3 Sensitivity of Mountain Ecosystems to Climate Change

Introduction

This section deals with the sensitivity of mountain hydrology and water resources, biodiversity, wetlands, and ultimately human wellbeing, in the Eastern Himalayas, to climate change. Issues and concerns related to some ecosystem connected disasters, such as floods, droughts, and GLOFs, are also discussed briefly.

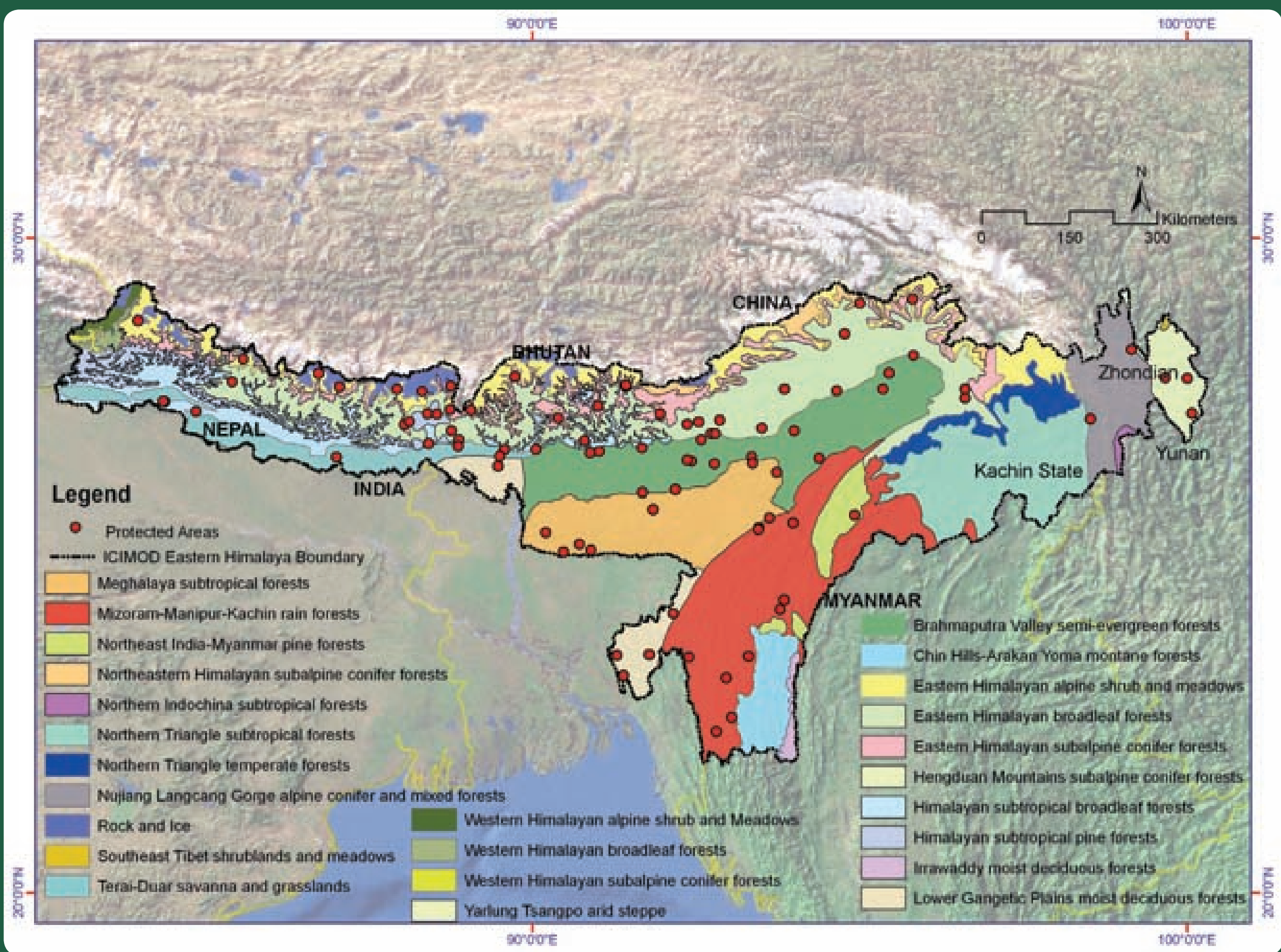
Sensitivity of Biodiversity

Range of biodiversity

The EH region intersects three global biodiversity hotspots; it contains 38.9% of the Himalayan hotspot, 7.7% of the Indo-Burma hotspot, and 12.6% of the Mountains of Southwest China hotspot. WWF (2004) has identified 25 ecoregions within the EH boundary; 12 in the Himalayan, 8 in the Indo-Burma, and 5 in the Mountains of Southwest China hotspot (Chettri et al. 2010). At present, there are 17 protected area complexes, 41 candidate priority areas of high biodiversity importance, 175 key biodiversity areas, and 5 landscape complexes (Terai Arc Landscape, Bhutan Biological Conservation Complex, Kangchenjunga-Singhalila Complex, Kaziranga-Karbi Anlong Landscape, and North Bank Landscape), which are of high conservation significance (CEPF 2005) (Figure 7).

