

Perspectives on water and climate change adaptation

The changing Himalayas – Impact of climate change on water resources and livelihoods in the Greater Himalayas



World Water Council
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The logo of the International Centre for Integrated Mountain Development (ICIMOD), featuring the acronym 'ICIMOD' in green with a blue wave-like graphic underneath.



This Perspective Document is part of a series of 16 papers on «Water and Climate Change Adaptation»

‘Climate change and adaptation’ is a central topic on the 5th World Water Forum. It is the lead theme for the political and thematic processes, the topic of a High Level Panel session, and a focus in several documents and sessions of the regional processes.

To provide background and depth to the political process, thematic sessions and the regions, and to ensure that viewpoints of a variety of stakeholders are shared, dozens of experts were invited on a voluntary basis to provide their perspective on critical issues relating to climate change and water in the form of a Perspective Document.

Led by a consortium comprising the Co-operative Programme on Water and Climate (CPWC), the International Water Association (IWA), IUCN and the World Water Council, the initiative resulted in this series comprising 16 perspectives on water, climate change and adaptation.

Participants were invited to contribute perspectives from three categories:

- 1 **Hot spots** – These papers are mainly concerned with specific locations where climate change effects are felt or will be felt within the next years and where urgent action is needed within the water sector. The hotspots selected are: Mountains (number 1), Small islands (3), Arid regions (9) and ‘Deltas and coastal cities’ (13).
- 2 **Sub-sectoral perspectives** – Specific papers were prepared from a water-user perspective taking into account the impacts on the sub-sector and describing how the sub-sector can deal with the issues. The sectors selected are: Environment (2), Food (5), ‘Water supply and sanitation: the urban poor’ (7), Business (8), Water industry (10), Energy (12) and ‘Water supply and sanitation’ (14).
- 3 **Enabling mechanisms** – These documents provide an overview of enabling mechanisms that make adaptation possible. The mechanisms selected are: Planning (4), Governance (6), Finance (11), Engineering (15) and ‘Integrated Water Resources Management (IWRM) and Strategic Environmental Assessment (SEA)’ (16).

The consortium has performed an interim analysis of all Perspective Documents and has synthesized the initial results in a working paper – presenting an introduction to and summaries of the Perspective Documents and key messages resembling each of the 16 perspectives – which will be presented and discussed during the 5th World Water Forum in Istanbul. The discussions in Istanbul are expected to provide feedback and come up with suggestions for further development of the working paper as well as the Perspective Documents. It is expected that after the Forum all documents will be revised and peer-reviewed before being published.

1 **The changing Himalayas – Impact of climate change on water resources and livelihoods in the Greater Himalayas**

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The 'greater Himalayan region', sometimes called the 'Roof of the World', is noticeably impacted by climate change. The most widely reported impact is the rapid reduction in glaciers, with profound future implications for downstream water resources. The impacts of climate change are superimposed on a variety of other environmental and social stresses, many already recognised as severe (Ives and Messerli, 1989).

1 Introduction

1.1 The region

The 'Roof of the World' is the source of ten of the largest rivers in Asia (Table 1). The basins of these rivers are inhabited by 1.3 billion people and contain seven megacities. Natural resources in these basins provide the basis for a substantial part of the region's total GDP, and important environmental services, which are also of importance beyond the region (Penland and Kulp, 2005; Nicholls, 1995; Woodroffe et al., 2006; Niou, 2002; She, 2004; Macintosh, 2005; Sanlaville and Prieur, 2005). China and India are today experiencing strong economic growth, growing international importance, and a rapid reduction in poverty. China and India are also the two leading producers of rice in the world, most of the harvest coming from irrigated agriculture in the Ganges, the Yangtze, and the Yellow River basins. However, as noted in the Stern Report on 'The Economics of Climate Change', "China's human development could face a major 'U-turn' by this mid-century unless urgent measures are now taken to 'climate proof' development results" (Stern, 2006).

Continuing climate change is predicted to lead to major changes in the strength and timing of the Asian monsoon, inner Asian high pressure systems, and winter westerlies – the main systems affecting the climate of the Himalayan region. The impacts on river flows, groundwater recharge, natural hazards, and the ecosystem, as well as on people and their livelihoods, could be dramatic, although not the same in terms of rate, intensity, or direction in all parts of the region. Given the current state of knowledge about climate change, determining the diversity

of impacts is a challenge for researchers, and risk assessment is needed to guide future action.

1.2 Himalayan climate and water

The Himalayas display great climatic variability. The mountains act as a barrier to atmospheric circulation for both the summer monsoon and the winter westerlies. The summer monsoon dominates the climate, lasting eight months (March–October) in the Eastern Himalayas, four months (June–September) in the Central Himalayas, and two months (July–August) in the Western Himalayas (Chalise and Khanal, 2001). The east-west variation is based on the dominance of different weather systems, which in turn cause the monsoon to weaken from east to west. The monsoon penetrates northwards along the Brahmaputra River into the southeast Tibetan Plateau, but rarely as far as the Karakoram (Hofer and Messerli, 2006; Rees and Collins, 2006). The highest annual rainfall in the region occurs in Cherpunjee in India, amounting to more than 12,000 mm.

The monsoon rainfall is mainly of an orographic nature, resulting in distinct variations in rainfall with elevation between the southern slopes of the Himalayas and the rain shadow areas on the Tibetan Plateau (Mei'e, 1985). On the meso-scale, the impacts of climate are mainly due to local topographic characteristics (Chalise and Khanal, 2001), with dry inner valleys receiving much less rainfall than the adjacent mountain slopes due to the lee and orographic effect. This suggests that the currently measured rainfall, which is mainly based on measurements of rainfall in the valley bottoms, is not representative for the area, and the use of these data results in significant underestimates.

Table 1: Principal rivers of the Himalayan region – basin statistics.

River		River basin				
River	Annual mean discharge m ³ /sec*	% of glacier melt in river flow+	Basin area (km ²)	Population density	Population x1000	Water availability (m ³ /person/year)
Amu Darya	1376*	not available	534739	39	20855	2081
Brahmaputra	21261*	~ 12	651335	182	118543	5656
Ganges	12037*	~ 9	1016124	401	407466	932
Indus	5533	up to 50	1081718	165	178483	978
Irrawaddy	8024	unknown	413710	79	32683	7742
Mekong	9001*	~ 7	805604	71	57198	4963
Salween	1494	~ 9	271914	22	5982	7876
Tarim	1262	up to 50	1152448	7	8067	4933
Yangtze	28811*	~ 18	1722193	214	368549	2465
Yellow	1438*	~ 2	944970	156	147415	308
Total					1,345,241	

Source: IUCN et al. 2003; Mi and Xie 2002; Chalise and Khanal 2001; Merz 2004; Tarar 1982; Kumar et al. 2007; Chen et al. 2007

* The data were collected from the Global Runoff Data Centre (GRDC) from the following most downstream stations of the river basin; Chatly (Amu Darya), Bahadurabad (Brahmaputra), Farakka (Ganges), Pakse (Mekong), Datong (Yangtze), Huayankou (Yellow)

+ Estimation of the melt water contribution is difficult and varies in an upstream and downstream situation; approximates are given here.

Note:
The hydrological data may differ depending on the location of the gauging stations. The contribution of glacial melt is based on limited data and should be taken as indicative only.

Table 2: Glaciated areas in the greater Himalayan region.

Mountain range	Area (km ²)
Tien Shan	15,417
Pamir	12,260
Qilian Shan	1,930
Kunlun Shan	12,260
Karakoram	16,600
Qiantang Plateau	3,360
Tanggulla	2,210
Gandishi	620
Nianqingtangla	7,540
Hengduan	1,620
Himalayas	33,050
Hindu Kush	3,200
Hinduradsh	2,700
Total	112,767

Source: Dyurgerov and Meier 2005

Table 3: Glaciated areas in the Himalayan Range.

