Dynamics 14, 267–274)

that with a warming rate of 0.04° C yr^{-1} (4° C per century) and no increase in precipitation, little glacier ice would be left by 2100, whereas if warming is restricted to 0.01° C yr^{-1} and precipitation increases by 10% per degree of warming, then ice losses will be restricted to 10 to 20% of the 1990 value. It must be emphasized that the results are far from certain, and that the actual response of glaciers will exhibit considerable regional variability.

In some regions, it is very likely that glaciers will largely disappear by the end of this century, whereas in others glacier cover will persist but in a reduced form for many centuries ahead (Kulkarni *et al*., 2007; Ye *et al*., 2008; Bhambri *et al*., 2009; Nicholson et al, 2009; Wang *et al*., 2009; Yang *et al*., 2009; Caidong and Sorteberg, 2010; Federici *et al*., 2010; Kaser et al, 2010; Liu *et al*., 2010; Peduzzi *et al*., 2010; Shahgedanova *et al*., 2010; Shekhar *et al*., 2010).

Bahr *et al.* (2009) made a first-order estimate of the minimum future sea-level contribution from all glaciers and ice caps, based on the idea that most are currently out of equilibrium with current climate and still need to complete their adjustment to past climate changes. The delayed adjustment is equivalent to approximately 18 cm sea level rise (averaged over the entire globe) in the next couple of decades. This represents a lower bound, as global temperatures are almost certain to continue increasing over the next century, causing additional ice mass losses.

CASE STUDY

Impacts of climate change on high-mountain glaciers in the Alps: Observations and results from modeling studies

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Alpine glaciers lost about one-third of their total area from 1850 until the 1970s, and almost one half was gone by the year 2000. Starting from the last glacier inventory of the 1970s, little change was observed in the area until 1985 (–1%), but then a strong decrease (–20%) until the year 2000 occurred. This area loss was accompanied by a strong loss of glacier mass of about –11 meters water equivalent (m w.e.) or –0.8 m w.e. per year. This is more than three times the reconstructed long-term mean mass loss from 1850 to the 1970s of about –0.25 m w.e. per year (e.g. Hoelzle *et al*., 2003). The strong glacier decline is most likely a response to the sudden increase in Alpine temperature of about 1° C in the 1980s, which has shifted the equilibrium line altitude (ELA) by about 150 m upwards (precipitation has not changed much). This has reduced the accumulation area of most glaciers drastically and they react with an adjustment of their size to the new climatic conditions.

Simple models based on rules of thumb allow us to determine the consequences of such step changes in climatic conditions on future glacier evolution over large regions. With an assumed steady-state accumulation area ratio (AAR0) of 0.6, it can be calculated that about 40% of the total glacier area will disappear for a 150 m upward shift of the ELA. At current rates and considering the already lost glacier area since 1985, area loss will at least continue until 2015 and much longer for large glaciers with a response time of more than 30 years. In particular the large glaciers display strong evidence of down-wasting (e.g. collapse holes, disintegration) rather than retreat of the terminus. Based on current climate scenarios as published in the last IPCC report, it can be expected that glacier decline will continue and most glaciers in the Alps will disappear by 2100. Because glaciers as well as their meltwater in summer plays an important economic role in the Alps (e.g. hydro-power, discharge regime, tourism, natural hazards), concern is growing that the currently observed and future glacier changes will have adverse effects on human welfare (Elsasser and Bürki, 2002). In consequence, several projects have recently started that should improve the modeling of future climate change impacts on glaciers and runoff. The output from regional climate models (RCMs) and their efficient coupling to the much higher resolution impact models (e.g. distributed mass balance or hydrologic models) is in the centre of the scientific investigations (e.g. Paul and Kotlarski, 2010).

Downstream impacts of changing glaciers, snow and ice

The importance of glaciers for freshwater supply to downstream populations

Glacier melt contributes to river flow in many parts of the world, so changes in glacier mass can affect the availability of freshwater supply at diurnal, seasonal and multi-annual timescales. The importance of the glacial contribution to runoff depends on the magnitude of other components of the hydrological cycle, and is thus regionally highly variable.

Water is stored in glaciers in the form of snow (short-term reservoir) and ice (long-term reservoir), and is released by melting after some delay. At first, the most recent snow cover (e.g. from the previous accumulation season) melts and later snow from previous years that is located in the accumulation area melts. Both contributions do change the storage of short-term reservoirs. The ice that melts at the same time in the ablation region is much older (tens to thousands of years) and reduces the long-term reservoir that is in principal replaced by glacier flow. For a glacier extent that is in balance with climate, the amount of ice that is melting at the glacier tongue is replaced by the supplies from ice flow. The latter changes only slowly and in response to the long-term mass balance history. In this regard the mass balance in a specific year can be seen as the direct and un-delayed response to the annual atmospheric conditions, whereas the advance or retreat of a glacier tongue is a delayed, filtered and enhanced response to a (more long-term) change in climate.

On an annual time scale, the water that comes from a glacierized catchment is the sum of the precipitation and the melted snow and ice (minus some evaporation). Both contributions can have a pronounced seasonality (e.g. spring-time snow melt, glacier melt in summer, highest precipitation in autumn) and will thus strongly vary by region and degree of glacierization. On a decadal time scale, also a change in the long-term reservoirs will have an impact on runoff characteristics, as a diminishing glacier cover will produce less meltwater. However, in the coming decades there can also be first an increase of the glacier contribution to runoff (e.g. Huss *et al*. 2008), in particular when large glaciers are located in the catchment, that adjust their size only with some delay to the climatic forcing.

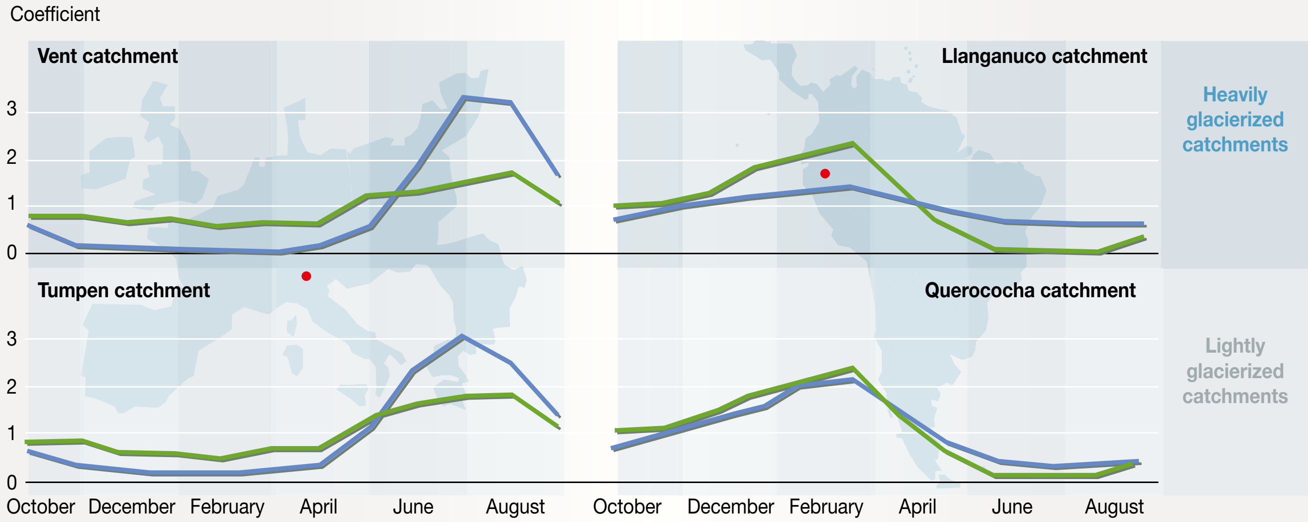
The role of glaciers on river flow can therefore be summarized as: (i) influencing daily and seasonal patterns of river flow, and (ii) increasing or decreasing total annual flows through long-term changes in the reservoirs, i.e. the area covered by glaciers and their respective volume. The impact of both effects on river flows further downstream depends crucially on the magnitude of other components of the hydrological cycle (e.g. rainfall, evaporation, groundwater flow), and thus varies greatly between regions (Immerzeel *et al*., 2010; Pellicciotti *et al*., 2010).

The influence of glaciers on seasonal distribution of river flow is strongly dependent on annual temperature and precipitation cycles, and the proportion of the catchment occupied by glacier ice. Figure 4 compares precipitation and river flow data for heavily and lightly glacierized catchments in the European Alps and Peru. In the European Alps, runoff is greater than precipitation in summer in both heavily and lightly glacierized catchments. This is because the Alps experience a large seasonal temperature cycle, and precipitation falls as snow in winter, providing a source of meltwater into the summer even where no glaciers are present. In Peru, on the other hand, temperature varies less throughout the year and there is less annual variation in snow cover. Thus, runoff is much greater than precipitation in the dry season (June–August) in heavily glacierized catchments, but not in lightly glacierized catchments. *The implication is that the removal of glaciers from catchments will have a much larger impact on water resources in Peru than in the European Alps*. Without a glacial source of meltwater, river discharges closely follow the precipitation cycle, with very little runoff in the dry season.

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

Reduction of the mass of glacier ice in a catchment will increase the annual river flow, so it will be greater than the precipitation total. This extra component of river flow has been called the 'deglaciation discharge dividend' (Collins, 2008), and will increase if melt rates rise in a warming climate. As glaciers shrink, however, the discharge dividend decreases because a smaller area of ice contributes meltwater. This will be the long term result. For the coming decades the areas will not change much, but the melt will nevertheless strongly increase due to downwasting of the flat and thick tongues from large glaciers.

Seasonal patterns of precipitation and runoff



Source: Kaser, G., *et al., The impact of glaciers on the runoff and the reconstruction of mass balance history from hydrological data in the tropical Cordillera Blanca, Peru*, Journal of Hydrology, 2003

Figure 4: Seasonal patterns of precipitation (Cp) and runoff (Cq) coefficients in heavily glacierized (top panels of the Vent (41% glacierized) and Llanganuco (33% glacierized) and lightly glacierized catchments (bottom panels Tumpen (2% glacierized) and Querococha (3% glacierized)), in the European Alps (left) and Peru (right), respectively (Kaser *et al.*, 2003).

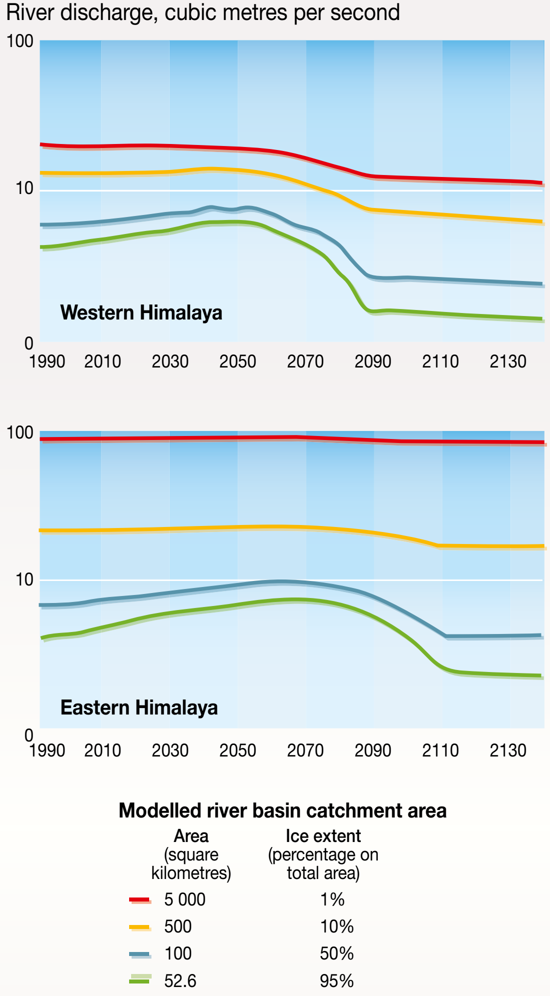
Eventually, when glaciers vanish completely, the discharge dividend is zero and annual river flows are equal to the precipitation. In a review of data from mountain regions in North and South America, central Asia and the European Alps, Casassa *et al.* (2009) showed that higher latitude/higher altitude glacier basins are still in the increasing glacier runoff stage, while some lower latitude/lower altitude basins are already experiencing decreased glacier runoff due to climate warming.