The EH, has diverse climatic conditions and complex topography, and thus contains different types of forests

Figure 7: **Ecoregions and protected areas in the EH**



and vegetation. The vegetation types can be broadly categorised into: tropical, sub-tropical, warm temperate, cool temperate, sub-alpine, and alpine types, which can be further classified into layers based on other bioclimatic attributes (Chettri et al. 2010). A recent review revealed that the EH is home to a remarkable number of globally significant mammals (45 species); birds (50 species); reptiles (16 species); amphibians (12 species); invertebrates (2 species); and plants (36 species). The majority of these species (about 144) are found particularly in the North Eastern states of India (CEPF 2005). Besides supporting one of the world's richest arrays of alpine flora, about one-third of the total flora is endemic to the region (WWF and ICIMOD 2001; Dhar 2002). Details on species significance, distribution, endemism, and other measures of conservation status are replete in documentation elsewhere and require no further mention here.

Farming systems

The majority of people living in the EH depend on pastoralism, agriculture, and agroforestry systems for their subsistence livelihoods. These farming systems support a wide range of agrobiodiversity that nurtures and maintains the region's genetic resources for food, nutrition, and economic prosperity. The EH is also recognised as the centre of origin of over 50 important tropical and subtropical fruits, cereals, and rice (Vavilov 1926; Chakravorty 1951; Hore 2005). High-altitude rangelands could be the most sensitive agroecosystem in terms of the effects of erratic shifts in rainfall patterns, greater variability, and frequent extreme events of both precipitation and temperature. The fertility of agricultural soil may deteriorate with increased temperature, higher evapotranspiration rates, and soil erosion from intense precipitation events. Such productivity loss would translate into a greater risk of food insecurity. Temperature (hot and cold) and moisture (dry and wet) related stresses, along with reduced availability of feed and fodder could lower livestock productivity and pollinator activities. Alien invasive species may overwhelm extant communities bringing drastic changes to ecosystems, and rendering them less functional and useful to other plants and animals and to humans. Climate change can also exacerbate pests and diseases in plants, animals, and humans, thereby deepening the poverty trap and frustrating efforts to achieve the Millennium Development Goals (MDGs).

Species distribution

Climate change has contributed to substantial species range contractions and extinctions in the past, and future projections indicate that climate change will influence species persistence leading to a disproportionate distribution of species along ecological zones (Wilson et al. 2007). The consequences of biodiversity loss from climate change are likely to be the greatest for poor and marginalised people, who depend almost exclusively on natural resources. Grabherr et al. (1994) estimated that a 0.5°C rise in temperature per 100 m elevation could lead to a theoretical shift in altitudinal vegetation belts of 8 to 10 m per decade. In the EH, this altitudinal shift is expected to be around 20 to 80 m per decade (based on current estimates of temperature increases of around 0.01°C to 0.04°C/yr) with greater shifts at higher altitudes, as the rate of warming is expected to increase with altitude. However, such projections assume that species will adapt or shift with climate change. Apart from animals and some seasonal, annual, and biannual plant species, the scope for species to keep pace with projected climate change is very limited.

Unfortunately, there is still no straightforward explanation as to how ecosystems and ranges may shift; notwithstanding this, the mechanistic hypothesis has assumed almost factual dimensions. The multiple factors in the ecological and physiographic changes along the altitudinal gradient and the difference in species survival strategies means that the communities remaining within a bioclimatic regime could be quite different in the future with climate change.

Land cover and land use

Land cover and land use changes can lead to deforestation, land degradation, habitat modification, forest fragmentation, and biotic attrition, besides transmitting positive feedback to the climate system and thereby accelerating climate change. The latest land cover change assessment from the 1970s to 2000s uncovered significant changes in the EH (Table 13).

Table 13: **Land cover and land cover change in the Eastern Himalayas from the 1970s to 2000s (sq.km)**

Broad land cover types	1970s	2000s	Change %
Forest	273,426	264,117	-3.4
Shrubland	43,050	60,443	40.4
Cultivated land	112,631	113,233	0.5
Grassland	39,902	36,639	-8.2
Bare land	22,589	23,953	6.0
Water bodies	4,119	4,108	-0.2
Snow cover	27,514	20,741	-24.6

At the broad classification level, shrubland increased by 40% and bare area by 6%, whereas snow cover decreased by 25%, grassland by 8%, and forest by 3%. From an ecoregional perspective, EH broadleaf forests increased by 10,449 km^2; Brahmaputra Valley semi-evergreen forests decreased by 3678 km^2; Himalayan subtropical pine forests increased by 1183 km^2; shrubland in the Brahmaputra Valley semi-evergreen forests, and Eastern Himalaya broadleaf forest decreased by 4289 km^2 and 2073 km^2, respectively; grassland in the Eastern Himalaya broadleaf forests decreased by 4483 km^2; and snow cover in the Eastern Himalayan alpine and meadows decreased by 2775 km^2. These figures are at best indicative as there are inherent limitations with the time-series imageries used for inputs, as well as differences in scale in land cover and in the ecoregional data.