Drainage basin	No. of glaciers	Total area (km ²)	Total ice reserves (km ³)
Ganges River	6,694	16,677	1971
Brahmaputra River	4,366	6,579	600
Indus River	5,057	8,926	850
Total	16,117	32,182	3,421

Source: Qin 1999

A substantial portion of the annual precipitation falls as snow, particularly at high altitudes (above 3000m) feeding the Himalayan glaciers. The high Himalayan and inner Asian ranges have the most highly glaciated areas outside the polar regions (Owen et al., 2002; Dyurgerov and Meier, 2005). Glaciated areas in the greater Himalayan region cover an area of more than 112,000 km² (Table 2). The Himalayan Range alone (a sub-region) has a total area of 33,050 km² of glaciers or 17% of the mountain area (as compared to 2.2% in the Swiss Alps) with a total ice volume of ca 3,421 km³ (Table 3), which provides important short and long-term water storage facilities. These figures are very tentative, however, and need to be followed up with more research.

Glaciers undergo winter accumulation and summer ablation in the west, but predominantly synchronous summer accumulation and summer melt in the east. The main melting occurs in high summer; however, when this coincides with the monsoon, it may not be as critical for water supply as when the melting occurs in the shoulder seasons: spring and autumn. When the monsoon is weak, delayed, or fails, melt-water from snow and ice may limit or avert catastrophic drought.

Water from both permanent snow and ice and seasonal snow is released by melting, some to be temporarily stored in high altitude wetlands and lakes, but most flowing directly downstream in the large river systems, giving a distinct seasonal rhythm to annual stream flow regimes in these rivers. The contribution of snow and glacial melt to the major rivers in the region ranges from 2% to 50% of the average flow (see Table 1). In the 'shoulder seasons', before and after precipitation from the summer monsoon, snow and ice melt contribute about 70% of the flow of the main Ganges, Indus, Tarim, and Kabul rivers (Kattelmann, 1987; Singh and Bengtsson, 2004; Barnett et al., 2005). The rivers of Nepal contribute about 40% of the average annual

flow in the Ganges Basin, which alone is home to 500 million people, about 10% of the total human population of the region. Even more importantly, they contribute about 70% of the flow in the dry season (Alford, 1992). In western China, glacial melt provides the principal water source in the dry season for 25% of the population (Xu, 2008). The Indus Irrigation Scheme in Pakistan depends on 50% or more of its runoff originating from snowmelt and glacial melt from the eastern Hindu Kush, Karakoram, and western Himalayas (Winiger et al., 2005).

2 Observed and projected effects of climate change

Climate change is currently taking place at an unprecedented rate and is projected to compound the pressures on natural resources and the environment associated with rapid urbanisation, industrialisation, and economic development. It will potentially have profound and widespread effects on the availability of, and access to, water resources. By the 2050s, access to freshwater in Asia, particularly in large basins, is projected to decrease.

2.1 Rising temperatures

IPCC's Fourth Assessment Report (IPCC, 2007a; 2007b) concludes that there is more than a 90% chance that the observed warming since the 1950s is due to the emission of greenhouse gases from human activity. Temperature projections for the 21st Century suggest a significant acceleration of warming over that observed in the 20th Century (Ruosteenoja et al., 2003). In Asia, it is very likely that all areas will warm during this century. Warming is least rapid, similar to the global mean warming, in Southeast Asia, stronger over South Asia and East

Asia, and greatest in the continental interior of Asia (Central, West, and North Asia). Warming will be significant in arid regions of Asia and the Himalayan highlands, including the Tibetan Plateau (Gao et al., 2003; Yao et al., 2006).

Based on regional climate models, it is predicted that the temperatures in the Indian sub-continent will rise between 3.5 and 5.5 °C by 2100, and on the Tibetan Plateau by 2.5 °C by 2050 and 5 °C by 2100 (Rupa Kumar et al., 2006). However, because of the extreme topography and complex reactions to the greenhouse effect, even high resolution climatic models cannot give reliable projections of climate change in the Himalayas.

Various studies suggest that warming in the Himalayas has been much greater than the global average of 0.74 °C over the last 100 years (IPCC, 2007a; Du et al., 2004). For example, warming in Nepal was 0.6 °C per decade between 1977 and 2000

(Shrestha et al., 1999). Warming in Nepal and on the Tibetan Plateau has been progressively greater with elevation (Tables 4a and 4b and Figure 1), and suggests that progressively higher warming with higher altitude is a phenomenon prevalent over the whole greater Himalayan region (New et al., 2002) (Figure 2).

In many areas, a greater proportion of total precipitation appears to be falling as rain than before. As a result, snowmelt begins earlier and winter is shorter; this affects river regimes, natural hazards, water supplies, and people's livelihoods and infrastructure, particularly in basins such as the Tarim, which is dependent upon glacial melt in summer. The extent and health of high altitude wetlands, green water flows from terrestrial ecosystems, reservoirs, and water flow and sediment transport along rivers and in lakes are also affected.

Table 4a: Regional mean maximum temperature trends in Nepal from 1977–2000 (°C per year).

Region	Seasonal			Annual	
	Winter (Dec–Feb)	Pre-monsoon (Mar–May)	Monsoon (Jun–Sep)	Post-monsoon (Oct–Nov)	(Jan–Dec)
Trans-Himalayas	0.12	0.01	0.11	0.1	0.09
Himalayas	0.09	0.05	0.06	0.08	0.06
Middle Mountains	0.06	0.05	0.06	0.09	0.08
Siwaliks	0.02	0.01	0.02	0.08	0.04
Terai	0.01	0	0.01	0.07	0.04
All Nepal	0.06	0.03	0.051	0.08	0.06

Updated after Shrestha et al., 1999

Table 4b: Average annual increase in temperature at different altitudes on the Tibetan Plateau and surrounding areas 1961–1990 (°C per decade).

Altitude (m)	No. of stations	Spring	Summer	Autumn	Winter	Annual average change
< 500	34	–0.18	–0.07	0.08	0.16	0.00
500–1500	37	–0.11	–0.02	0.16	0.42	0.11
1500–2500	26	–0.17	0.03	0.15	0.46	0.12
2500–3500	38	–0.01	0.02	0.19	0.63	0.19
> 3500	30	0.12	0.14	0.28	0.46	0.25

Source: Liu and Hou, 1998.