River discharge increases up to a point during the shrinking of glaciers, and the contribution to river flow is flow is greatest where glaciers occupy a large fraction of the catchment (i.e. in the high mountains), and progressively decreases downstream. This is because the glacial contribution to runoff decreases with increasing distance from the glacier fronts, as the river flow is supplemented by precipitation, groundwater flow, and tributary rivers from non-glacierized catchments. In some publications, estimates have been made of the glacial contribution to river flow for major river systems (e.g. Xu *et al.*, 2009). Such statistics are misleading, because the percentage varies along the course of the river. Detailed analyses of individual river basins are unavailable at the time of writing, and are urgently needed.

Downstream variation in the impact of glacier recession is illustrated in Figure 5, which shows modelled river flows for idealized catchments under climates representative of the western and eastern Himalaya and a 0.06° C per year warming scenario. In the upper parts of the river basins, where glaciers occupy 95% of the catchment area, the impact of glacier shrinkage is large. River discharges increase until mid-century, after which they decline to a base level equal to the annual precipitation totals. When larger catchments are considered, the percentage glacierized area is smaller, and the impact of glacier shrinkage is much reduced. For modelled catchments with an area of 5,000 square km and 1% glacier cover, the impact of deglaciation is barely detectable in the 'eastern' area, where there is high monsoon precipitation in

➔ **Figure 5:** Modelled impact of glacier shrinkage in hypothetical river basins in climates representative of the western (a) and eastern (b) Himalaya. Note that the river discharge (Q) has a logarithmic scale. (Rees and Collins, 2006).

Glacier shrinkage in hypothetical river basins



Notes:
1. The represented scenario includes idealized catchment under climates representative of western and eastern Himalaya and a 0.06° C annual temperature increase.

2. Logaritmic scale for river discharge.

Source: Rees, H.G., and Collins, D., N., *Regional differences in response of flow in glacier-fed Himalayan rivers to climatic warming*, Hydrological Processes, 20, 2157–2169, 2006.

summer. The effect is more significant in the 'western' area with its dry summer, but the downstream decrease in impact is still clearly evident.

It should be noted that the patterns of river flow shown in Figure 5 are not intended to be realistic predictions of what will happen to river flows in the Indian Subcontinent, but to illustrate the general principle that the impact of glacier mass loss will decrease downstream, and will be regionally variable, depending on glacier area, the rate of glacier melt, and the magnitude and seasonal distribution of precipitation in the catchment. *Semi-arid regions are likely to be the most adversely affected, whereas the effect of glacier retreat in monsoonal Asia will probably be buffered by other components of the hydrological system*. While the results indicate that the more alarmist predictions of the impacts of climate change are highly implausible, they do support the idea that glacier recession is likely to have a major impact in some areas. Detailed scientific studies of specific regions are urgently needed. It is however also clear that glacial melt is not the only factor impacting intensity and timing of water flow. Timing and intensity of the monsoon, other rainfall and especially land use practices such as deforestation, overgrazing, agricultural systems and settlement patterns are, on average, even more important for water flow in the lower and thus more densely populated parts of the catchments.

Effects on humans and livelihoods

Supply of and changes in meltwater and runoff from glaciers in high mountains can affect human populations and livelihoods in a number of ways. The term 'livelihood' includes the capabilities, assets (material and social resources), and activities for ensuring means of living (Carney 1998). Sustainable livelihoods deal with the idea of coping with and recovering from stresses and shocks (resilience). Climate change and more variability in water flow resulting in either too much water or too little water increases the vulnerability of mountain livelihoods. Downstream impacts of changes in water flow from high mountain glaciers may affect different aspects of human livelihoods. The agricultural and food production systems will be affected by water stress. UNDP (2006) has estimated a 30% decrease in crop yields in Central and South Asia by the mid 21st century due to increased temperatures and water stress. At the same time, crop yields may increase at higher altitudes and latitudes because of decreased frost and cold damage.

Changes in water flow can affect human health in a number of ways. Higher temperatures may lead to increased endemic morbidity and mortality due to diarrhoel and vector-borne diseases such as malaria, primarily associated with floods and droughts in the Himalayas (ICIMOD, 2007), but possibly also in other mountain regions. A warmer climate at higher altitudes may however also reduce the need for fuel wood and thus reduce the frequency of associated respiratory diseases which are often prevalent in mountain communities. Mountain infrastructure such as hydropower plants, roads, bridges and communication systems are at risk with climate change and more variability in water runoff. With increased frequencies of landslides and flash floods, technical installations will become more vulnerable, and reduced water flow in dry seasons will make it even more difficult to meet energy demands.

Other effects may be related to changes in forest ecosystems and forest productivity. Tourism could be both positively and negatively affected. More natural hazards could mean increased danger when travelling across high mountain routes and possibly also reduced attractions if mountain environments lose significant portions of the glacial landscape. At the same time, warmer and drier periods in parts of the annual cycle could also make it more attractive for some tourism segments to travel at higher altitudes (Benniston, 2003; Jianchu *et al.*, 2007).

CASE STUDY

Impact of climate change in the Hindu Kush-Himalaya mountains on water resources and overall economy of Pakistan

Amir Muhammed, National University of Computer and Emerging Sciences, Islamabad, Pakistan

Pakistan is a low-income developing country with widespread poverty and related socio-economic problems. Agriculture is the dominant sector of the national economy. Being mainly an arid to semi-arid country, agriculture production is largely dependent on the availability of irrigation water. Pakistan has one of the largest man-made contiguous irrigation systems in the Indus basin which is based on the water available from the Indus River and its tributaries. Part of the Indus river flow is provided by glacial melt from the glaciers of the Himalayan Mountains, the proportion depending on location.

Pakistan desperately needs to increase its agricultural production to meet the growing needs of the burgeoning population and to improve its economy. The country is already short of irrigation supplies to meet the current requirements. Climate change scenarios for the next about 50 years project higher temperatures in the high Himalayas resulting in more rapid melting of the glaciers which are an important source of water of the Pakistani rivers. It is projected that after initial increase in the river flows for 2–3 decades, the flows will decrease substantially resulting in greatly reduced supplies in the vast irrigation system. This will result in a major setback to the national agriculture and the overall economy. Several comprehensive studies have been undertaken on the overall availability of water supplies and the national requirements for the irrigation, domestic and industry sectors and these predict a major shortfall in the availability of water even for the most urgent requirements. This critical situation requires comprehensive analysis and identification of measures to mitigate the situation, arising mainly from climate change in the high mountains resulting in rapid melting of the glaciers and eventually shrinking of the glacier size and reduction in the resulting river flows. Reduced water availability coupled with the increase in ambient temperature in most parts of Pakistan will result in a critical situation for the national economy. Some of the measures being considered are building of additional dams to store surplus water during monsoon season, change in the cropping patterns to suit the changed climatic situation and water availability, increased emphasis on water use efficiency and gradual reduction in area under water-intensive crops like rice and sugarcane.

CASE STUDY

Contribution of glacier melt to river runoff in a medium sized Alpine catchment

Gernot Koboltschnig, Dept. for Water Management Amt der Kaerntner Landesregierung, Provincial Government of Carinthia, Austria

The contribution of glacier melt was investigated for the 5% glacierized Upper Salzach catchment area (593 km²) in the eastern European Alps. The basin is situated in the north of the Hohe Tauern region in the central Alps of Austria (Fig. 6). The land cover of the Upper Salzach watershed is dominated by coniferous forests as well as grassland and rocky areas. Settlements can mainly be found in the valleys, whereas Mittersill is the largest village with a population of about 5500 inhabitants.

For this study the hydrological model PREVAH was applied using an advanced temperature-index approach on an hourly time basis and driven by air temperature and precipitation observations from in and around the basin (Koboltschnig *et al.*, 2008).

The model was calibrated in a 3 year period and validated in another 3 year period based on a two-step procedure using observed discharge and satellite derived snow-cover distribution. Nash-Sutcliffe Efficiency Criteria (R^2) of the hourly discharge simulations were between 0.83 and 0.89 with the exception of the extreme summer of 2003 which had an R^2 of 0.74. The reliability of model results was good as the model simulated all components of the hydrologic cycle considering the water balance. By applying a multi-criteria result validation approach, not only the discharge at the basin outlet was used for validation purposes, but the simulated snow cover area (SCA) was also compared to satellite observations of SCA. Additionally, simulated glacier mass balances were compared to nearby observed glaciers. In contrast with other studies where an excess

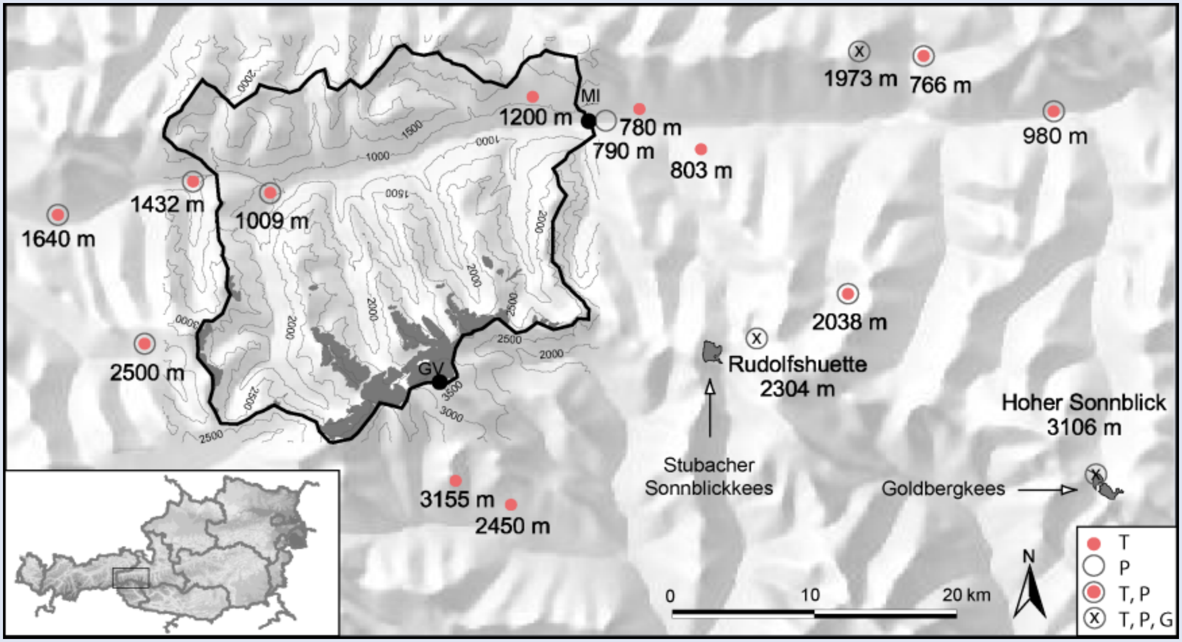
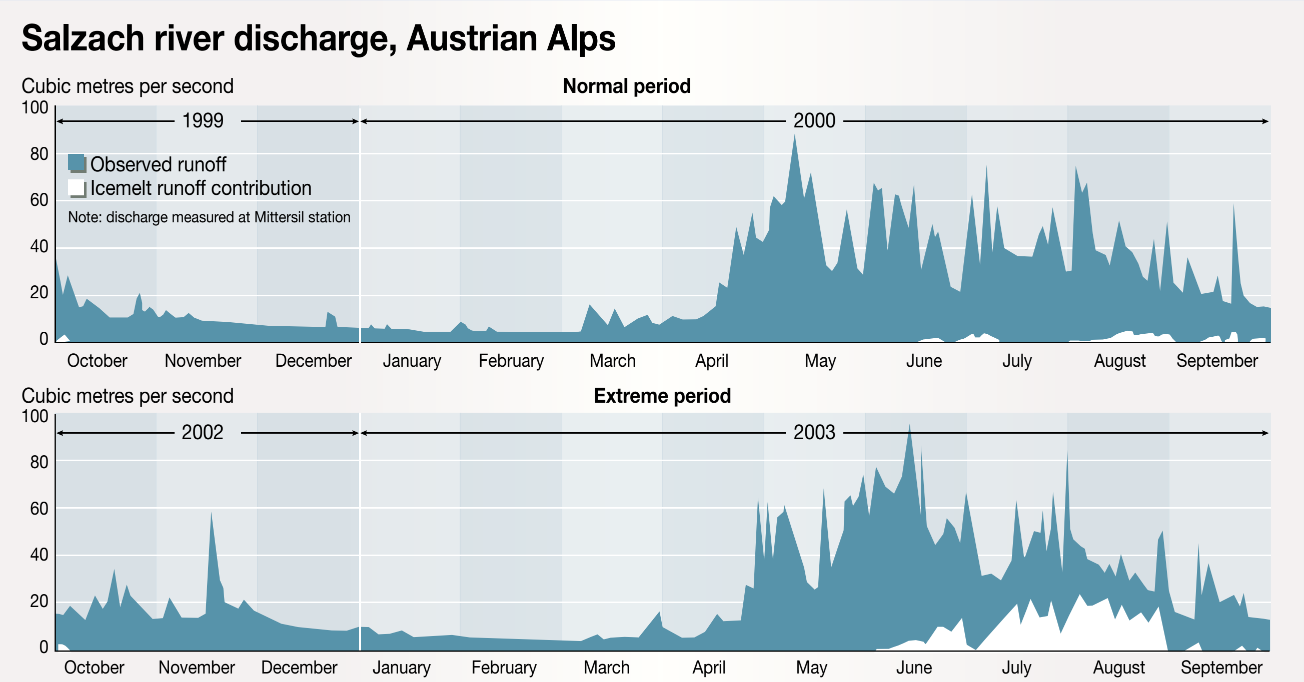