Critical habitats

The EH contains numerous critical habitats, and species like the greater one-horned rhinoceros, now mostly under protected area systems. Among the ecoregions, the EH broadleaf forests, Brahmaputra Valley semi-evergreen forests, and Himalayan subtropical pine forests have the highest conservation value due to the presence of more mammals and birds, and plant richness (WWF and ICIMOD 2001). The alluvial grasslands of the tropical forests support a high density of tigers. The Brahmaputra and Ganges rivers are home to the endangered Gangetic dolphin (*Platanista gangetica*). Herptiles residing in the moist forests and ephemeral freshwater habitats are also vulnerable to the impacts of climate change. A list of sensitive ecosystems was identified in close consultation with stakeholders in the region taking into account the significance of composite impacts observed from multiple stressors, including climate change, and the vulnerable biodiversity entities they are associated with (Table 14).

Table 14: **Critical ecosystems in the Eastern Himalayas with respect to climate change**

Critical habitat	Change indicator	Example of observed changes	Vulnerable entities
Alpine/sub-alpine ecosystems lying between the tree line at 4000 m and the snow line at 5500 m	• Changes in ecotones • Desertification • Declining snowfall, glaciation events • Changes in species composition • Growth in unpalatable species; decreasing productivity of alpine grasslands	Transformation of earlier *Quercus-betula* forest into the 'Krummholz-type' of vegetation comprising species of *Rhododendron*, *Salix*, and *Syringia*	Ungulate species, Himalayan pica, high value medicinal plants, botanically fascinating species (bhootkesh, rhododendron, etc.), curious species (succulents, *Ephedra*), alpine scrub flora
Cool-moist forests	• Changes in ecotones • Loss of habitat • Blockage of migration routes	Decline in population of species of *Mantesia*, *Ilex* and insectivorous plants	Habitat specialists such as red panda, blood pheasant, microflora and associated fauna
Cloud forests at temperate elevations where moisture tends to condense and remain in the air	• Less precipitation and cloud formation during warmer growing season • Loss of endemics/specific flora and fauna • Upward range shift • Desertification of soil affecting the water retention capacity of forests	-	Endemic epiphytes and lichen, wildlife dependent on cloud forest vegetation (diversity of insects)
Areas with intensive agriculture	• Reduced agro-biodiversity (monoculture) • Low employment/gradual loss of traditional knowledge • Degradation of soil quality • Potential increase of GHG emissions	Loss of traditional varieties such as upland varieties of rice, indigenous bean, cucurbits and citrus varieties; pest increases in citrus species	Crops, cereals, and vegetables
Freshwater wetlands	• Loss of wetlands due to sedimentation, eutrophication, drying, drainage • Successional shift to terrestrial ecosystems • Increased salinity in aquifers	Decrease in population of *Sus salvanius*; beels and associated biodiversity are changing	Large mammals such as crocodiles, river dolphins, wild buffaloes; wetland plant species; migratory avian species
Riparian habitats nurtured by silt deposited by overflowing rivers	• Damage or destruction of riparian habitats by floods/GLOFs/ riverbank erosion • Degradation due to increased/reduced deposition of sediments • Reduced stream flow • Disrupted successional stage	Loss of pioneer species such as *Saccharum spontaneum* and other tree species leading to a change in species composition of alluvial grasslands	*Ibis bill* (has nesting habitat in riparian zones); market-valuable tree species found in riparian zone as sisso, simal
Ephemeral stream habitats	• Loss of ephemeral stream habitats • Increased salinity • Riverine systems impacted	Riverine island ecosystems such as Majuli in Assam are being threatened	Ephemeral stream species, especially herpetofauna

Source: Compiled from information provided during the consultation processes

Sensitivity of Hydrology and Water Resources

Water is one of the most important sectors on which climate change can have a profound impact, which in turn can have second order impacts on other sectors. While a consensus exists on the likely impacts of climate change on the water resources of the Himalayas, quantitative analyses of such changes are sparse due to the dearth of baseline data essential for such analyses. The climate modelling described in the previous section for the whole region was further refined for the two major river basins in the EH: the Brahmaputra and Koshi basins. Basin-level hydrological modelling was conducted for the two SRES storylines (A2 and B2) using PRECIS-generated future climate scenarios to the end of the century. These potential impacts serve as an indication of the sensitivity of hydrology and water resources. More details are provided in Gosain et al. (2010).

The results of the hydrological modelling for the transient period centred on the 2080s and the A2 SRES storyline indicate that the total annual rainfall received by the Brahmaputra basin part of the region is likely to increase by about 23% with associated increases in groundwater recharge (31%) and surface runoff (48%). Snowfall during the period will decline by 12% in water equivalent depth, but the snowmelt is like to increase by about 32% from the present rate. The water balance sheet shows an overall increase in water yield (38%). Earlier suggestions that snowfields may disappear from the EH remain a plausible future outlook. Changes in snow-cover dynamics will directly affect biodiversity at high elevations. PET is also likely to increase (20%), due to enhanced soil water availability and higher temperatures in this future. The greater percentage increase in PET compared with precipitation over the North Eastern states of India, excluding the West Bengal Hills, Sikkim, and the western part of Assam, means relatively drier years lie ahead, with implications for water resources and drought-related problems in that part of the EH.