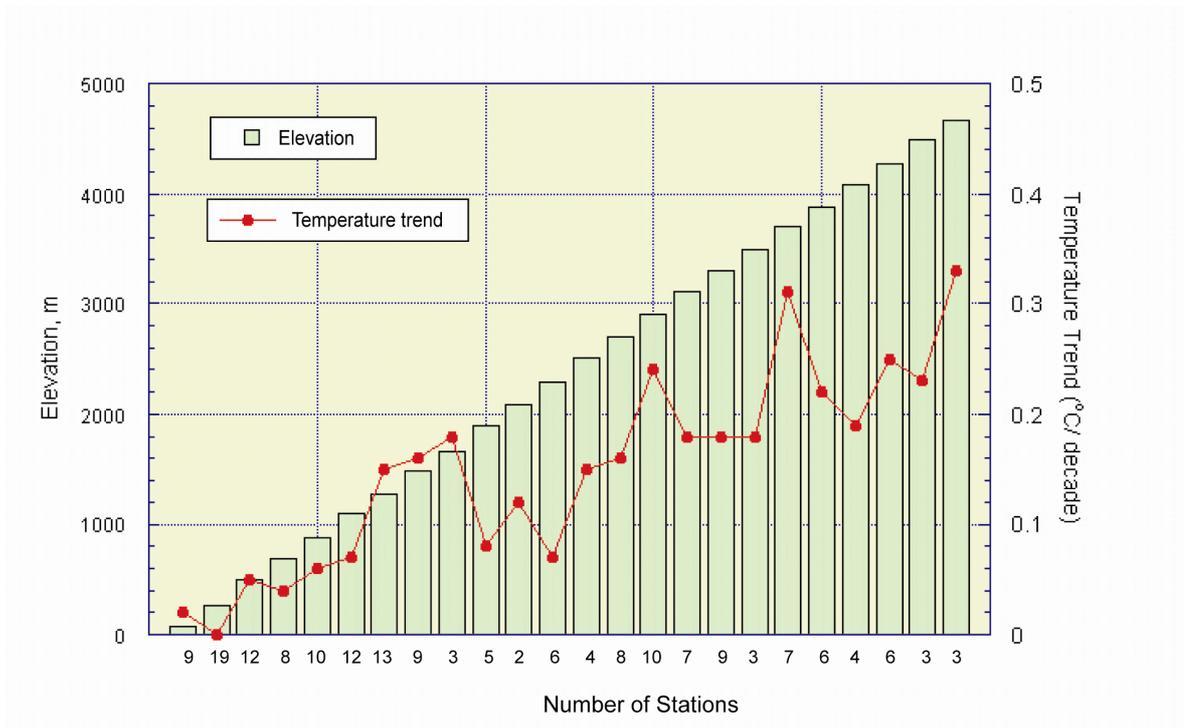


Figure 1: Dependence of warming on elevation on the Tibetan Plateau (Liu and Chen, 2000).

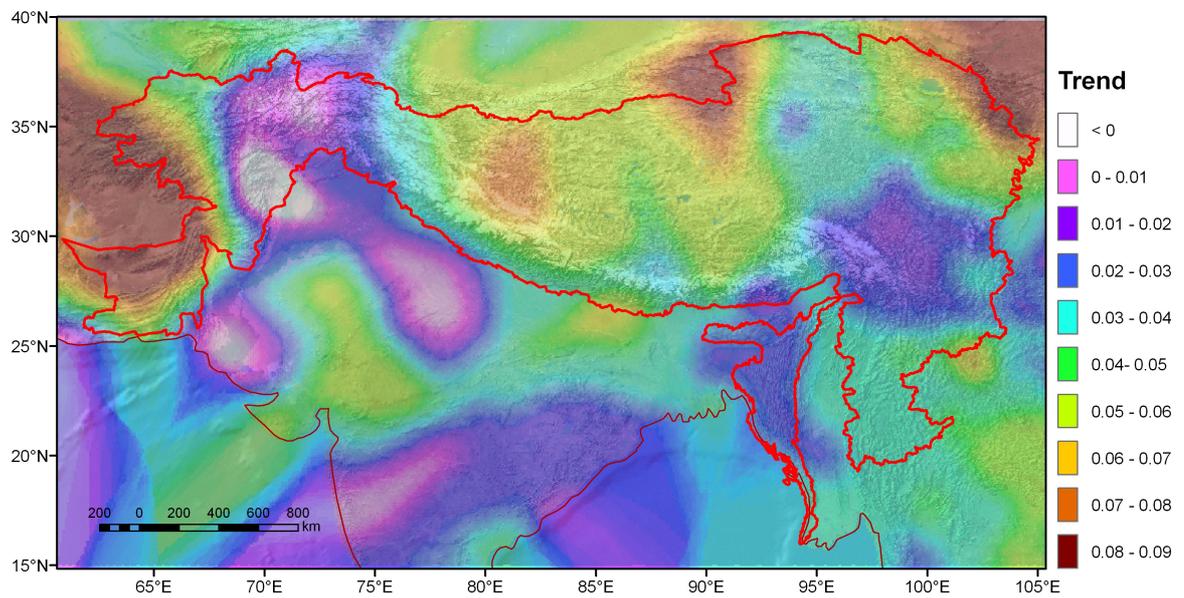


Figure 2: Spatial distribution of annual temperature trends for the period 1970–2000 (Data Source: New et al., 2002)

2.2 Precipitation trends

Long-term paleo-climatic studies (e.g. ice core studies on the Tibetan Plateau) show that both wet and dry periods have occurred in the last millennium (Tan et al., 2008, Yao et al., 2008). During the last few decades, inter-seasonal, interannual, and spatial variability in rainfall trends have been observed across Asia. In the Himalayan region, both increasing and decreasing trends have been detected. Increasing trends are found on the Tibetan Plateau in the north-east region (Zhao et al., 2004) and eastern and central parts (Xu et al., 2007), while the western Tibetan region exhibits a decreasing trend; northern Pakistan also has an increasing trend (Farooq and Khan, 2004); Nepal showed no long-term trend in precipitation between 1948 and 1994 (Shrestha et al., 2000; Shrestha, 2004).

A decrease in monsoon precipitation by up to 20% is projected by the end of the century in most parts of Pakistan and in south-eastern Afghanistan. A similar reduction in precipitation is projected for the southern and eastern Tibetan Plateau and for the central Himalayan range. Increases in the range of 20 to 30% are projected for the western Himalayan Kunlun Range and the Tien Shan Range (Rupa Kumar et al., 2006).

There is a major need for more research on Himalayan precipitation processes, as most studies have excluded the Himalayan region due to the region's extreme, complex topography and lack of adequate rain-gauge data (Shrestha et al., 2000).

2.3 Glacial retreat

Himalayan glaciers are receding faster today than the world average (Dyurgerov and Meier, 2005) (Figure 3). In the last half of the 20th Century, 82% of the glaciers in western China have retreated (Liu et al. 2006). On the Tibetan Plateau, the glacial area has decreased by 4.5% over the last twenty years and by 7% over the last forty years (CNCCC, 2007), indicating an increased retreat rate (Ren et al., 2003). Glacier retreat in the Himalayas results from "precipitation decrease in combination with temperature increase. The glacier shrinkage will speed up if the climatic warming and drying continues" (Ren et al., 2003).

The IPCC Fourth Assessment Report (IPCC, 2007a; 2007b) states that there is a high measure of confidence that in the coming decades many glaciers in the region will retreat, while smaller glaciers may disappear altogether. Various attempts to model changes in the ice cover and discharge of glacial melt have been made by assuming different climate change scenarios. One concludes that with a 2 °C increase by 2050, 35% of the present glaciers will disappear and runoff will increase, peaking between 2030 and 2050 (Qin, 2002).

Retreat in glaciers can destabilise surrounding slopes and may give rise to catastrophic landslides (Ballantyne and Benn, 1994; Dadson and Church, 2005), which can dam streams and sometimes lead to outbreak floods. Excessive melt waters, often in combination with liquid precipitation, may trigger flash floods or debris flows. In the Karakoram, there is growing evidence that catastrophic rockslides have a substantial influence on glaciers and may have triggered glacial surges (Hewitt, 2005).