Figure 6: Upper Salzach catchment with the outlet at Mittersill (MI) at 780 m a.s.l. Mount Großvenediger (GV) at 3666 m a.s.l. is the highest peak in that area. Dark grey areas indicate glaciers. Rings, dots and crosses show meteorological stations within and outside the basin. Arrows show glaciers with mass balance observations.



Source: redrawn from Koboltschnig, *et al.*, 2008.

Figure 7: Observed (dotted line) and simulated hydrograph (grey) at the gauging station Mittersill and contributing fraction of ice melt (blue) for the normal (1999–2000) and the extreme (2002–2003) period.

melt is calculated, the glacier melt contribution in this study considers the entire firn/ice melt of glaciers, which can be above zero even in years with a positive glacier mass balance.

Simulated contributions of glacier melt (firn/ice melt) to annual total runoff were calculated between 1 and 4%. In the period 1999–2000, when the glacier mass balance of Goldbergkees and Stubacher Sonnblickkees have been observed to be zero or slightly above zero, the annual contribution of glacier melt was calculated as 1% (Fig. 7). The highest monthly contribution in 2000 was 4% for the month of August, and the highest daily glacier melt was 12% on 26 August 2000.

The exception was the outstanding hot and dry summer in 2003, when glaciers contributed 15% of the annual runoff and 58% to the August runoff (Fig. 7). The maximum daily contribution was calculated as 69% for 13 August 2003. At that time the observed annual mass balance of the Goldbergkees was –1.8 m and at the Stubacher Sonnblickkees it was –2.87 m.

This study shows that the glacier melt contribution at one specific point along the basin drainage varies seasonally and from year to year depending on temperature and precipitation cycles. Due to the relatively small fraction of glacierized areas the contribution of glacier melt in the Upper Salzach catchment is normally quite small, but had a respectable influence during the extraordinary hot and dry summer of 2003. Nevertheless the mean discharge during summer (JJA) 2003 was only 86% compared to the long term mean JJA discharge (1951 to 2006) and only 80% for August 2003.

Glacier Lake Outburst Floods (GLOFs)

In mountain regions, potentially unstable lakes can form when advancing glaciers block drainage routes, or when basins open up between retreating glaciers and abandoned terminal moraines. Glacier lake outburst floods (GLOFs) have caused loss of life, and loss of agricultural land and infrastructure. There is some indication that the frequency of GLOFs has increased due to climate change, and the impacts of GLOFs are very likely to increase in the coming decades as glacier retreat continues. GLOFs can have a very large impact locally, but the number of people affected by potential GLOFs is far less than those impacted by other types of floods.

Fluctuations of mountain glaciers, and other changes in the mountain cryosphere, lead to shifts in the distribution and frequency of hazards. During glacier advances, lakes can form due to the formation of cross-valley ice dams, and during glacier retreat lakes can develop in the gap between frontal or side moraines and the receding ice. GLOFs occur when the ice or moraine dam fails, and can be triggered by seismic activity, landslides or avalanches from mountains or hanging glaciers (Fig. 8 and 9). In the Hindu-Kush Karakoram, GLOFs are normally linked to the weakening of ice dams due to recent glacier thinning (Bajracharya *et al*. 2007). In high mountain regions, numerous moraine-dammed lakes have formed recently due to the retreat of debris-covered glaciers, leading to widespread GLOF hazards. Particularly affected areas include the central and eastern Himalaya and the Cordillera Blanca in Peru (Carey, 2005). At least 30,000 people have been killed by over 30 glacier disasters in the Cordillera Blanca region of Peru since 1941 (Carey, 2005).

Many of the Himalayan rivers originate from glaciers, and since most glaciers in this region are retreating a large number of proglacial lakes located between the glacier tongue and the frontal moraines are growing. These are best described as dynamic glacial lakes systems since smaller lakes in some locations merge into larger water bodies as they grow. Focusing simply on the number of lakes may be misleading as the number of lakes may be reduced while the volume of stored water increases. There have been at least 35 GLOF events in Nepal, Pakistan, Bhutan and China during the last century. Nepal alone has already experienced 15 GLOFs (Fig. 10) (Richardson and Reynolds, 2000).

GLOFs have also been recently reported in 2008 and 2009 from the Northern Patagonia Icefield. In these occasions, an estimated 200 milion tons of water spilled into the Colonia river, Chile (Dussaillant *et al*., 2010). More recent near doubling in the frequency of GLOFS in the Yarkant region of Karakoram, China, from 0.4 times annually 1959–1986 to 0.7 times annually in 1997–2006 has been attributed to the rise in warming (Chen *et al*., 2010)

Although infrequent, largely unpredictable and localised, impacts can be devastating as shown by the GLOF in Langmoche valley in eastern Nepal in 1985, which washed away bridges, agricultural land, homes and people and impacted areas 90 km downstream (Vuichard and Zimmerman, 1987). An estimated four million cubic meters of sediment-laden water destroyed a hydropower station, 14 bridges, 30 houses and farm lands worth four million US dollars. Loss of life was remarkably small, because a religious festival was in progress and few people were in the valley bottoms. To date, GLOF impacts have been largely confined to mountain communi-

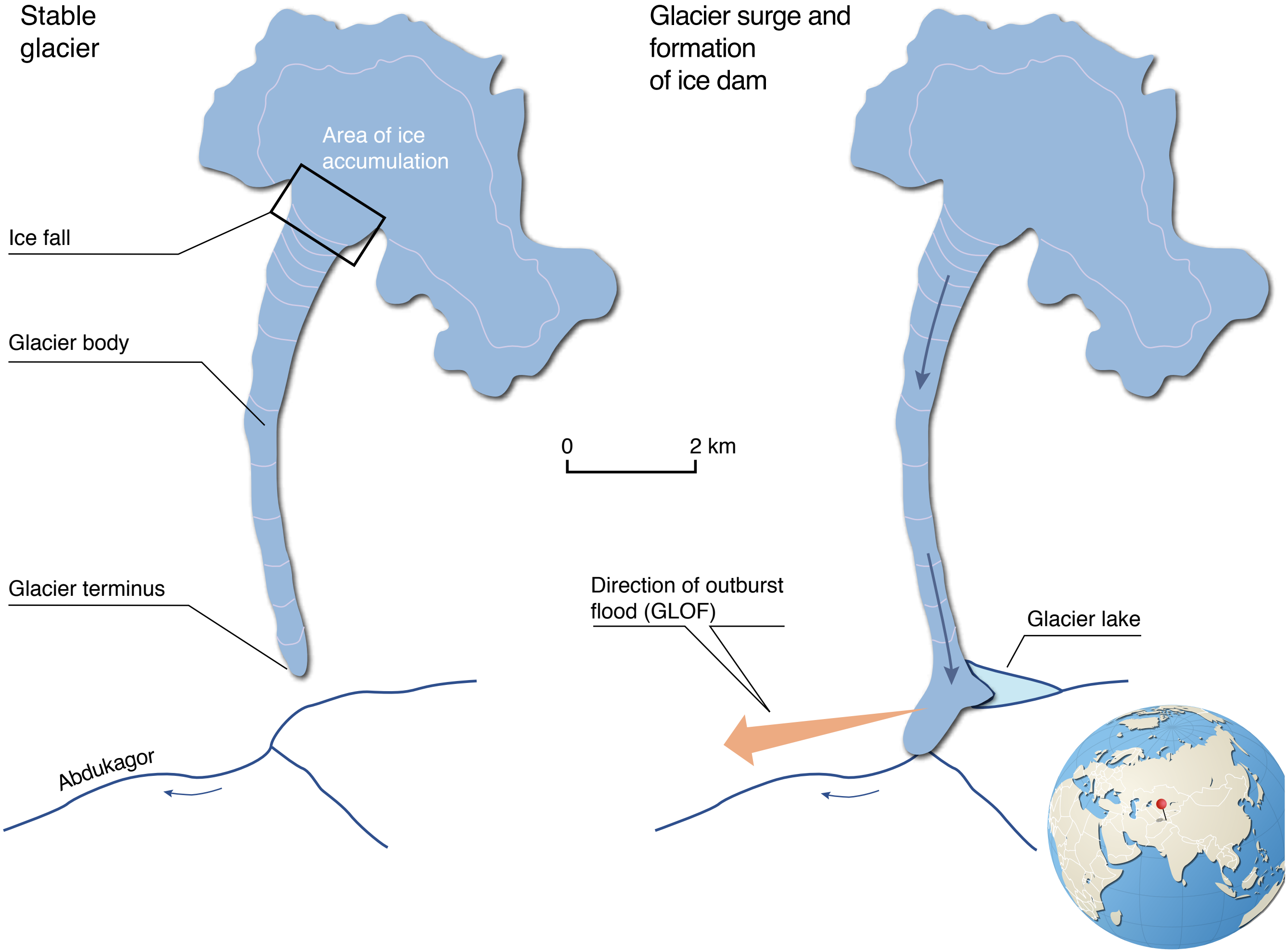


Figure 8: Formation of ice dammed lake by an advancing (surging) glacier: Medvezhi Glacier, Pamirs.

ties, because farther downstream the flood peaks are generally within the range of non-catastrophic river discharges (Cenderelli and Wohl, 2003). In the next few decades GLOF impacts will likely extend farther downstream than those experienced to date, as climate changes lead to lake formation on larger high-altitude glaciers. So far GLOFs have been relatively rare events, but there is little doubt that the potential for more outbursts as well as drastic consequences will increase.