Similarly, the 14% increase in future precipitation simulated for the B2 scenario was associated with a 7% decrease in snowfall, a 29% increase in snowmelt, a 28% increase in surface runoff, and a 19% increase in groundwater recharge, resulting in a 22% net increase in total annual water yield in the Brahmaputra basin. This potential impact on the annual water balance components is summarised in Table 15.

Sediment loading in the rivers is predicted to increase by 39 to 95% by the 2080s over the assessed futures. As a result, water quality is expected to decrease drastically increasing the risk to human health. Dams, reservoirs, canals, and waterways are likely to suffer from massive siltation, reducing their economic lifespan and incurring huge costs in de-silting and restoration work. The impact on hydropower plants could, in turn, affect human wellbeing through reduced quality of life, reduced productivity, and loss of revenue from power export for countries like Bhutan, where economic success is premised on sustained hydropower generation.

Spatial analysis of the basin level prediction of water balance components indicates that stream flows will increase significantly across most of the Brahmaputra basin in response to precipitation and temperature changes. The hydrological system of the basin is sensitive to climatic variations, both on a seasonal basis and over longer time periods. The scenario outcomes indicate that precipitation and increased temperature shifts will have a much greater impact on future flow changes. The results also show that the effects will vary spatially across the basin in A2 and B2 scenarios, relative to baseline conditions.

The Koshi basin drains much of the western part of the EH. The impacts of climate change on water balance components will be far more extreme in the Koshi basin than in the Brahmaputra basin (Table 16). Precipitation increases are expected to be between 2.3 and 9.5% for the range bounded within the B2 and A2 scenarios for the time slice centred on the 2080s. Within the same scenario envelope of plausible climate change, snowfall may reduce by 19.3 to 23% compared to current levels, while snowmelt may increase by 74 to 76% compared to present rates of melting. Such a grave situation would basically mean dry streams and riverbeds in winter, loss of high altitude wetlands, even faster receding glaciers, and far greater risk of GLOFs.

Potential evapotranspiration is predicted to increase by 20.5 to 35.5% during the same period, which is 4 to 10 times more than predicted increases in precipitation. Under such a situation, drought-related disasters could become more frequent. Biodiversity is likely to trend towards a reduction in species richness; species composition may shift towards xeric communities with the remaining biodiversity concentrated in a few localised and shrinking habitats. Agriculture will be impacted severely with serious implications for people's livelihood strategies.

On the other hand, the projections of 48 to 79% increase in groundwater recharge, 48 to 66% increase in surface

Table 15: **Projected average annual water balance components (mm) for the Brahmaputra basin**

Water balance component (mm)	Simulated (baseline)	Scenario A2	Scenario B2	% Change A2	% Change B2
Precipitation	2136.9	2631.2	2429.2	23.13	13.68
Snowfall	341.4	301.1	318.6	-11.79	-6.68
Snowmelt	113.8	150.2	146.5	32.01	28.69
Groundwater recharge	511.2	670.1	606.1	31.08	18.57
Water yield	1230.4	1704.9	1506.8	38.56	22.46
Surface runoff	709.4	1048.5	904.8	47.81	27.54
AET	538.4	611.6	597.9	13.59	11.05
PET	916.5	1097	1020	19.70	11.30

Source: Gosain et al. (2010)

Table 16: **Projected average annual water balance components for the Koshi basin (mm)**

Water balance component (mm)	Simulated (baseline)	Scenario A2	Scenario B2	% Change A2	% Change B2
Precipitation	1966.7	2153.6	2012.4	9.50	2.32
Snowfall	1225.4	945.2	988.8	-22.86	-19.31
Snowmelt	259.4	456.8	451.8	76.10	74.17
Groundwater recharge	161.6	289.1	238.8	78.93	47.78
Water yield	786.5	1338.9	1170.9	70.23	48.88
Surface runoff	582.0	965.2	860.2	65.84	47.79
AET	143.9	205.3	187.8	42.67	30.51
PET	333.6	452.1	402.1	35.52	20.53

Source: Gosain et al. (2010)

runoff, and a total flow increase of 49 to 70% is an encouraging deviation from those components of the water balance discussed earlier. Against this, sediment loading in the basin is projected to increase from the present day simulation of 1882 t/ha to 3590 to 4194 t/ha by the 2080s, depending on the development trajectory selected. This could mean serious management problems for water resources projects and may cause the degradation of wetlands.