2.4 Runoff over time and space

Mountain regions provide more than 50% of the global river runoff, and more than one-sixth of the Earth's population relies on glaciers and seasonal snow for its water supply. The effects of climatic change are of tremendous importance to the often densely populated lowland regions that depend on mountain water for their domestic, agricultural, and industrial needs (e.g., Barnett et al., 2005; Graham et al., 2007). The processes that determine the conversion of precipitation into runoff and downstream flow are many and complex. Changes in precipitation type (rain, snow) and its amount, intensity, and distribution over time and space have a direct impact on total and peak river runoff, potentially moving it away from agricultural and dry season demands and towards monsoon flash floods. Evapotranspiration rates, linked to temperature, have an effect on the amount of water available for runoff. However, one of the main concerns in relation to climate change in the Himalayan region is the reduction of snow and ice, which reduces the water storage capacity. Initially, it is likely that the stable base-flow – derived from melting ice and snow – will increase, particularly during warm and dry seasons. It is not unlikely that this will appear as a positive, comforting sign,

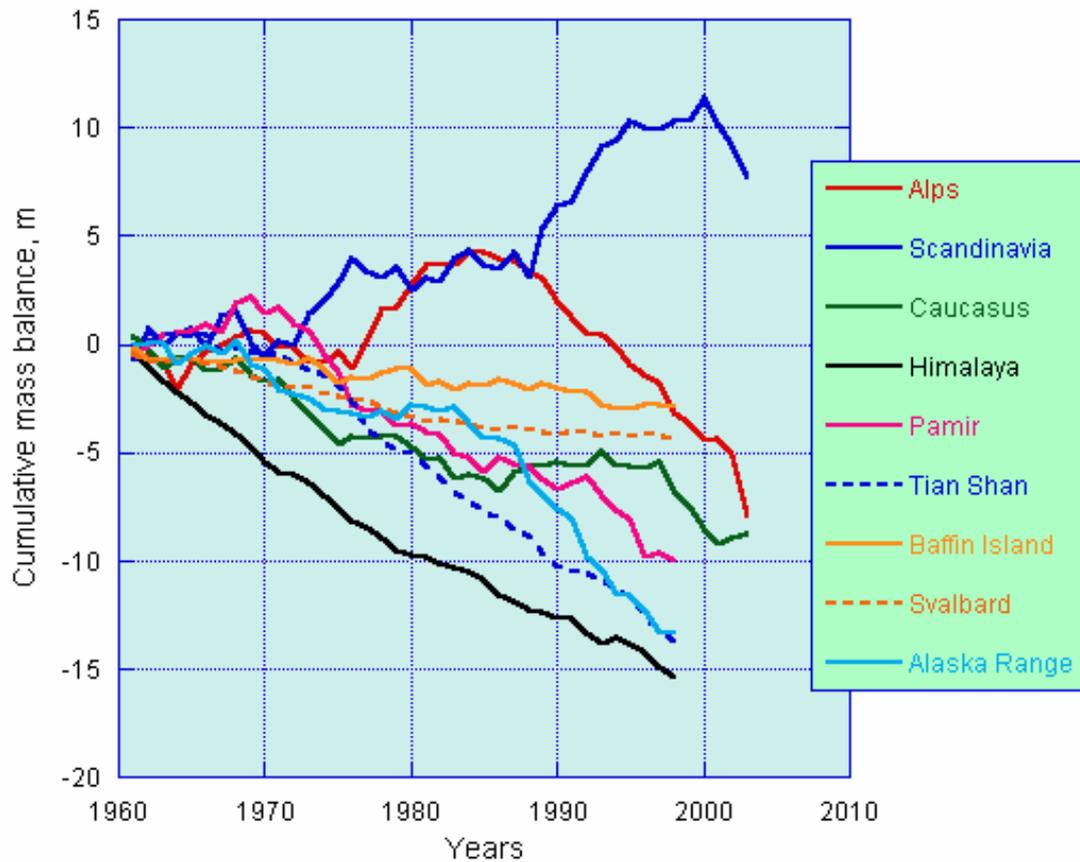


Figure 3: Rapid retreat of greater Himalayan glaciers in comparison to the global average (Source: Dyurgerov and Meier 2005).

detering and delaying required emergency initiatives. However, as the far-away and high-altitude reservoirs of snow and ice continue to decrease, eventually disappearing, the variability of downstream runoff will increase, potentially dramatically, and progressively reflect direct rainfall-runoff, which in turn will mirror precipitation and evapotranspiration rates.

In Asia, climate change induced glacial melt could seriously affect half a billion people in the Himalayan region overall and a quarter of a billion people in China, who all depend on glacial melt for their water supply (Stern, 2007). In South Asia, hundreds of millions of people depend on perennial rivers such as the Indus, Ganges, and Brahmaputra – all fed by the unique water reservoir formed by the 16,000 Himalayan glaciers. The current trends in glacial melt suggest that the low flow will become substantially reduced as a consequence of climate change (IPCC, 2007a). The effect of this on, for example, food production and economic growth is likely to be unfavourable. The situation may appear to be normal in the region for several decades to

come, and may even include increased amounts of water available to satisfy dry season demands. However, when the shortage arrives, it may happen abruptly, with water systems going from plenty to scarce in perhaps a few decades or less. Some of the most populated areas of the world may “run out of water during the dry season if the current warming and glacial melting trends continue for several more decades” (Barnett et al. 2005). Flooding may also arise as a major development issue. It is projected that more variable, and increasingly direct, rainfall runoff will also lead to more downstream flooding.

2.5 Permafrost

Areas in the high mountains and on the high plateaus not covered in perennial snow and ice are underlain by permafrost. Permafrost areas will be sensitive to degradation with climate warming. Recent studies show that the extent of permafrost is shrinking and that the active layer thickness (the upper portion of soil that thaws each summer) is

increasing, and, further, that this has altered the hydrological cycle, vegetation composition, and carbon dioxide and methane fluxes that appear linked to permafrost degradation (Lawrence and Slater, 2005). The areas covered by permafrost are much larger than those covered by glaciers or perennial snow, especially in China. Permafrost plays a critical role in ecology, slope stability and erosion processes, and surface water hydrology. On the Tibetan Plateau, the recent warming has been associated with decreasing areas of permafrost and a rise in the elevation of its lower altitude, as well as progressive thinning. For example, in the past three decades, on the Central Tibetan Plateau in the Kekexeli Wildland Area, the lower limit of permafrost has risen by approximately 71 m, while the sustained thickness has decreased by at least 20 cm (Wu et al., 2001). Meanwhile, the extent of seasonal thawing has intensified over large areas of permafrost causing increased ground instability and erosion (Zhao et al., 2004), with consequences such as the activation of the soil carbon pool and northward expansion of shrubs and forests (Lawrence and Slater, 2005). The disappearance of permafrost and expansion of non-permafrost will accelerate desertification on the Tibetan Plateau (Ni, 2000). Notwithstanding, there is almost no information about the full extent and behaviour of high mountain permafrost areas in the region.

2.6 Water-related hazards

According to the United Nations International Strategy for Disaster Reduction (UNISDR), in 2007, seven of the top ten natural disasters by number of deaths occurred in four of ICIMODs member countries (Bangladesh, China, India, and Pakistan), accounting for 82% of total natural disaster related deaths worldwide. This indicates not only the prevalence of disasters in the region, but also the susceptibility of the region to such events (Table 5). Climate change involves, perhaps most seriously, changes in the frequency and magnitude of extreme weather events. There is widespread agreement that global warming is associated with extreme fluctuations, particularly in combination with intensified monsoon circulations.

The lack of data frequently observed in the region hinders a comprehensive assessment of changes in extreme climatic events. Available studies suggest changes in climatic patterns and an increase in extreme events. An increase in the frequency of high intensity rainfall often leading to flash floods and land slides has been reported (Chalise and Khanal, 2001; ICIMOD, 2007a; Figure 4). In parts of Central Asia, regional increases in temperature will lead to an increased probability of events such as mudflows and avalanches that could adversely affect human settlements (Iafiazova, 1997).