Five major GLOFs also took place in April, October and December 2008, and again in March and September 2009 in the Northern Patagonia Icefield, Chile (Dussaillant *et al.*, 2010). On each event, the Cachet 2 Lake, dammed by the Colonia

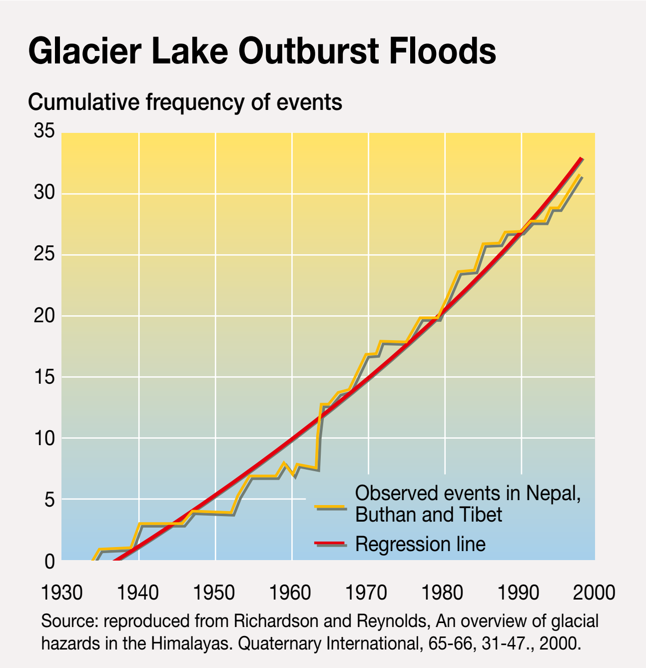
Glacier, released circa 200 million tons of water into the Colonia river. The lake has rapidly refilled, suggesting high risk of further GLOFs. Indeed, the peak discharge was estimated to surpass 3000 m³/second. Such events may in the future endanger continued hydropower development in the region (Dussaillant *et al.*, 2010).

Large glacier lakes do not necessarily imply high risk of flooding, however, and GLOF risks depend on site-specific factors such as moraine-dam stability and triggering mechanisms. Given the physical and economic damage that glacial hazards can cause, it is important to be able to identify and define the degree of hazard objectively. Over the last decade or so significant advances have been made in the use of Remote Sensing techniques to map, classify and categorize glacial lakes. These methods have been used not only to monitor changes in the glacial lake systems but also to identify areas where lakes have the potential to form and grow perhaps two to three decades into the future, based on the rate of ice flow, low surface gradient of the debris-covered glacier, and negative mass balance. Similarly, advances in ground-based survey methods, such as the use of geophysical techniques, have helped to provide information about the integrity of the moraines themselves. It has been demonstrated that by using Multi-Criteria Analysis it is possible to gauge the degree of glacial hazard quantitatively. By analysing a given glacial lake system, basic threshold parameters such as lake volume, moraine dimensions, etc., can be determined. Similarly, parts of the same environment that could trigger a lake outburst, for instance, can also be identified and rated so that a hazard score can be assigned by which it can be graded. This affords a method of prioritising lakes objectively within a whole catchment or region. As climate continues to change, the nature of glacial hazards in a given region also has the potential to alter with time. Debuttressing of steep rock slopes as

➔ **Figure 9:** ASTER image of retreating glaciers and moraine-dammed lakes in Bhutan (28 October 2009). The large lake to the right (Luggye Tsho) partially drained in 1994, carving the prominent flood track and causing widespread damage and loss of life downstream.

glaciers down-waste, thawing of permafrost, changes to the boundary between cold-based and polythermal glaciers, and potential buoyancy of previously submerged stagnant ice masses within lakes, are some of the features that might be expected to become evident.

Climate change is affecting the supply of water from down-wasting glaciers with severe consequences in terms of water resource management. When a GLOF occurs it can cause major changes to the course and characteristics of an affected river system, often for many years afterwards. Communities can suffer damage to houses, bridges, paths, access to grazing lands, and valuable food-producing land can be destroyed. Increased geotechnical effects are observed such as more landslides resulting from greater erosion of the toes of unstable slopes, and loss of agricultural land and forestry. Suspended sediment loads increase in the river water, with effects on the river ecology and resulting in greater abrasion of hydropower turbine blades and greater rates of sedimentation. All of these changes have economic as well as physical consequences.



Source: reproduced from Richardson and Reynolds, An overview of glacial hazards in the Himalayas. Quaternary International, 65-66, 31-47., 2000.

Figure 10: Cumulative frequency graph of GLOFs in Nepal, Bhutan and Tibet. The best-fit line suggests an increase in GLOF frequency through time, although older events may be under-reported. GLOFs also took place in Patagonia, Chile in 2008 and 2009 (Dussaillant *et al.*, 2010)(From Richardson and Reynolds, 2000).

The vulnerability to GLOFs varies from region to region depending on terrain, land use patterns and population density as well as the likelihood of the dams breaching. A great number of people are potentially in danger should the lakes classified as dangerous in the Hindu Kush-Himalayas drain. In most cases, there would be little or no warning, with insufficient time for complete evacuation. Much larger numbers of people would be affected through loss of property, farmland and livelihoods. Damage to households, private property and agricultural lands would be in the range of several tens to possibly hundreds of millions USD (Khanal 2010). A major concern should GLOFs increase is the subsequent damage to hydropower stations downstream. Early warning systems are clearly needed, but difficult and costly to implement. Given the vastness and remoteness of the mountain areas and GLOF locations in question, remote sensing techniques appear as the only feasible means to achieve reasonable predictions of potential GLOFs on a larger scale (Qincey *et al.*, 2005; 2007).

Siphons have also played a key role in remediation of lakes in the Cordillera Blanca, Peru, and have helped reduce the volume of a lake that, when it eventually breached, only affected the immediate area downstream, with no loss of life or significant damage. The affected lake was later safely remediated by constructing a series of four tunnels separated by 5 m vertically through bedrock into the base of the lake. On 11th April 2010, a rock and ice avalanche cascaded into this lake and produced an avalanche push wave about 28 m high that overtopped the rock dam and flooded downstream affecting farm land and destroying the water supply for the local town. However, no-one was killed. The remediation undertaken in 1993 had lowered the lake level by 20 m providing a freeboard of 23 m. Consequently the bulk of the push wave was retained within the rock basin, significantly reducing the flood volume and attenuating the peak flow rate. It is thought

CASE STUDY

GLOF hazards in Bhutan and the management of glacial lakes in high mountain environments

John M. Reynolds, Reynolds International Ltd, UK

The potential for glacial lakes to cause devastation became reality in Bhutan on the 7th October 1994 when Luggye Tsho, one of the lakes in the Lunana region, burst through its left lateral moraine (see Fig. 8–10). The ensuing Glacial Lake Outburst Flood (GLOF), which contained an estimated 18 million cubic meters of water, debris and trees, swept downstream, killed 21 people, and travelled over 204 km before crossing the border into India and finally dissipating. On the 30th April 2009, Tshojo Glacier is thought to have been the source of an outburst that caused panic downstream at Punakha, where the fatalities occurred in the 1994 flood. No loss of life has been reported from this latest event. Over the last ten years a significant amount of work has been and is being done in Bhutan to address the issue of hazardous glacial lakes. Not only is this important in order to preserve life and protect property; it is also vital if Bhutan is to develop its substantial hydro-electric power generation potential. Having identified and prioritised its hazardous glacial lakes, the Government of Bhutan has taken practical measures to mitigate Raphstreng Tsho between 1996 and 1998 by constructing an open channel to lower the lake level by several metres. However, in 1998 the adjacent Thorthormi Glacier was found to be downwasting, breaking up in parts, and developing interconnected supra-glacial ponds extremely rapidly. It was identified as being potentially the most hazardous glacial lake in Bhutan.

Indeed, as predicted, the lakes have coalesced and enlarged; the ice-cored moraine dam separating them from the lower-lying Raphstreng Tsho has degraded significantly since 2004. It is estimated that if Thorthormi lakes burst into Raphstreng Tsho and hence downstream, it could generate a GLOF with a potential volume greater than 53 million cubic meters of water, nearly three times the volume of the 1994 flood, and cause substantial damage downstream and into northern India again. In recognition of the growing urgency to mitigate the situation, a $7.8 million program to lower the Thorthormi Glacier lakes was sanctioned by the UNDP and is due to commence in June 2009.

Mitigation works both at Raphstreng Tsho and Thorthormi Glacier represent significant logistical and technical challenges in such remote locations. The cost of the latter project is over 2.5 times more expensive than that of the Tsho Rolpa GLOF Risk Reduction project to remediate the 110 million m3 glacial lake in Rolwaling, Nepal, which was completed in July 2000. This comprised the excavation of a 100 meter long open channel with sluice gates that allowed the controlled lowering of the lake by 3.5 m. Although a major piece of engineering construction, where all the heavy machinery had to be airlifted to site in parts and rebuilt, it represents only an interim remediation, with a further lowering of the lake by 11.5 m having been recommended to achieve sufficient volume reduction to afford an internationally accepted Factor of Safety. Tsho Rolpa was also significant in that it was the first place in the Himalayas where siphons had been used. Siphons were installed in 1995 and ran without significant maintenance for 18 months.

that, had the remedial work not been undertaken at this lake, the number of fatalities in April would have been measured in the hundreds.

The Peruvian authorities have had substantial experience in the remediation of glacial lakes, having undertaken the first works in response to the catastrophic inundation of Huaraz in 1941, which resulted in over 5,000 fatalities (Carey, 2009). The types of engineering works undertaken since then include the construction of open channels, culverts within engineered dams, siphons and tunnels. Indeed, the remediation of Laguna Parón not only gave a way of controlling the lake for the purpose of hazard management but also to provide a means of controlling water flow into the local river system to use the water reservoir as a resource. There is now considerable interest in the control of glacial lakes as part of the management of water resources, and for local electrification and larger scale hydropower generation, as well as for protection of major infrastructure and downstream communities.

Flash floods

Flash floods are common to most mountain areas and a continuous challenge to water resources management and disaster reduction management in particular. They represent some of the most devastating types of floods due to rapid occurrences, large quantities of water, high sediment content and fast moving flood waves. They are a typical feature of steep topography where the land has limited retentive capacity in areas with high variability in rainfall, such as in monsoon regions.