The hydrological systems of the Brahmaputra and Koshi river basins are very sensitive to climate change, variability, and extremes, both on a seasonal basis and over longer time periods. Simple shifts in precipitation and temperature can have a considerable impact on future flow regimes. Furthermore, increases in water yield and surface runoff are much higher during the wet months and less so, or absent, during the dry months, suggesting the possibility of an increase in flood frequency and magnitude as well as an increase in droughts. The effects, however, vary spatially across the basins and under different assumptions about the future, with more prominence in the lower parts of the basins. The study is preliminary in view of the data used for analysis, and the results are far from conclusive.

Wetlands

Ecologically, wetlands are transitional (ecotonal) systems between upland terrestrial systems and deep open water systems. They are typically characterised by the presence of aquatic vegetation (hydrophytes) (Mitsch and Gosselink 2007). Wetlands are an integral component of a river basin. Spatially, they occupy positions all along river courses, from their headwaters to their mouth (delta). The EH is extremely diverse in this respect due to the presence of large river basins and an altitude-defined ecological range from glaciers to floodplains (Gopal et al. 2010).

The Millennium Ecosystem Assessment (MEA 2005) grouped ecosystem services into four types: i) provisioning (such as food and water); ii) regulating (such as regulation of floods, droughts, land degradation, and disease); iii) supporting (such as soil formation and nutrient cycling); and iv) cultural (such as recreational, spiritual, religious, and other non-material services). Some of these are summarised briefly in Table 17.

The Global Lake and Wetland Database (GLWD; Lehner and Doll 2004) recognises lakes as distinct from wetlands and maps only lakes larger than 10 ha. Their

Table 17: **Ecosystem services provided by wetlands (ecosystem services types taken from MEA 2005)**

Services	Examples
Provisioning	
Food	Production of fish, wild game, fruits, and grains
Freshwater	Storage and retention of water for domestic, industrial, and agricultural use
Fibre and fuel	Production of logs, fuelwood, peat, fodder
Biochemicals	Extraction of medicines and other materials from biota
Genetic materials	Genes for resistance to plant pathogens, ornamental species, and so on
Regulating	
Climate regulation	Source of, and sink for, greenhouse gases; influence local and regional temperature, precipitation, and other climatic processes
Water regulation (hydrological flows)	Groundwater recharge/discharge
Water purification and waste treatment	Retention, recovery, and removal of excess nutrients and other pollutants
Erosion regulation	Retention of soils and sediments
Natural hazard regulation	Flood control, storm protection
Pollination	Habitat for pollinators
Cultural	
Spiritual and inspirational	Source of inspiration; many religions attach spiritual and religious value
Recreational	Opportunities for recreational activities
Aesthetic	Many people find beauty or aesthetic value in aspects of wetland ecosystems
Educational	Opportunities for formal and informal education and training
Supporting	
Soil formation	Sediment retention and accumulation of organic matter
Nutrient cycling	Storage, recycling, processing, and acquisition of nutrients

Source: Gopal et al. (2010)

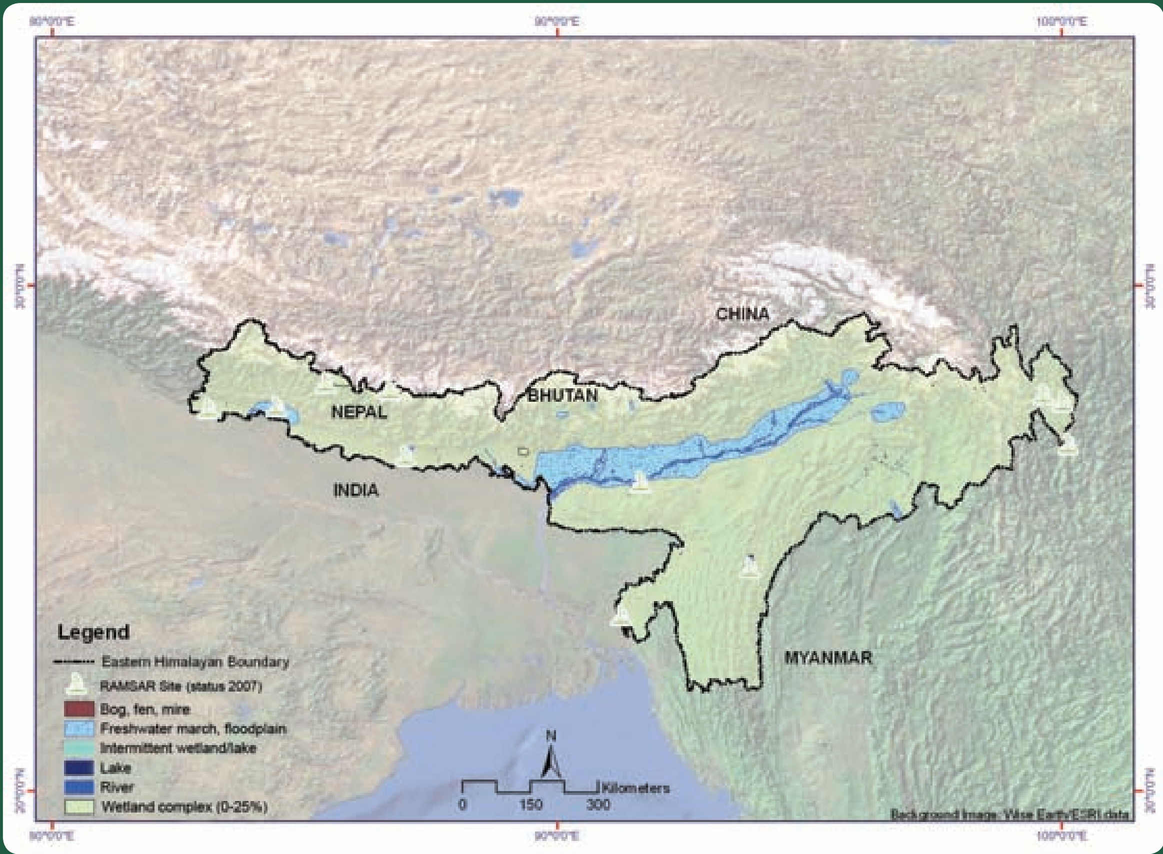
maps show only four lakes larger than 50 km^2 in the EH region, and only 210 between 50 km^2 and 10 ha. The vast majority of lakes in the region are very small (<1 ha) and remain unmapped. Lehner and Doll (2004) estimated the maximum area under all kinds of wetlands by superimposing published maps from different sources. These maps treat the entire Brahmaputra River valley as a wetland (floodplain) (Figure 8).