Table 5: Natural disasters in 2007 by number of deaths.

Type of disaster (month)	Country	Number of deaths
Cyclone Sidr (November)	Bangladesh	4234
Flood (July–August)	Bangladesh	1110
Flood (July–September)	India	1103
Flood (August)	Korea DPR	610
Flood (June–July)	China PR	535
Earthquake (August)	Peru	519
Heat wave (July)	Hungary	500
Cyclone Yemyin (June)	Pakistan	242
Flood and landslides (June)	Pakistan	230
Flood (July)	India	225

Source (UNISDR, 2007)

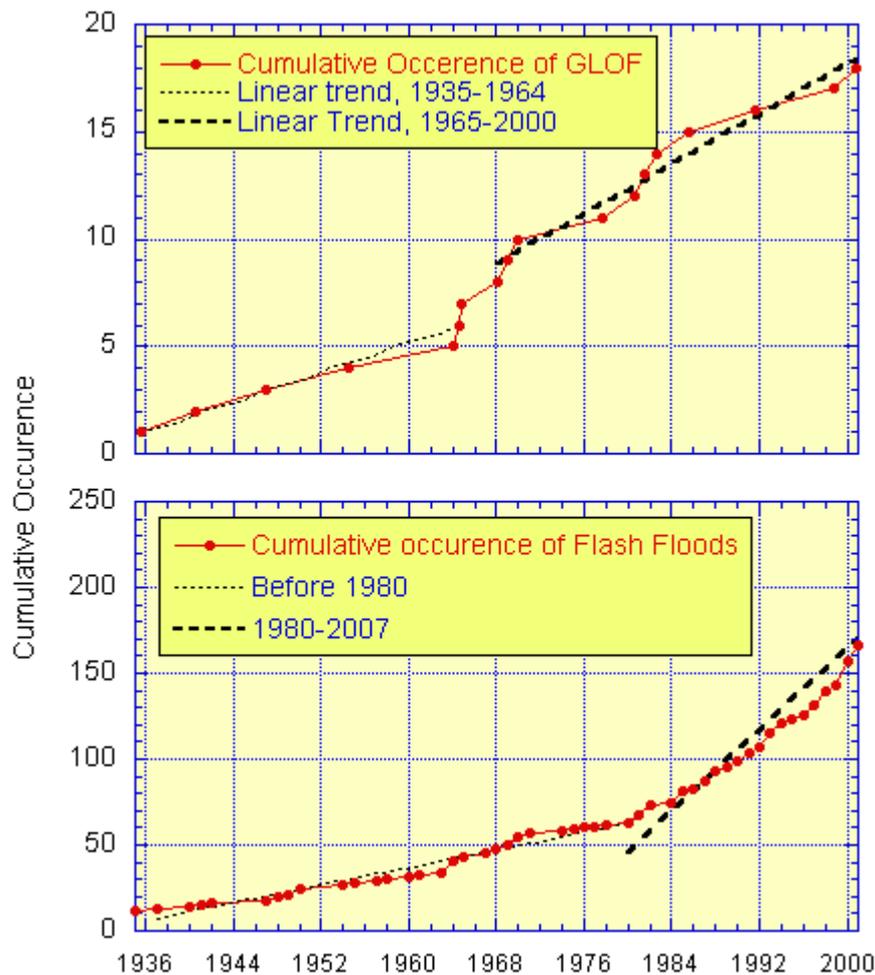


Figure 4: Cumulative frequency of GLOFs and flash floods in the HKH region.

In the eastern and central Himalayas, glacial melt associated with climate change, has led to the formation of glacial lakes behind terminal moraines. Many of these high-altitude lakes are potentially dangerous. The moraine dams are comparatively weak and can breach suddenly, leading to the discharge of huge volumes of water and debris. The resulting glacial lake outburst floods (GLOFs) can cause catastrophic flooding downstream, with serious damage to life, property, forests, farms, and infrastructure. In Nepal, twenty-five GLOFs have been recorded in the last 70 years, including five in the sixties and four in the eighties (Mool, 2001; NEA, 2004; Yamada, 1998). There is an indication that the frequency of GLOF events has increased in recent decades (Figure 4). In the HKH region two hundred and four glacial lakes have been identified as potentially dangerous lakes, which can burst at any time (ICIMOD, 2007b).

3 Consequences for livelihoods and the environment

3.1 Pastures and agriculture

The location and areas of natural vegetation zones on the Tibetan Plateau will substantially change under projected climate change scenarios. Areas of temperate grassland and cold temperate coniferous forest could expand, while temperate and cold deserts may shrink. The vertical distribution of vegetation zones could move to higher altitude. Climate change may also result in a shift of the boundary of the farming-pastoral transition region to the south in Northeast China, which may increase grassland areas and provide more favourable conditions for livestock production. However, the transition area of the farming-pastoral region is also an area of potential desertification, and if protection measures are not taken in new transition areas, desertification may occur (Li

and Zhou, 2001; Qiu et al., 2001). More frequent and prolonged droughts as a consequence of climate change together with other anthropogenic factors may also result in desertification.

There is significant uncertainty about the effects of global warming on the vegetation and animal productivity of large dryland ecosystems. Although high altitude drylands might enjoy increases in net primary productivity (NPP), locally, the greatest confidence is in predicting implications for vegetation production, with lesser confidence in implications for vegetation composition, animal production, and adaptation options (Campbell and Stafford Smith 2000). Climate change has been reported to impact on grassland productivity, ecosystems, and the distribution and composition of plant communities (Wilkes, 2008). Some rangelands might suffer from degradation due to the warmer and drier climate (Dirnbock et al., 2003). Degraded rangeland already accounts for over 40% of dryland on the Tibetan Plateau (Zhong et al., 2003; Gao et al., 2005); and it is expanding at a rate of 3 to 5% each year (Ma and Wang, 1999). Increases in evaporation, reduction in snow cover, and fluctuations in precipitation are key factors contributing to the degradation of dryland ecosystems.

The possibility of alterations in the overall albedo, water balance, and surface energy balance in high-altitude grasslands and the increasing degradation and desertification of arid areas is causing concern. Signs of the effects of climate change on grasslands have been documented in the northeast Tibetan Plateau where *Kobresia* sedge and alpine turf communities are changing to semi-arid alpine steppes, known as 'black bleaching' (Ma and Wang, 1999; Miller, 2000). Qinghai Province in China alone has more than 20,000 km² of degraded rangeland.

Upward movement of the tree line and encroachment of woody vegetation on alpine meadows are reported widely. In the eastern Himalayas, the tree line is rising at a rate of 5 to 10 m per decade (Baker and Moseley, 2007). As temperature rises, species shift their ranges to follow their principal habitats and climatic optima.

Increasing temperatures and water stress are expected to lead to a 30% decrease in crop yields in Central and South Asia by the mid-21st Century (UNDP, 2006). At high altitudes and latitudes, crop yields should increase because of reductions in frost and cold damage. It will be possible to grow rice and

wheat at higher latitudes than is currently the case in China.

Irrigated lowland agriculture, found in all of the large basins receiving their runoff from the Hindu Kush-Himalayan system, is projected to suffer negatively from lack of dry season water. Considering that the reported or projected glacial melt water component amounts to, for example, 20 to 40% per capita in Western China (Tao et al., 2005), 50% or more in the Indus (Tarar, 1982), and 30% in the major rivers in Nepal during pre-monsoon (Sharma 1993), the implications of dry season water stress are likely to be massive. In addition, an increase in agricultural water demand by 6 to 10% or more is projected for every 1 °C rise in temperature (IPCC, 2007a). As a result, the net cereal production in South Asian countries is projected to decline by at least between 4 to 10% by the end of this century, under the most conservative climate production projections (IPCC, 2007a).