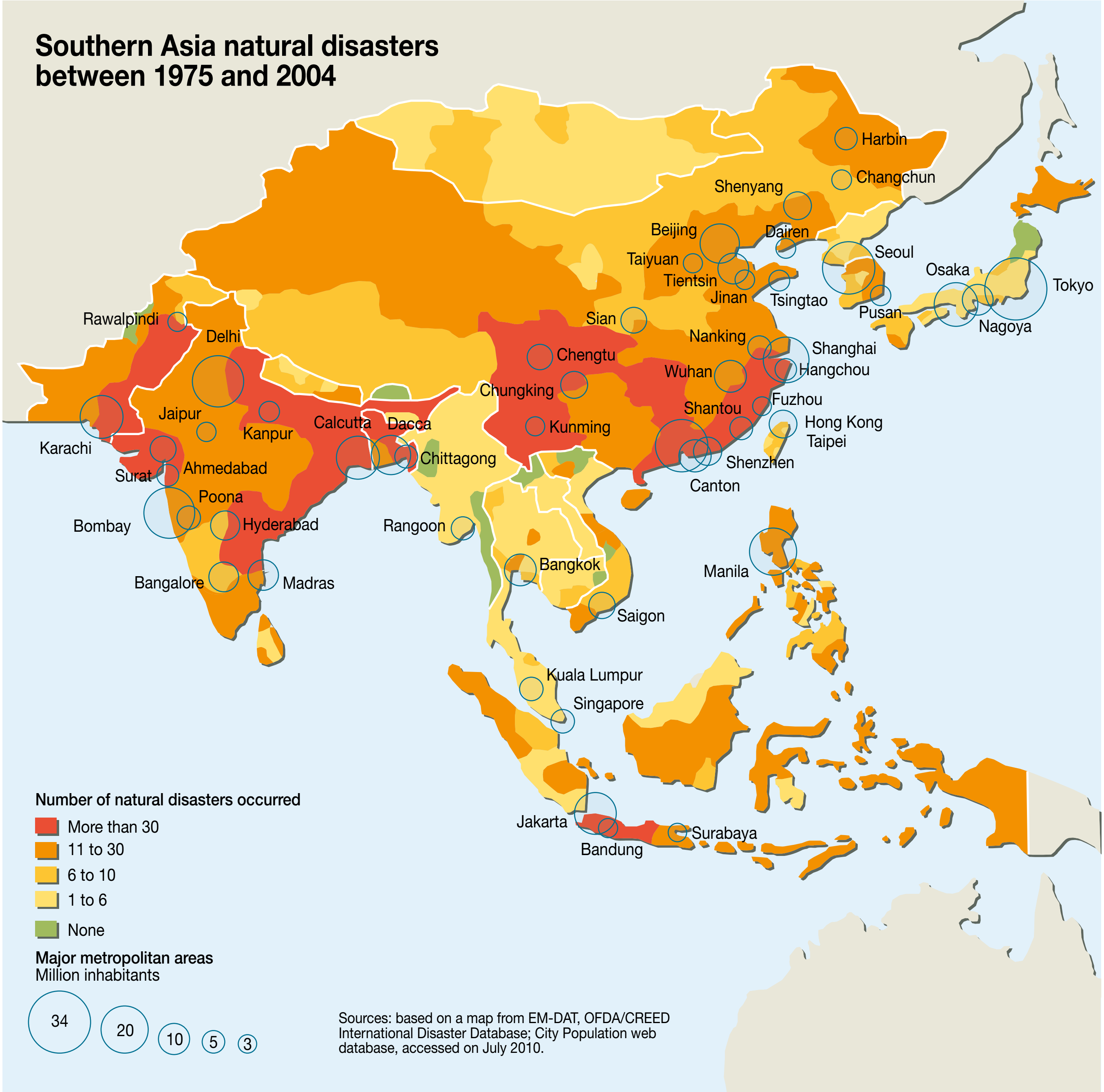
While GLOFs can be considered a special type of flash flood, flash floods in general can originate in different ways and are affected by multiple processes. Perhaps the most common are episodes of intense rainfall, typically in monsoon and rainy seasons. The phenomenon is well known to many mountain communities and populations living below mountain ranges. In many mountain communities people have learned to interpret weather signs as warning of flash floods and have to some extent adapted reasonably well to these dangers. However, flash floods often do not follow predictable patterns, and there may not be much warning as the floods vary with the amount of rain that is discharged and can also be caused by rapid melting of snow and ice, something which may be related to climate change in ways not previously experienced in these communities. Flash floods are also caused by failure of man-made and natural dams and can be triggered by landslides and debris or seismic activity.

Flash floods pose a serious threat to people in mountain regions and have severe downstream effects. In contrast to most GLOFs which occur in sparsely populated high mountain regions, a large proportion of flash floods occur in more densely populated middle hill and mid-mountain regions where social, humanitarian and economic impacts are much greater. Numbers are highly uncertain and most likely underreported, but *flash floods in the Himalayas are estimated to cause the loss of at least 5000 people every year* (Jianchu *et al.* 2006). An unknown, but probably much higher number is affected in a variety of negative ways. Floods destroy bridges, roads, buildings, agricultural lands and settlement areas. Flooding also increases erosion and the sediment load of the water. They can also lead to unusually high water flows in steep rivers and have been known to exceed predictions for maximum flows. For example the Kulekhani hydropower plant in Nepal was designed for a maximum flow of 8000 cubic meters per second. A previous peak flow of 12000 cubic meters was rejected as a statistical outlier. However, in 1993 a cloudburst led to a flash flood with 15 000 cubic meters per second that severely damaged the plant. Similarly a single flash flood the same year knocked out half of the country's electricity production for several months leading to a major economic impact to Nepal (NCVST 2009).

Many mountain regions are characterised by limited space that is both suitable and safe for human habitation. In northern Pakistan for instance, communities are often located on or close to alluvial fans since almost any other space is uninhabitable due to the ruggedness of the terrain. However, alluvial fans are frequently the core path of flash floods. Flash floods have significant negative impacts on socio-economic conditions and livelihoods. Flooding destroys productive land, buildings and roads, hence loss of valuable property and working capacity of communities. It also causes human injury and deaths, and typically elderly, children and women are the most vulnerable as in most cases related to natural hazards.

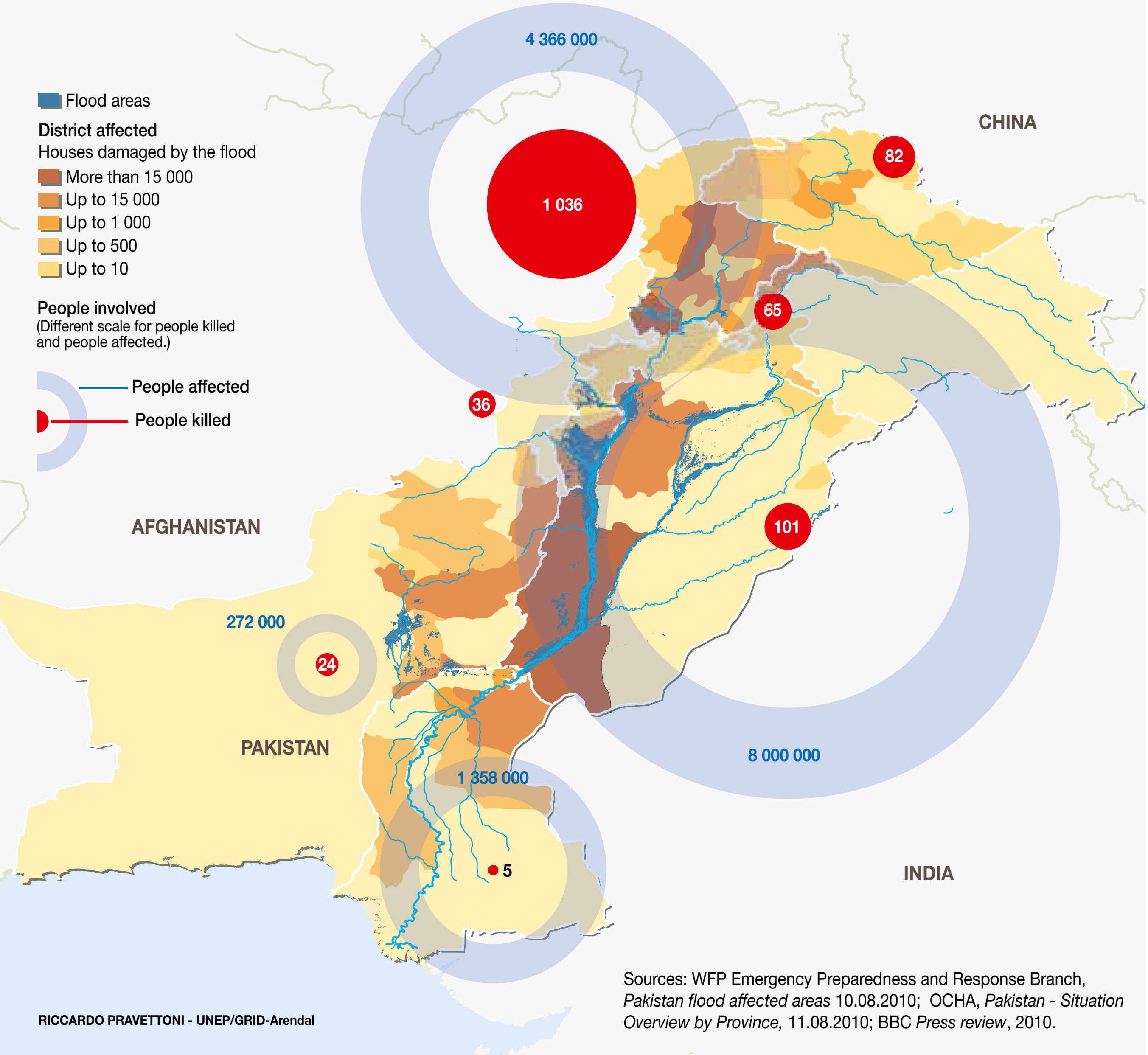
➔ **Figure 11:** Overview of natural disasters in Asia between 1975 and 2004. Floods account for a very significant proportion of the disasters observed.

Southern Asia natural disasters between 1975 and 2004



Sources: based on a map from EM-DAT, OFDA/CREED International Disaster Database; City Population web database, accessed on July 2010.

Victims and affected people in Pakistan flood, August 2010



Sources: WFP Emergency Preparedness and Response Branch, *Pakistan flood affected areas* 10.08.2010; OCHA, *Pakistan - Situation Overview by Province,* 11.08.2010; BBC *Press review*, 2010.

RICCARDO PRAVETTONI - UNEP/GRID-Arendal

Seasonal floods and droughts

Seasonal or riverine floods are less contingent on glacial melt than the different types of flash floods. Impacts on humans and livelihoods from glacial melting in high regions will in most cases be much more localised and of a smaller overall magnitude than seasonal flooding in the lowlands. From a glacial and hydrological perspective it is unlikely that glacial melting will have significant impacts on the large-scale seasonal flooding in the lowlands of the large river basins in the HKH region.

However, human adaptation to different types of water stress and water hazards is a continuum of strategies and actions. All types of floods have potential impacts on people and livelihoods, but adaptive responses vary greatly given the different nature and magnitude of flash floods and seasonal floods. China, India and Venezuela are the most vulnerable countries in the world to flooding in terms of the average number of people exposed and killed. Predicted increases in future climate variability in the Himalayan region implies that floods of different types and droughts will remain a challenge to a significant portion of the world's population.