There are almost no studies or assessments of climate change impacts on freshwater wetlands in developing countries in general, and in the Himalayan region in particular. Thus the following account is more general, and based largely on extrapolation of information from temperate regions (NIE 2008). An important consideration in the EH is the difference in impacts along altitudinal gradients, and their cascading influence at successively lower elevations. However, very little is known about the altitudinal differences in climate change, except for a general positive trend in temperature increase with altitude.

An increase in CO_2 concentration generally enhances the rate of photosynthesis to a certain level, unless other factors become limiting. The plant communities of EH wetlands range from alpine to tropical and are likely to respond differently. This will certainly have major implications for the carbon sequestration potential of the wetlands. For aquatic plants and phytoplankton in rivers and lakes, increased CO_2 levels may enhance rates of photosynthesis at higher elevations, but at lower elevations the increased temperature may result in lower solubility of CO_2 and, hence, it is unlikely to affect photosynthesis.

The temperature increase will affect practically all biological activity. Almost invariably, rises in surface air temperature increase net productivity in cooler regions. However, the response could be quite different in the tropical-type climate where further temperature rises could actually reduce photosynthetic rates as the physiological mechanisms are activated to cope with heat stress. An increase in temperature will result in an ascending snowline, and species distribution is expected to shift to higher elevations. The temperature lapse rate in the EH is around 0.5°C for every 100 m rise in elevation, and for every 1°C rise in temperature, most species are likely to extend their distribution upwards by about 200 m. Exotic invasive species such as potomogaton (locally

Figure 8: **Wetlands in the Eastern Himalayas**



known as sochum) have been extending their range into the mountains in Bhutan and may spread further to higher elevations where wetland rice has occupied new production areas.

Increased water temperature results in lower availability of dissolved oxygen, alters the ice-free period, increases biological activity which exhausts remaining oxygen, and changes the pattern of thermal mixing in water bodies to create anaerobic conditions leading to eutrophication. The consequences of these changes for food web interactions, community structure, nutrient dynamics, and water quality are likely to be critical for the ecological health of the wetlands and living communities deriving benefits from them.

Wetlands are highly vulnerable to hydrological changes, not only in quantity and quality, but also in the frequency, duration, and timing of water availability. Changes in hydrological regimes caused by the melting of glaciers and changes in precipitation regimes will have the most significant and pronounced impacts on wetlands in the EH. The cascading effect due to the hydrological connectivity between upstream and downstream wetlands will result in places in the valleys and lower elevation areas being doubly vulnerable to climate change impacts. Besides, wetlands are both a source of, and sink for, greenhouse gases and this balance is again affected by changes in hydrology. Changes in organic matter production, its accumulation or mineralisation, and the microbial activities caused by water level changes will determine the amount of methane emission.

The sensitivity of wetlands to, and potential impact of, climate change in terms of their services is difficult to assess without proper information of specific relevance to the EH. However, the importance of wetlands to the ecological integrity of the mountain environment and people living there needs no further emphasis. The provision of water, food, biodiversity, and shelter/habitat are likely to be the most sensitive and experience the greatest impacts from climate change. Wetlands are rich in biodiversity, especially fish and waterfowl, and contain a large variety of grasses, herbs, and medicinal plants. Changes in water flow and high water temperatures could affect insects and other invertebrates with repercussions up the food chain for fish, amphibians, and waterfowl. Cold and cool water fish could face localised extinction, as they are highly temperature-sensitive. Changes in the timing and amount of rainfall could affect migration, spawning, dispersal, and growth in fishes like *Schizothorax sp*. and *Tor sp*. Wetland paddy sustains the livelihoods of a large population in EH countries, as well as providing fish, fodder, and sediments from lakes, streams, and floodplains. Increases in minimum temperatures above a threshold of 26°C at grain filling will reduce paddy grain yield by about 10% for every 1°C increase above the threshold. Therefore, rice yields could be affected by both increase and decrease in different altitudinal zones. Climate change will affect habitat characteristics through changes in water regimes, vegetation types, and sediment characteristics, and influence the migration pattern of birds and fish. Loss or degradation of wetland habitats will threaten many vulnerable and endangered species.