3.2 Ecosystems

Mountain ecosystems contain a series of climatically very different zones within short distances and elevations. They display a range of micro-habitats with great biodiversity (Körner, 2004). Mountain ecosystems are sensitive to global warming and show signs of fragmentation and degradation (Xu and Wilkes, 2004; Körner, 2004). Species in high-elevation ecosystems are projected to shift to higher altitudes, although alpine plant species with restricted habitat availability above the tree line are projected to experience severe fragmentation, habitat loss, or even extinction if they cannot move to higher elevations (Dirnbock et al., 2003). Climate warming may increase suitable habitats for the water hyacinth (*Eichhornia crassipes*), a noxious weed able to survive winter temperatures.

The impacts of climate change on forest ecosystems include shifts in the latitude of forest boundaries and the upward movement of tree lines to higher elevations; changes in species composition and in vegetation types; and an increase in net primary productivity (NPP) (Ramakrishna et al., 2003). In the eastern Himalayas, forest vegetation will expand significantly; forest productivity will increase from 1 to 10%; and it is expected that forest fires and pests such as the North American pinewood nematode

(*Bursaphelenchus xylophilus*) will increase as dryness and warmth increase (Rebetez and Dobbertin, 2004).

3.3 Human health

The impact of climate change on health conditions can be broken into three main categories: (i) direct impacts from phenomenon such as drought, heat waves, and flash floods, (ii) indirect effects due to climate-induced economic dislocation, decline, conflict, crop failure, and associated malnutrition and hunger, and (iii) indirect effects due to the spread and aggravated intensity of infectious diseases due to changing environmental conditions (WHO, 2005). The latter effect includes the expansion of vector-borne diseases such as malaria and dengue, and water-related diseases such as diarrhoea. Regions such as the Hindu Kush-Himalayas, located at the fringe of the current geographic distribution of these and many other diseases, are particularly susceptible to the negative effect of rising temperatures. It is projected that the spread of malaria, Bartonellosis, tick-borne diseases and infectious diseases linked to the rate of pathogen replication will all be enhanced. Malaria mosquitoes have recently been observed at high altitudes in the region (Eriksson et al., 2008).

Endemic morbidity and mortality due to diarrhoeal disease associated with floods and droughts are expected to rise in East, South and South-East Asia due to projected changes in the hydrological cycle (IPCC, 2007a). This will be on top of an already very high global burden of diarrhoea attributable to climate change. Empirical studies project that the population at risk of dengue fever will be larger in India and China. In these countries, a high increase in mortality due to heat stress is also projected.

However, there are also expected to be positive climate change induced effects on the health status of certain populations in the HKH region. High altitude areas, formerly too cold, will open up to new types of agricultural production and new livelihood opportunities, people will find their homes and villages more comfortable due to warmer conditions, and the risks associated with cold and respiratory diseases will be reduced as the use of fuelwood for heating is reduced.

3.4 Mountain infrastructure

Valuable infrastructure, such as hydropower plants, roads, bridges, and communication systems, will be increasingly at risk from climate change. Entire hydropower generation systems established on many rivers will be in jeopardy if landslides and flash floods increase, and hydropower generation will be affected if there is a decrease in the already low flows during the dry season. Engineers will have to consider how to respond to these challenges (OECD, 2003).

A specific hazard related to glacier retreat is the formation of pro-glacial lakes and in some cases the events of glacial lake outburst floods (GLOFs). These can have a devastating effect on important and vulnerable infrastructure downstream such as hydropower stations. Equally important, the operations of hydroelectric power stations will become more complex. With climate change, the complexity and variability of river flow generation will both rise (Renoj et al., 2007) and become increasingly difficult to predict. For example, although the annual average proportion of meltwater in river flow has been estimated at 13% for rivers flowing to the Ganges from Nepal, from March through May the monthly average proportion is more than 30% (Chaulagain, 2006). This could have serious implications on river flows and water availability for power plants for about six months per year.

The landmark Qinghai-Tibet Railway, built at a huge cost and associated with important development objectives, is partly built on permafrost. Projected widespread permafrost melting on the Tibetan Plateau can threaten future railway services (Xu et al., 2005; Chen et al., 2005). Likewise, the Yangtze River, China's largest river and a crucial supplier of water to industry, agriculture, and 500 million domestic users, experienced its lowest upper reaches flow since the 1920s in 2006. With upstream dryland expansion, melting glaciers, and aggravated sediment deposits that affect downstream flood discharge capacity (Wang et al., 2005), the Three Gorges Dam, the world's largest hydroelectric installation, is at risk.

3.5 Livelihoods, vulnerability and adaptation

The term ‘livelihood’ comprises the capabilities, assets (material and social resources), and activities required for ensuring a means of living (Carney, 1998). Sustainable livelihood includes the idea of coping with and recovering from stresses and shocks, and maintaining or enhancing existing capabilities and assets. Climate change has made the future of mountain indigenous people and their livelihoods more vulnerable and uncertain. The available scientific evidence suggests that climate change will place significant stress on the rural livelihoods of mountain people. Efforts to reduce vulnerability and enhance the adaptive capacity of at-risk groups need to take a proactive approach that addresses the social processes leading to vulnerability and the structural inequalities that are often at the root of social-environmental vulnerabilities.

Adaptation to climate change is both related to vulnerability, which can be defined as the “degree to which individuals and systems are susceptible to or unable to cope with the adverse effects of climate change” (Smit and Pilifosova, 2001), and to future potential impacts, either avoidable or unavoidable. Effective adaptation includes both the establishment of adaptive capacity (awareness, governance, and knowledge) and the adaptation itself (change of behaviour, practices, and livelihoods according to new conditions) (Mirza, 2007). Adaptation consists of a multitude of options depending on the scale, context, and approach. The scale of adaption may be local, national, or regional; the context of the adaptation will determine the type of adaptation (e.g. new farming practices in a rural context or water demand management in an urban context); and the approach to adaptation may focus on general poverty alleviation, enhanced transparency in decision making, or the empowerment of women, among other things.

Structural inequalities that make adaptation by poor people more difficult will need to be levelled. It is important to note that poor and marginalised people already face all of the difficulties that we usually associate with climate change. This is nothing new to them. They are already facing poor health, susceptibility to floods and landslides, and a lack of adequate shelter, food, and water. While they do need climate change adaptation, they need poverty alleviation even more.

China and India’s current rapid economic development, which is moving many tens of thousands of people out of poverty every day, may also provide the best way to handle a changing world. It should be noted that much of the adaptation to climate change will be found outside the sphere of natural sciences. For example, to focus only on flood-safe housing or new types of pest-resistant crops is not enough. The focus must include enhanced capacity to adopt (implying a comprehensive approach) new adaptation strategies. “An adaptation strategy to reduce vulnerability to future climate change needs to be incorporated in regulatory procedures, integrated natural resources management and other development planning procedures” (UNDP-GEF, 2007). As poverty is widespread in the Himalayan region, the empowerment of poor people to adapt to climate change is critical.

Examples of enhancing adaptive capacity at different levels may include introducing and/or enhancing governance to climate focus development, mainstreaming climate change into development planning; and institutional and policy reforms (Mirza, 2007), general political reform and associated openness (ibid), health education programmes (WHO, 2005), and the development of early warning systems for floods, flash floods, and droughts.