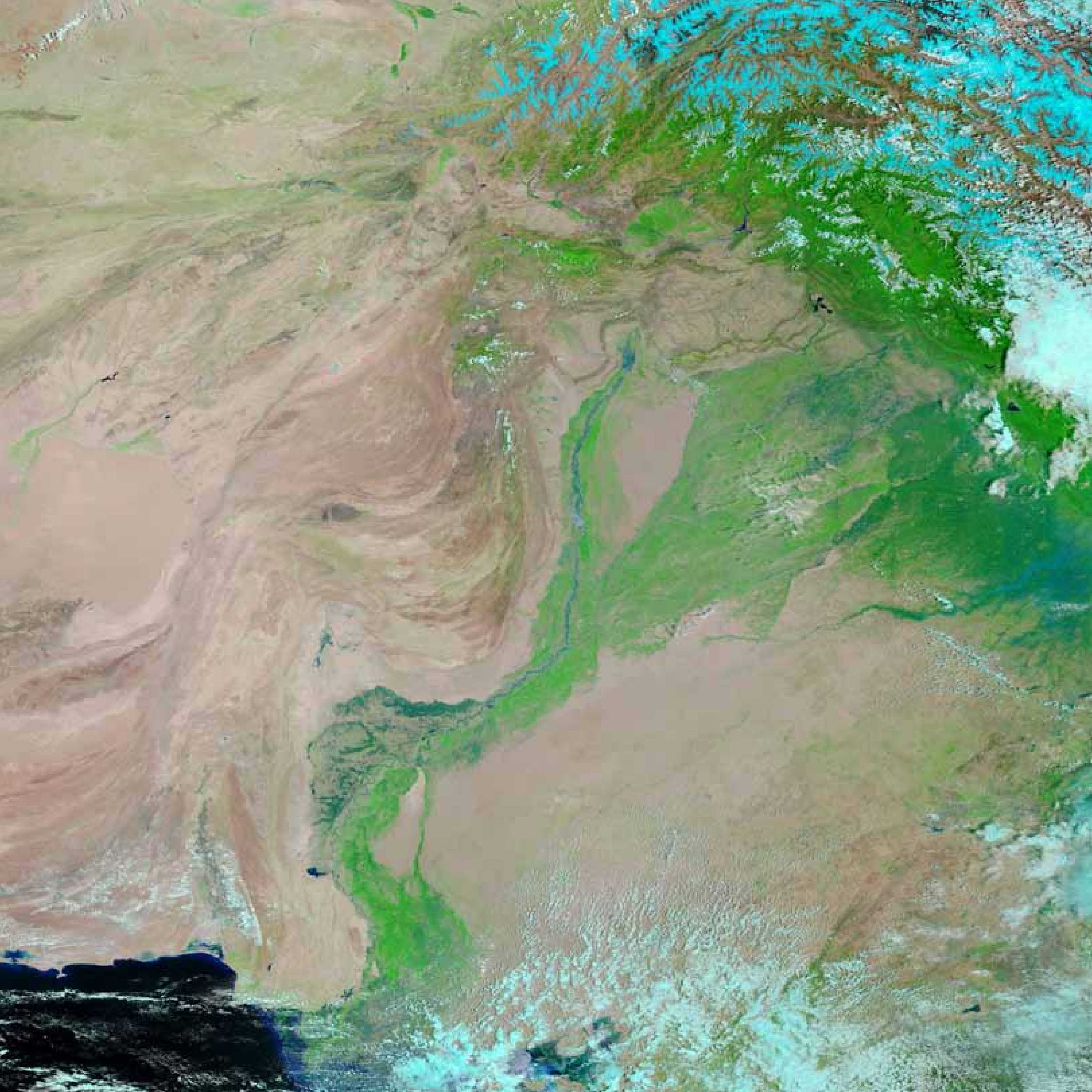
Seasonal flooding can occur along all the major watersheds in the Himalayan region (Figure 11–14). The largest problems occur in flood prone areas with high population densities. This includes parts of northeast India, south-central Nepal, central and southern Pakistan, large parts of Bangladesh and lower reaches of the large rivers in China. In India around 40 million people are affected by flooding annually and the damage has been estimated to USD 240 million as an annual average. Here 40 million hectares of land are at risk every year. An average of 1800 people are killed by floods each year in India, which is roughly one quarter of the total number of people killed in natural disasters.

← **Figure 12:** Persons killed and affected by floods in Pakistan in August 2010. An estimated 20.5 million people were affected, over 1700 were killed, 6 million were displaced and 1.89 million houses were destroyed. By November 2010, over 7 million were still affected and lacked proper housing (OCHA, Nov. 15th, 2010)

In China, 8% of the middle and lower reaches of the seven large rivers are prone to floods. Approximately 130 million are exposed to flooding on average every year and around 2000 people die in floods every year. The flood prone parts of China house one-half of the country's population who produces 70% of the industrial and agricultural value of the country. More than 8 million hectares are flooded annually, and more than 100 medium to large cities have been affected by flooding during the past 30 years. The resultant economic losses comprise almost 25% of the annual world economic loss caused by floods (Zhang *et al.* 2003).

In Bangladesh, 86 million people were affected by natural disasters, predominantly floods, between 1998 and 2008 (World Disasters Report 2009). As much as 80 million may be prone to flooding one way or another (FAO 2001). An average of 500–1000 die in floods annually. Around 13 000 persons were killed in natural disasters in Bangladesh this ten year period (World Disasters Report 2009). The 1998 flood was the most severe in the 20th century and an estimated 30–32 million people were affected (Hofer and Messerli, 2006). Major riverine floods appear on average every 3–4 years . Most of the northern parts of the country are affected by flash floods at longer cycles, approximately every 20 years.

In Pakistan, an average of 10–15 million people are exposed to flooding and 250–300 people die in floods every year (Fig. 13 and 14). In August 2010, two weeks of intense monsoon rains caused major rivers to flood villages, washed away



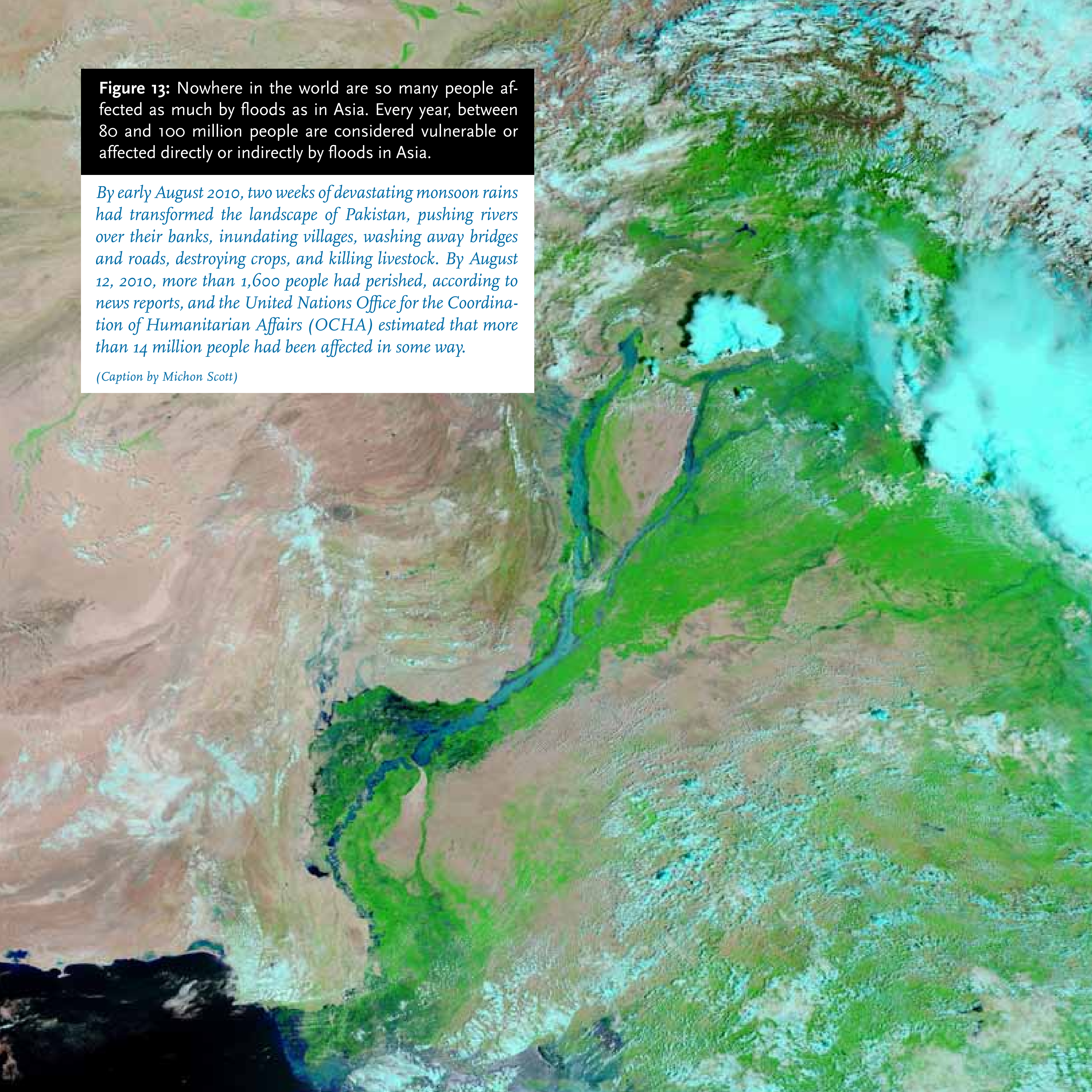
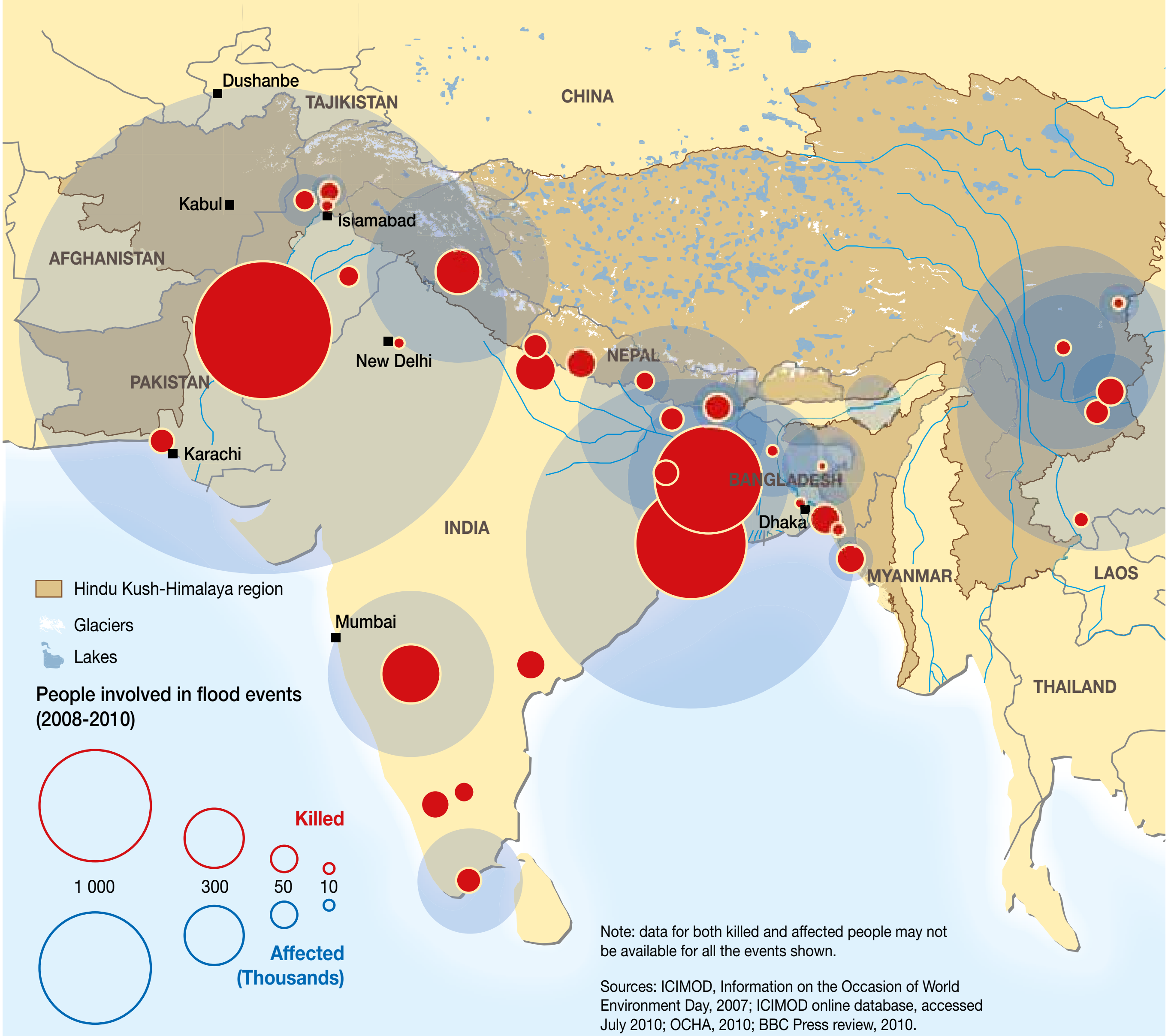


Figure 13: Nowhere in the world are so many people affected as much by floods as in Asia. Every year, between 80 and 100 million people are considered vulnerable or affected directly or indirectly by floods in Asia.