The capacity of wetlands to regulate floods and droughts is limited by their morphological and hydrological characteristics. Increased runoff from melting snow and glaciers will increase erosion and enhance sediment flow loading. Siltation with sediment deposits in lake basins and floodplains will reduce their capacity for floodwater retention. Acute water supply this century will affect their drought regulating function, as there may later be little or no water in the wetlands. Changes in plant communities will also contribute to the alteration of this wetland function. Declining levels of dissolved oxygen with increased water temperature, and changes in mixing patterns in deep water wetlands, will degrade water quality. The ability of microorganisms and benthic invertebrate communities to degrade organic matter is likely to decline significantly with negative implications for water quality and methane emission. Climate change will trigger increased emission of GHGs from many wetlands, as lower solubility of oxygen at increased temperature will lead to eutrophication. Methane emission occurs from a variety of wetlands during the summer thawing of ice in permafrost regions (e.g., Rinne et al. 2007). Longer and warmer growing seasons are projected to result in the desiccation of peat and the production of CO_2. Melting ice will result in the production and ebullition of methane from glacial lakes that have accumulated organic matter from littoral vegetation and organic sediment.

Wetlands in the EH have great spiritual and cultural value as they are considered sacred in different faiths and are important for cultural tourism. The high altitude lakes are of particular significance in this respect (Gopal et al. 2008). Changes in their ecological characteristics caused by climate change may affect their significance as sites of cultural and religious tourism.

Hydrometeorological hazards

Natural hazards in the EH are mainly hydrometeorological in nature, amplified by the fragile environment, which is extremely sensitive to external perturbations. The extreme relief of the mountains coupled with monsoonal vagaries has left communities vulnerable to natural hazards like floods, landslides, and droughts (Pathak et al. 2010). The most common occurrences are flash floods associated with extreme weather events, glacial lake outburst floods, and rivers breaking their banks from excessive runoff due to incessant monsoonal downpours. Frequently, these events assume disastrous proportions with large-scale destruction of mountain ecosystems and untold human suffering. The fragile Himalayan geology facilitates mass wasting when intense precipitation occurs. Intense rainfall events in mountainous areas can overwhelm the water storage capacity of the regolith (the surface layer of loose rock) and trigger hill slope failures (e.g., Gabet et al. 2004). Huge rock avalanches and landslides can create landslide dams in the narrow river valleys (for example, Tsatichhu in Bhutan). Over the coming decades, there is likely to be a steady increase in human exposure to events such as droughts, floods, and storms. Extreme weather events will become more frequent and more intense, with less certainty and predictability in the timing of the monsoon and rainfall.

The impacts of climate change on mountain glaciers and permafrost are not only important in the context of ecosystem services, but also in connection with glacier and permafrost related hazards. In the Eastern Himalayas, particularly in Bhutan and Nepal, there is concern about supraglacial and moraine-dammed lakes, caused by general glacier retreat since the Little Ice Age ended, because of their potential to breach catastrophically (Quincey et al. 2007). The glaciers of the EH are shrinking at an alarming rate with meltwater feeding into the ever-expanding lakes. Recent observations have estimated the maximum rate of glacial retreat at about 41 m/yr in the Indian Himalayas, 74 m/yr in Nepal, and 160 m/yr in Bhutan (Bajracharya et al. 2007). The retreat of the Luggye glacier in Bhutan between 1988 and 1993 is the fastest on record in the whole of the Himalayas.

Considering the significant warming trends projected for the future, glacial lakes are likely to expand, increasing the potential for larger GLOFs in the region. GLOFs are not recent occurrences, but their frequency and the threat they pose have increased several fold in recent times. A number of glacial lakes in the EH have the potential to burst with catastrophic consequences to nature and humans alike. Nepal has 12 potentially dangerous lakes, there are 14 in Sikkim, and 24 lakes are reported to be potentially dangerous in Bhutan (Mool et al. 2001a,b) [but note that these figures have recently been revised, Ives et al. 2010, ed]. GLOFs have hit Bhutan before, most recently in 1994 when the 140 m deep Luggye Tsho burst releasing 10 million m^3 of flood water. Hazard levels of floods are expected to increase and human settlements will be exposed to greater risk, not only to the loss of livelihood, but also from increased morbidity and mortality as a result of poor health. A GLOF event could also trigger dam breach flooding downstream. Elaboration on the natural and human-induced hazards, associated risks, and their evolution to disastrous proportions are provided in other sections of this report on ecosystem functioning and service provision.