4 Lack of knowledge – unknown downstream effects

The impact of climate change on the Himalayan cryosphere is not understood well enough to support estimates of the full scale of the downstream impact of reduced snow and ice coverage. While in-depth studies of glaciers, snow, and permafrost have been carried out in some areas, they are scattered widely in space and time. Few detailed investigations of the response of snow and ice to climate warming have taken place in the Himalayan and other high ranges. Baseline studies are lacking for most areas, particularly for areas higher than 4,000 masl, and there has been little long-term monitoring of climatic variables, perennial snow and ice, runoff, and hydrology in the extraordinary heterogeneity of mountain topography (Liu and Chen, 2000; Rees and Collins, 2006; Messerli et al., 2004). In addition, the one common feature that all mountain areas share with one another – complexity caused by topography – causes

temperature and precipitation to vary over very short distances (Becker and Bugmann, 1997), which in turn makes projections difficult.

Three levels of impact to climate change can be identified: i) local effects, ii) downstream effects, and iii) global feedback effects. The development of adaptive strategies can be approached from the perspective of each of these three different levels. Firstly, adaptive strategies can be developed at the local level, looking at local effects within the Himalayas and giving priority to local adaptation. Secondly, adaptive strategies can be developed from the perspective of the downstream level, evaluating the downstream effects of climate change and designing adaptive strategies around these effects. Thirdly, adaptive strategies can be developed on the global level, based on the potential feedback mechanism of the environmental changes in the Himalayas to global warming. All three levels are interlinked and interrelated, but full of uncertainty.

4.1 Local effects

Few model simulations have attempted to address issues related to future climatic change in mountain regions, primarily because the current spatial resolution of models is too crude to adequately represent the topographic and land use details (Beniston et al., 2003). Most climate models and predictions for high-altitude areas (above 4,000 masl) are dependent on extrapolation from hydro-meteorological stations at comparatively low altitudes and upon assumptions based on other, better-studied, parts of the world (Rees and Collins, 2004). The importance of the most widespread cryogenic processes – avalanches, debris flows, rock glaciers, alpine permafrost, and surging glaciers – has been recognised and their incidence recorded for certain areas. Yet, almost no basic scientific investigation of these cryogenic processes has taken place in the greater Himalayan region, even though they involve significant hazards, which may increase or decrease risk in given areas. The immense diversity of local effects found within the region should be recognised: diversity of climates and topo-climates, hydrology and ecology, and, above all, of human cultures and activities. Before effective responses can be developed, much work has to be carried out to identify and predict the possible effects of climate change across different systems –

from glaciers to water resources, from biodiversity to food production, from natural hazards to human health – and filtered through diverse contexts. In particular, to date there has been little engagement with local populations to learn from their knowledge and experience in adapting to unique and changing environments and to address their concerns and needs (Xu and Rana, 2005).

4.2 Downstream effects

The downstream effects of changing water flow regimes in the large Himalayan rivers are to a great extent, unknown. Few (if any) studies have attempted to model the impact of a 30–50% reduction in dry season flow on, for example, downstream economic growth, livelihood conditions, and urban water use. It is likely that these changes will have major impacts on downstream societies; however, these impacts are largely unknown. Impacts on water resources will differ depending upon the importance or influence of different sectors (such as tourism, irrigated agriculture, industry and resource extraction), the ecosystems involved, and on the mitigation measures implemented to reduce water-induced hazards. There are substantial variations within, as well as between, these sectors in different countries and valleys in the region.

4.3 Global feedback effects

Glaciation in low latitudes has the potential to play an important role in the global radiation budget. A climatic feedback mechanism for Himalayan glaciation shows that a higher glacier free or low albedo surface has a cooling effect over the Himalayas and a warming effect over the Persian Gulf and the Arabian Peninsula (Bush, 2000). The Himalayan region is also an important carbon sink, particularly in terms of carbon storage in the soil of grasslands, wetlands, and forests. Wang et al. (2002) estimate that the organic carbon content of soils subtending grasslands on the Qinghai-Tibet Plateau total 33,500,000,000 metric tons, representing almost one quarter of China's total organic soil carbon and 2.5% of the global pool of soil carbon. Climatic variables influence soil carbon stocks through their effects on vegetation and through their influence on the rate of

decomposition of soil organic matter. In grassland ecosystems, net ecosystem productivity (that is, the amount of carbon sequestered) is very small compared to the size of fluxes, so there is great potential for changes affecting fluxes to change the net flow of carbon, and for grasslands, therefore, to shift from being a CO₂ sink to a CO₂ source (Jones and Donnely, 2004), contributing further to global warming.

5 Policy recommendations

5.1 Reducing scientific uncertainty

Develop scientific programmes for climate change monitoring:

Credible, up-to-date scientific knowledge is essential for the development of a climate change policy, including adaptation and mitigation measures. The current review finds a severe lack of field observations. It is essential to develop a scientific basis, in collaboration with government agencies and academia. Remote sensing allows for regular and repeated monitoring of snow cover, which can be carried out by countries such as China and India, with results shared with those lacking such technological infrastructure. Studies need to include both ground-based and satellite-based monitoring. Well-equipped stations and long-term monitoring, networking, and cooperation within and outside the region are essential. Participatory methods of assessing and monitoring climate and environmental change, local perceptions, and practices at the local level are also required. Local communities can play a role in determining adaptation practices based on local information and knowledge. School science programmes can be developed and introduced in local communities.

Application of regional climate models (RCMs): The Himalayas are not well represented in global models because of the coarse resolution of such models. Regional climate models, with a higher resolution than global ones, need to be constructed for 'hotspots' and run for shorter periods (20 years or so). The results of RCMs have to be downscaled and applied to impact assessments, particularly for watersheds or sub-catchments.

5.2 Mitigation measures

Beyond the Kyoto protocol: With rapid regional economic growth, China and India, in particular, should accept equal, albeit differentiated, responsibility as developed countries for controlling increasing carbon emissions. Countries should jointly develop a regional action plan for the control of emissions. Participation of all countries has to be achieved by allowing them to interpret the mandates of international agreements according to their national interests and priorities.

Land-use management for carbon sinks and reduced emissions:

Many countries in the Himalayas have experienced forest recovery (or transition), through policy intervention and the participation of local communities in forest management. Examples include forest conservation in Bhutan, tree plantations in China, community forest user groups in Nepal, and joint forest management in India. The forests conserved have contributed significantly to carbon sequestration (Fang et al., 2001).

Payment for ecosystem services (PES): The mountains of the greater Himalayas provide abundant services to the downstream population in terms of water for household purposes, agriculture, hydropower, tourism, spiritual values, and transport. Upstream land and water managers shoulder the heavy responsibility of ensuring reliable provision of good quality water downstream. PES schemes can be developed at different scales, from local to national to regional, and involve local communities, governments, and the private sector. To date, the opportunities to establish PES schemes in the Himalayas to ensure safe provision of good quality water remain largely unexplored. However, land and water managers, as well as policy and decision makers, should be encouraged to look for win-win solutions in this context.

Development of alternative technologies: Novel and affordable technologies and energy resources that do not emit greenhouse gases are needed. Notable examples in the region include the diffusion of hydropower in Bhutan, solar energy and biogas in China, bio-diesel and wind energy in India, and biogas and micro-hydropower in Nepal.

5.3 Adaptation measures

Disaster risk reduction and flood forecasting: Floods are the main natural disaster aggravating poverty in the Himalayas where half of the world's poor live.

Technical advances in flood forecasting and management offer an opportunity for regional cooperation in disaster management. Regional cooperation in transboundary disaster risk management should become a political agenda. Preparedness is essential in order to reduce the potential destruction from natural disasters

(www.disasterpreparedness.icimod.org).