By early August 2010, two weeks of devastating monsoon rains had transformed the landscape of Pakistan, pushing rivers over their banks, inundating villages, washing away bridges and roads, destroying crops, and killing livestock. By August 12, 2010, more than 1,600 people had perished, according to news reports, and the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) estimated that more than 14 million people had been affected in some way.

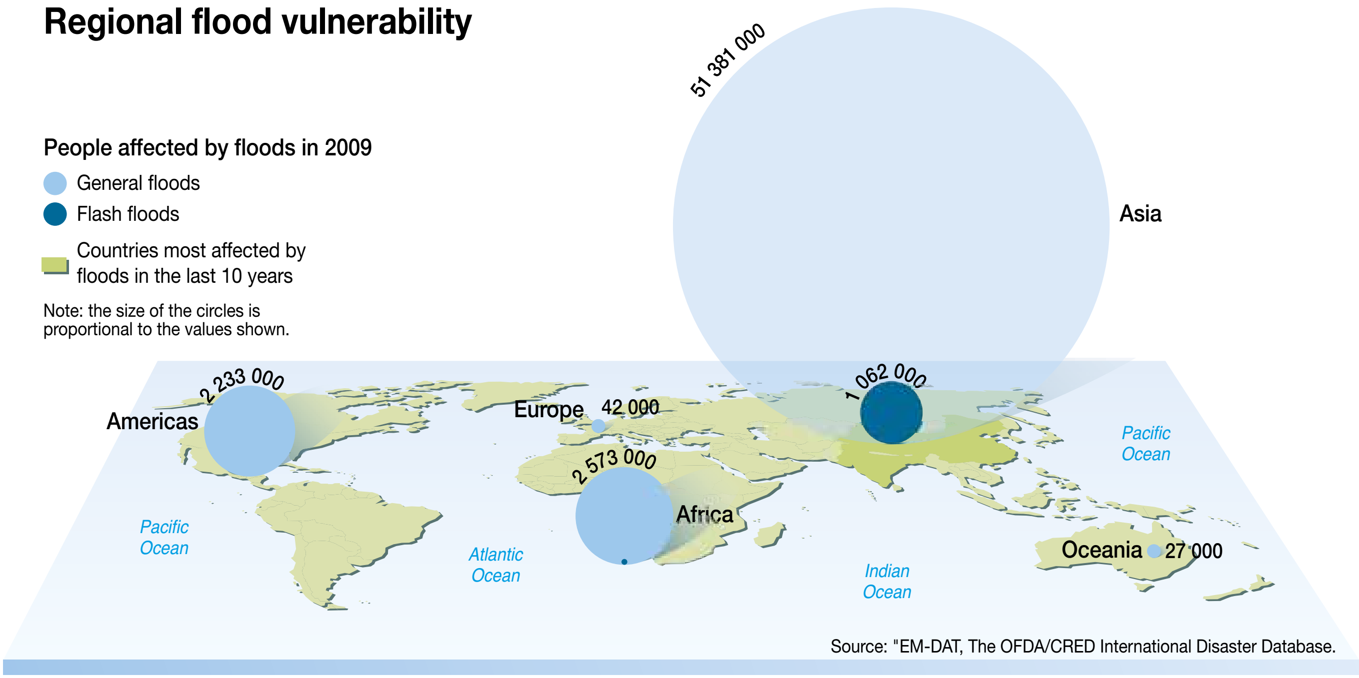
(Caption by Michon Scott)

Recent flood events in the Hindu Kush-Himalaya region



Note: data for both killed and affected people may not be available for all the events shown.

Sources: ICIMOD, Information on the Occasion of World Environment Day, 2007; ICIMOD online database, accessed July 2010; OCHA, 2010; BBC Press review, 2010.



Source: "EM-DAT, The OFDA/CRED International Disaster Database.

← **Figure 14:** Recent flood events in Hindu Kush-Himalaya.

↑ **Figure 15:** Regional flood vulnerability.

roads and bridges and croplands, including killing livestock and many people. An estimated 20.5 million people were affected, over 1,700 were killed, 6 million were displaced and 1.89 million houses were destroyed. By November 2010, over 7 million were still affected and lacked proper housing (OCHA, Nov. 15th, 2010)

Parts of Nepal are vulnerable to seasonal flooding and an estimated 250–300 persons die in floods each year while 5–6 million are physically exposed to flooding. In contrast Bhutan is to a much smaller extent exposed to large scale seasonal flooding and vulnerability here is largely associated with flash floods (FAO 2001). Only a few persons are killed each year. 200 persons are reported killed by natural disasters during 1998–2008. However around 200 000 are thought to be exposed to flooding each year.

Since Asia comprises a large portion of the World's population, and more than 40% of all the floods in the world occur in Asia, a large number of people are affected by disasters (Fig. 14). More than 40% of the people killed by natural disasters are killed in Asia (Fig. 15). In the ten-year period from 1999–2008, 402 floods were recorded in Africa, 342 in the Americas, 259 in Europe and 649 in Asia. In the same time period close to 1 billion people were affected by floods in Asia whereas the corresponding figures for Europe were around 4 million, for the Americas 28 million and Africa 22 million. The vast majority of people either injured, made homeless or otherwise affected by natural disasters on a global basis, i.e. 80–90% live in Asia. As a rough estimate floods appear to cause 20–25% of all deaths associated with natural disasters across Asia (World Disaster Report, 2009, USAID, 2007, UNU-IAS, 2008).

Challenges ahead

Data availability and accessibility

Improved understanding of the effect of climate change in high mountains on downstream communities and water resources will require significant efforts to develop databases and analytical capacities. Currently most projections of climate change are based on general circulation models (GCM) which attempt to mathematically model interactions between oceans, atmosphere and large land areas, typically on the order of hundreds to thousands of square kilometres. The models present two significant challenges. Firstly, the models have a low resolution and have a very limited capability to provide detailed predictions for smaller areas. Large mountain regions like the Himalayas and Andes are extremely diverse and complex in terms of geography, ecology and socio-cultural conditions, and there is a great need for higher resolution models with better predictive capacity at smaller scales. Secondly, the current models are in themselves uncertain as our understanding of climate change is limited, i.e. we have limited knowledge of the key natural processes and of which choices we will make in the future with regards to energy consumption and greenhouse gas emission.

Extensive coordination and cooperation among mountain nations and institutions is required in order to fill data gaps and develop regional assessment models. In some cases relevant data sets exist on a national level, but are not accessible for regional analysis and cooperation due to strategic or other reasons. In any case current databases and capacity is limited and several factors play a part; the number of years of observation (often short term), quality and availability of data, distribution of observation networks, capacity to analyze and compute data, financial constraints, and lack of time to achieve required results. Currently the paucity of data in many areas, the lack of institutional capacity to analyze, correct and verify data and short duration of data records limit the validity of current models.

Modelling water flow is complicated

Mountain regions contribute a substantial proportion of the global river runoff (Viviroli *et al.*, 2003; Viviroli and Weingartner, 2004), *but modeling this runoff and future variability in time and space due to climate change is highly complicated*. The processes that determine the change from precipitation into runoff are many and complex. As mentioned earlier in this report runoff from melting ice is often a relatively small component in the total runoff regime, but still highly important as a long term, relatively stable supply of water. As noted above, the broad picture indicates that in the coming decades many large glaciers will retreat and a high number of small ones will disappear completely. This could mean that the supply of water will be favorable to agriculture and livelihoods in the short term with increasing amounts of water, but it could also contribute to excess water levels in some areas.

In the long run however, i.e. after a few decades when water levels may be drastically reduced due to the diminishment of high mountain glacier systems, impacts on downstream communities could become dramatic in some of the arid areas (ICIMOD, 2009a,b; UNEP, 2009; 2010a,b).

However, climate change does not only indicate higher temperatures, but also changes in overall precipitation, evapotranspiration, and changes in the balance between rain and snow which has great implications for runoff rates and storage of water. Intensity, amount and distribution of precipitation over time are all factors of importance for modeling runoff and impacts to ecosystems and human populations.

Seasonality is another factor that will affect mountain regions around the world differently. Most mountain areas have seasonal patterns to annual runoff regimes. In areas with monsoons, runoff from glacial melting is particularly important in the shoulder seasons. There are already many signs of more variation in seasonal weather patterns in high mountain ranges. Given current patterns and predictions, a likely scenario in the long run is that the monsoon becomes more variable, and that the water flow in the dry season is further reduced, in some cases to critical levels, due to disappearing glaciers (Jianchu *et al.*, 2009).

Because the impact of glacier melt on river regimes is so variable between regions, it is vitally important to model hydrological impacts of climate change on a catchment-by-catchment basis. This task presents considerable challenges due to the great number and diversity of glaciers in high mountain catchments, complexity of the terrain and local microclimates, and lack of data on many components of the hydrological system. Until such studies are conducted, however, any predictions about the impacts of climate change remain speculative.

Regional differences present challenges

Mountain regions are diverse and complex ecological and socio-cultural systems. The world's high mountain ranges and glaciers are suffering the impacts of a global phenomenon, but the way these consequences are dealt with will need to vary considerably with the local context. Mountains regions are and will be among the most impacted regions in the world, but current policies and actions aimed at alleviating impacts of climate change do not adequately benefit mountain regions.Furthermore, the diversity and heterogeneity of mountain ecosystems mean that adaptation and mitigation strategies must be tailored to specific natural- and livelihood conditions in order to be effective. The span between adaptation and mitigation should be thought of as a continuum. A particular strategy for storing water or food may work well in a particular setting, but have little or no relevance in another context. However, while recognizing the challenges related to regional differences in mountain settings, these areas also require global solidarity and concerted regional cooperation. Adaptation is in many cases about making micro-level changes within national responsibilities, but the large mountain regions also need regional, and even transboundary actions. Many watersheds and river systems in high mountain areas flow across more than one country. The established national and bilateral perspectives on water management will not suffice for dealing with future challenges. *In a likely future of increased water scarcity in the dry season and enhanced hazards in the rainy season the pressure to find improved means to deal with too much water and too little water will increase dramatically.*

This can only be addressed through integrated water resources management across broader scales.

Water stress impacts food security

In the future, many regions will undoubtedly experience water scarcity (UNEP 2010). Firstly, population growth is increasing the demand for water, and while 20 to 30% of current global water consumption is by households and industry, rising populations will also increase the agricultural production demand for water. Secondly, the higher demand

for cereals for production of animal feed and for human consumption will increase water demand by an additional 30–50% within a few decades; and perhaps by 70–80% by 2050. Thirdly, climate change may not only disrupt monsoon patterns, it may also significantly alter the main flow and seasonality of many of the large Asian rivers within a few decades, with disastrous impacts on food production as a result (Nellemann and Kaltenborn, 2009).

The demand for food and irrigation water will continue to increase towards 2050 as a result of population growth of an additional one billion people in Asia, increased incomes, and growing consumption of meat. In Pakistan, for example, one of the countries with the highest water scarcity and extreme dependency on the Indus River, the population is projected to increase by 82% from around 184 million in 2010 to around 335 million by 2050. By then, meat consumption per capita will have doubled worldwide and over half of the world's cereals will be used to feed livestock, compared to one-third today. Indeed, this cereal alone could have fed the entire projected population growth. Instead, unless changes are made, our water consumption to grow irrigated cereals for animal feed will have to increase by at least 30–50%, if not more, simply to support heavily fertiliser-based production schemes. In some regions, as in Pakistan, water demand will increase by 50–70% by 2050, while availability will decline at the same time.

Irrigated croplands, mainly rice, in the watersheds of major Asian rivers are all to some extent depending on runoff from the high mountain regions in addition to monsoon rains which also recharge groundwater reservoirs. Given the high level of uncertainty regarding future runoff levels, and also the highly variable contribution of glacial water and snowmelt from the mountains, future agricultural production also faces significant uncertainty. For rivers like the Indus, Syr Darya, and Amu Darya, a major decline in the water flow will have devastating impacts on food production and domestic availability, as there are few, if any, alternatives to this water.

The irrigated cropland in the basins of those Asian rivers that are most dependent upon the mountains for water flow, comprises approximately 857,830,000 ha. The average production of irrigated rice is projected at 6 tonnes/ha (range 2–10 tonnes/ha), compared to 2–3 tonnes/ha for non-irrigated land (average of both combined, about 3.3 tonnes/ha in Asia). Water from the Hindu Kush-Himalayas and the central Asian mountain region thus supports the production of over 500 million tonnes of cereals per year, equivalent to nearly 55% of Asia's cereal production and 25% of the world production today. By 2050, as projected by FAO, global cereal production needs to be around 3000 million tonnes in order to meet demand. However, some estimates suggest that due to environmental degradation in the watersheds, floods, and reduced water flow due to climate change in the Hindu Kush-Himalayas, cereal production in Asia could become 10% to 30% lower than projected demand, corresponding to a 1.7–5% global reduction in cereal production (Nellemann and Kaltenborn, 2009; UNEP, 2009). While we do not at this stage have any good projections, the numbers do reveal how important irrigation water and flood control is in the Hindu Kush-Himalayas region for global food security (UNEP, 2009).

Mitigation and adaptation to climate change and water stress

People living in mountain regions across the world are used to environmental change and are regularly dealing with too much or too little water, both conditions often occurring within the same season or within short periods of time. Hence many mountain peoples have developed a series of strategies for dealing with a dynamic environment and have considerable adaptive capacity. For instance, many Himalayan farmers are now increasing food and water storage capacities to better prepare for floods and droughts (Dekens and Eriksson 2009). However, most mountain regions are now experiencing greater ranges and rates of change, that likely will stress and in many cases exceed the adaptive capacities of the social-ecological systems.

There are also signs that increasing climate variability is exceeding the traditional knowledge of how to cope with environmental stress (ICIMOD, 2009a–b). Furthermore, the upstream-downstream linkages and the high dependence of lowland communities on upland water resources is becoming a critical issue of global proportions. Climate change will have impacts on the entire hydrological cycle in mountain areas (Eriksson *et al.*, 2009) and high mountain glaciers will play a significant role in the uncertainty of future water supply. Future adaptation will need to be planned through state and other formal institutions, as well as through autonomous actions, i.e. actions and strategies by people in their local environment.

The predicted climate changes will require massive adaptation in upstream as well as downstream locations. While fatalities and extreme events such as GLOFs may catch extensive media attention, it is clear that the required responses to climate change and variable water flow from high mountains must be of different types and on different levels. Vast numbers of people are affected in some regions by floods and droughts, in the case of Asia up to hundreds of millions each year. In contrast, relatively few people are actually killed by these disasters. For instance in one district in Western Nepal floods killed 26 people in the year 2008, but more than 2000 houses were completely damaged and 13 000 houses were partially damaged, and large food reserves were lost (Dixit *et al.*, 2009).

Floods and other disasters lead to serious health risks, degradation of livelihoods, food insecurity and general decline in quality of life. *Short term responses will in many cases still be disaster management, but in the medium and long term perspective the focus must be on adaptation to significant changes in environmental conditions and runoff from high mountain glaciers and watersheds.*

Vulnerability is already high and imminent in many mountain regions as well as in downstream plains housing large portions of the world's population and it will increase in the future as the populations in exposed areas increase and as the effects of global warming are felt in these areas. In the Himalaya as well as the Andes, droughts and flooding will become more common, as will wind and cyclones, diseases and pests, soil erosion, and losses of soil organic matter (IIED, 2009; Leduc, 2009). Even in the Alps, a fairly prosperous region, many farmers now lack the water they need to irrigate their fields, especially in the drier valleys that lie in the rain shadow of high ranges (Orlove, 2009).

Living in high mountain regions like the Andes and the Himalayan region is a daily challenge as the remoteness combined with the harsh environment and limited infrastructure hampers mountain peoples' economic development (IIED, 2009; Leduc, 2009). Mountain peoples' livelihoods are largely based on agriculture, livestock raising, exploitation of natural resources, small scale trade and migration (Leduc, 2008). People are used to seasonal and daily climate variability and variation in climate conditions at different altitudes and on slopes with different exposures (Rhoades, 2007). Traditional land-use systems have adapted to these variabilities through farming with complex soil and water management, a rich diversity of crops and varieties, and planting schemes adapted to altitude (IIED, 2009). Livestock is moved to graze on the high summer pastures after the snow has melted (Mountain Partnership, 2002).

Since mountain peoples are highly dependent on these natural resources to meet household needs, loss of biodiversity will have a great impact on people's health, as well as their livelihoods (Leduc, 2009). For the Tibetan culture and livelihoods, for instance, the alpine environment represents the highest diversity of plants used for medicine, food, grazing, wood, as well as cash from market sales. Changes in the mountain biodiversity will consequently impact Tibetan medicine, herding and economy (Salick *et al.*, 2009).

New and more effective systems in both capturing and storing water will become essential. This means both improved land management and improved storage methods, as well as traditional knowledge may provide important answers (Shresta 2009). In order to understand the potential for water storage for climate change adaptation, one must fill considerable data gaps and analyze natural storage systems in the cryosphere and biosphere as well as constructed systems. Natural systems include glacial lakes, snow, ice, soil moisture, groundwater aquifers, natural water bodies and wetlands. Constructed systems include reservoirs, artificial ponds, tanks, groundwater recharge systems, and temporary runoff collection areas. Historically, a wide range of techniques have been developed in different cultures to facilitate sustainable water management. Improved techniques for storage of water can benefit from a combination of traditional and more current scientific knowledge. Potential options are the installation of new water capture and storage methods, as well as the re-introduction of some of the ancient traditional irrigation systems, such as the qanat, foggara, karez, and falaj systems known from desert regions, and the pokhari, johad and pyne systems developed in hill areas. The 'zabo' approach from Northeast India to integrate cultivation and water management in hilly, temperate areas illustrate well a simple but effective principle. The upper hills are kept forested in order to collect and store rainwater in small reservoirs, while the middle terraces partly detain runoff through small ponds., Further down cattle fields are located, and the base of the slope is used for cultivating paddy (Upadhya, 2009). Increasing sustainability of water management systems also includes irrigation systems and pipelines from major rivers, as deforestation frequently increases the rate and speed of the flow of water into major channels. The required training, the revival of old knowledge and implementation will require funds and programmes directed towards adaptation.

Increasing water and irrigation efficiency will also require institutional measures that help transform natural storage options from a passive source to a planned active source. Several areas have been identified as important (Schild and Vaidya, 2009): There is a need for a comprehensive water risk assessment in order to document water availability, deficits in time and space and availability scenarios relative to climate change. There is also a clear need for increased monitoring of changes in snow and ice and measuring the monthly contribution of meltwater to river flow. Capacity building and training is needed for wetland conservation and water management. Water harvesting and watershed management in mountain areas build on large amounts of traditional knowledge that needs to be better documented, including assessing local governance and evaluating to what extent this knowledge can be brought into modern water resources management. In many cases water infiltration and groundwater aquifer recharge can be improved if proper techniques are employed. This, along with the development of modern, larger scale water storage systems requires capacity building and training. The exchange of scientific, technological and traditional knowledge on the stor-

Qanat

A *qanat* is a water management system used to secure reliable water supply to human settlements or irrigation in semi-arid and arid regions. Probably originating in Persia, the *qanat* system has been adopted and developed further in large parts of Asia and Europe. Its widespread use is reflected in the many names for the system and similar systems; *kārīz/kahan* (Persian), *khettara* (Morocco), *galeria* (Spain), *falaj* (United Arab Emirates and Oman), *kahn* (Baloch), *foggara/fughara* (North Africa), and *karez* (Armenia and China). A *qanat* consists of many well-like vertical shafts connected by a gently sloping tunnel (Fig. 16) Tapping into the subterranean water table, the *qanat* system is effective in delivering large quantities of water to locations lower than the water source without pumping.

Qanats have played a vital role in making areas inhabitable throughout history. It is estimated that only in Iran, around 50,000 *qanats* have been in use. Although expensive and labor-demanding to construct, the long-term benefits of *qanats* were substantial for the community. *Qanats* are relatively immune to natural disasters and war, and are not dependent on diesel pumps like modern wells. However, the wells and tunnels require periodical maintenance, and much of the traditional knowledge on maintaining and constructing *qanats* has been lost (Lightfoot, 1996; Motiee *et al.* 2006).

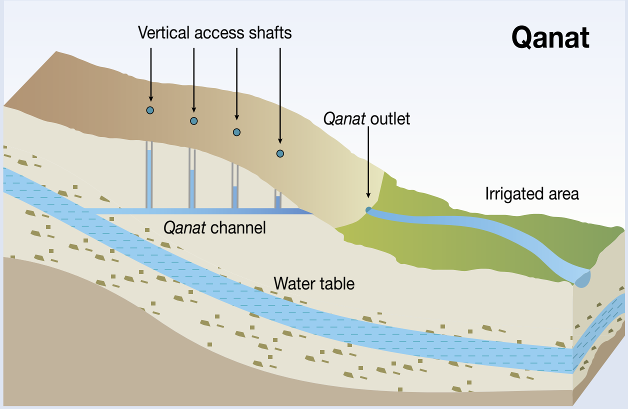


Figure 16: Cross-section of a *qanat*. Source: based on a ICQHS-UNESCO diagram.

age potential of glacial lakes and glacial and snowmelt water among major regions such as the Hindu Kush-Himalayas and the Andes will be of great importance.

Capacity building, investments in environmentally friendly, small-scale technology and development, and the implementation of improved irrigation systems, designed to optimize the water irrigation exactly according to plant demand, reducing evaporation, and reducing runoff, could likely increase efficiency in water usage several-fold. It is expected that major changes and efficiency improvements in the agricultural sector will take decades to implement. The time frame for implementation now is probably less than a couple of decades. In order to sustain populations we need a revolution in Asia – a ‘blue revolution‘ of water efficiency.

Reviews of current adaptation strategies in mountain regions suggest several important lessons. First of all adaptation and development must be considered a continuum. At one end are development activities such as providing drinking water, energy and food security, while at the other end are efforts required to reduce vulnerability to climate change and build resilience. Livelihood diversification is a key adaptation strategy, but it requires policy and institutional support. Likewise social networks and local institutions play a vital role in developing adaptive capacity. Furthermore, cultural norms affect adaptive behavior, but can also shift over time in response to environmental stress. If good governance and planning takes climate change into account, infrastructure development can contribute to enhancing water security and flood management. Also policy at different levels plays a paramount part in how successfully the effects of climate change are dealt with. Policy at national and international levels often has strong implications for local conditions, but higher level policies are often out of touch with local concerns and realities (ICIMOD, 2009).

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