Supporting community-led adaptation: One approach to vulnerability and local level adaptation is 'bottom-up' community-led processes built on local knowledge, innovations, and practices. The focus should be on empowering communities to base adaptations to a changing climate and environment on their own decision-making processes, and on participatory technology development with support from outsiders. For example, Tibetan nomads have already noticed the earlier spring and moved yaks to alpine meadows earlier than previously practised. Farmers in the floodplains of Bangladesh build houses on stilts, and Nepali farmers store crop seeds for post-disaster recovery. Priority should be given to the most vulnerable groups such as women, the poor, and people living in fragile habitats (e.g. along riversides and on steep slopes).

National adaptation plans of action (NAPAs): NAPAs are currently being prepared by countries under the initiative of the UN Framework Convention on Climate Change. They are expected (a) to identify the most vulnerable sectors to climate change and (b) to prioritise activities for adaptation measures in those sectors. NAPAs need to pay more attention to sectors such as water, agriculture, health, disaster reduction, and forestry, as well as the most vulnerable groups.

Integrated water resources management: Disaster preparedness and risk reduction should be seen as an integral part of water resources management. Integrated water resources management (IWRM) should include future climate change scenarios and be scaled up from watersheds to river basins. Water allocation for households, agriculture, and ecosystems deserves particular attention. Water storage,

based on local practices, should be encouraged in mountain regions.

5.4 Public awareness and engagement

Full disclosure and prior information for grass-root societies: Indigenous and local communities should be fully informed about the impacts of climate change. They have a right to information and materials in their own languages and ways of communicating.

Engagement of the media and academia: Awareness and knowledge among stakeholders about the impacts of global warming and the threat to the ecosystem, communities, and infrastructure are generally inadequate. The media and academia together can play a significant role in public education, awareness building, and trend projection.

Facilitation of international policy dialogue and cooperation: Regional and international cooperation needs to advance in order to address the ecological, socioeconomic, and cultural implications of climate change in the Himalayas. The international community, including donors, decision-makers, and the private and public sectors, needs to be involved in cooperative regional ventures. This is of particular importance for achieving sustainable and efficient management of transboundary rivers.

6 Conclusions

The Himalayan region contains one of the most dynamic and complex mountain systems in the world. This mountain system is extremely vulnerable to global warming (Bandyopadhyay and Gyawali, 1994). Uncertainties about the rate and magnitude of climate change and potential impacts prevail, but there is no question that climate change is gradually and powerfully changing the ecological and socio-economic landscape in the Himalayan region, particularly in relation to water. Business as usual is not an option. It is imperative for environmental decision makers and managers to revisit and redesign research agendas, development policies, and management and conservation practices, and develop appropriate technologies. The mitigation of

carbon emissions should be a responsibility shared between citizens and the private sector in the mountains, as elsewhere. Adaptation and mitigation measures intended to cope with climate change can create opportunities as well as offset the dangers of a warming planet; but they must be identified and adopted ahead of, rather than in reaction to, dangerous trends. Policies should be ‘adaptation friendly’.

Himalayan uncertainty: Recognising the lack of studies and basic data, we speak of uncertainty on a Himalayan scale. In no context is this more relevant than in predicting what climate change will entail. The physical manifestations of climate change in the mountains include locally, possibly regionally, extreme increases in temperature and in the frequency and duration of extreme events. It seems certain that there will be appreciable changes in the volume and/or timing of river flows and other freshwater sources. There is, however, great uncertainty about the rate, and even the direction, of these changes, because so little is known about the dynamics of Himalayan topo-climates and hydrological processes, and their response to changing climatic inputs. The global circulation models used to model climates capture global warming on a broad scale, but do not have adequate predictive power for even large Himalayan drainage basins. To reduce uncertainty, we need well-equipped baseline stations, long-term monitoring, networking, open data exchange, and cooperation between all Himalayan countries. ICIMOD can play a role in facilitating knowledge generation, exchange, and cooperation with international mountain research programmes such as the Global Observation Research Initiative in Alpine Environments (GLORIA), Global Mountain Biodiversity Assessment (GMBA), UNESCO Biosphere Reserves, Monsoon Asia Integrated Regional Studies (MAIRS), and the Mountain Research Initiative.

Adaptation: Adaptation is the need for flexibility and resilience. Climate change is not new to Himalayan people. During very long time periods every aspect of life has been adapted to, or stressed by, changing temperature regimes, water availability, and extreme events. Himalayan farmers and herders have a long history of adapting to these uncertainties, to other related and unrelated environmental changes, and to ecological surprises, whether through mobility of

people and land uses, or flexibility in livelihood strategies and institutional arrangements. Mountain people have lived with and survived great hazards such as flash floods, avalanches, and droughts for millennia. Building on this capacity to adapt and strengthening the socio-ecological system in the face of climate change is extremely important and an important step in achieving sustainable livelihoods. Climate change, as a public and global issue, has evolved from a narrow interest in the hydro-meteorological sciences, to a broad recognition that both the social consequences and policies of the human response to climate change have implications for all aspects of human development. Adaptive policies and major efforts to reverse the human drivers of climate change have to be incorporated into all sectors: land use, water management, disaster management, energy consumption, and human health. Hazard mapping would help both decision-makers and local communities understand the current situation, thereby enabling them to anticipate or assess their flexibility to adapt to future changes through proper planning and technical design.

Linking science and policy in climate change: Good science based on credible, salient, legitimate knowledge can often lead to good policies in the context of climate change and mountain specificities, and vice versa (Thompson and Gyawali, 2007). By credible, we mean knowledge that has been derived from field observations and tested by local communities. Salient information is information that is immediately relevant and useful to policy-makers. Legitimate information is unbiased in its origins and creation and both fair and reasonably comprehensive in its treatment of opposing views and interests. Policy is a formula for the use of power and application of knowledge. The question then becomes who has the power and who has the knowledge, scientific or local, or a combination of the two? Scientific knowledge is useful, but limited and full of uncertainties on the complex Himalayan scale. So, ‘nobody knows best’ becomes the model (Lebel et al., 2004). Alternative perspectives carry their own set of values and perceptions as to who should be making the rules, where the best knowledge to guide decisions lies, and what additional knowledge is needed. Multiple, sometimes contrasting, perspectives merge together in decision-making processes. In such processes, scientists have to generate new knowledge

with reduced uncertainty to facilitate a fact-based dialogue. The role of different actors in contributing to resolving scientific uncertainty, adaptation, mitigation, and public engagement through this approach can be summarised in the form of the matrix in Table 6. In such processes, international

cooperation is essential for the transfer of technology from outsiders to locals, to build regional cooperation into a global programme, and to develop the capacity to downscale important results to the regional HKH scale.

Table 6: Nobody knows best: Policy matrix to cope with Himalayan uncertainty.

	Scientific uncertainty	Adaptation	Mitigation
State	Regional cooperation, support long-term research, engage in research processes	Inter-sectoral collaboration, support for poverty alleviation and environmental conservation	Commitment to international treaties, developing good policies
Market	Partnership in research, new hardware and software for monitoring	New technology, support for community development and local education	Self-regulating and reducing greenhouse gas emissions
Civil society	Participatory vulnerability analysis, linking local to global, facilitating knowledge learning	Community preparedness, facilitating local learning and adaptation	Social auditing, green watch, and monitoring
Local community	Local indicators and monitoring, local knowledge, innovations, and practices	Improved land/resource management, preparedness for surprises	Renewable energy, alternative livelihoods, and migration
ICIMOD's role	Impact assessment, knowledge synthesis, regional database, forecasting, monitoring	Capacity building, support for mountain policies, pilot demonstration, optimising land-use patterns and livelihoods in mountain 'niches'	Facilitating the clean development mechanism (CDM) and carbon market place, designing payments for environmental services

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