Fire

Changing climatic conditions are likely to modify the frequency of fire outbreaks and intensity. Prolonged periods of summer drought may transform areas already sensitive to fire into regions of sustained fire hazard. Fires could also break out in regions that are currently relatively unaffected, as critical climatic, environmental, and biological thresholds for fire outbreaks are exceeded (Johnson 1992).

Sensitivity of Human Wellbeing

Climate change directly affects human wellbeing through extreme weather events and indirectly through its effects on ecosystems, the foundation of human wellbeing. Despite a general understanding and concern, we have limited and imprecise knowledge supported by scientific evidence on how climate change affects human wellbeing (Fang Jing and Leduc 2010). Knowledge and data on human wellbeing is particularly limited in the EH. To assess the future impact of climate change on human wellbeing, it is essential to benchmark the current status of human wellbeing in this region as a baseline for future projections. The demographic, socioeconomic, and poverty status of the EH can be used to proximally reflect 'materials for a good life', which is the basic aspect of human wellbeing. These indicators for the EH are well below the level of human wellbeing thought likely to be necessary to deal with the full spectrum of adverse climate change impacts anticipated in the region. Indicators include the following:

- Poverty levels are high and many people still exist on less than a dollar a day.
- Infrastructure, including roads, transportation, electricity and water supply, education and health care services, communication, and irrigation, is underdeveloped.
- The majority of the population relies on subsistence farming and forest products for their livelihood, which are highly sensitive to weather extremes, climate variability, and water availability, and, therefore, susceptible to climate change.
- Major health indicators such as the maternal mortality rate, infant mortality rate, and life expectancy at birth are at a low level.
- Other metrics are equally unsatisfactory, e.g., there is lack of access to safe drinking water and sanitation; weak health systems; economic and income monopolies; a high prevalence of water-borne diseases and undernourishment; frequent disasters such as flash floods and landslides; and huge inequalities and social exclusion based on wealth, religion, gender, caste, and others.

All these factors make the EH more vulnerable to climate change as the capacity to adapt is inadequate. Adaptive capacity is determined by the economic, socio-political, and technological attributes that empower people with freedom of choice and action.

Explorative surveys of local people's perceptions and societal experiences in their daily interactions with nature and the surrounding environment can provide insight into climate change sensitivity and likely impacts on human wellbeing in the future. Results from such surveys carried out in North East India and Bhutan uncovered some notable aspects of people's understanding and the coping mechanisms they resort to in dealing with environmental changes. People generally agree that changes are imminent and their reasoning was plausible in the light of trends in the recent past. They talked about the changes in the weather patterns, transformations in their way of life, and apparent transitions in their immediate physical surroundings, although they did not comprehend these developments from a global warming or climate change perspective. People are concerned about the sustainability of ecosystem services, especially if they have lived through unpredictable periods of bizarre weather conditions, food insecurity, and water shortages, and witnessed land degradation, a reduction in snowfall, wholesale deforestation, and the emergence of new pests and diseases. They are able to relate these changes to loss of livelihood, high morbidity and mortality, insecurity, and socio-cultural degeneration, ultimately leading to loss of freedom and opportunity.

In order to safeguard their wellbeing and adapt to the changing climate, people have engaged in different livelihood strategies by adopting more resilient food production systems or migrating to new locations. Productivity gains have come at the cost of eroding the genetic base of farming systems and polluting the ecosystems with excessive use of chemicals. Frequently noxious species are released or escape into the wider ecosystem, invading the natural space, disturbing the ecological harmony, and disrupting the food chain. Human migration exerts enormous pressure on nature from land degradation and extracts huge socioeconomic costs in terms of resettlement and reconnection to civic services. As natural resources and ecosystem services decline with increasing human interference through industrial and infrastructural development and overexploitation, human conflict and competition for scarce resources could reach alarming proportions, which in turn will set the context for further desolation.

Water stress and scarcity due to melting glaciers, reduced snowfall, variable rainfall, rising temperatures, and high evapotranspiration will severely affect agricultural production and hydropower generation, which are the main sources of livelihood and income in this region, particularly in Bhutan and Nepal. Climate change will directly affect human health through extreme weather and indirectly through a reduction in water quality and quantity, and poor sanitation leading to higher incidences of water-related diseases. Similarly, climate change will bring with it new threats from vector-borne diseases like malaria, cholera, and dengue as their epidemiology follows the warming trend. Malnourished people with weaker livelihood bases are likely to be even more affected by higher morbidity and mortality rates. Gender inequality is likely to increase with climate change. Collecting water, fuel, and food will become more time consuming and the drudgery involved will increase due to greater resource scarcity (Stern and Taylor 2007) this burden will be disproportionately shouldered by women in the Himalayan regions. The situation will become worse when large numbers of men migrate for work.

Climate change also presents new threats to ecosystems through overexploitation for food and materials during times of food shortage and decline or loss in monetary income. Considering the high population growth rate in the region, this will put additional strain on ecosystems. In the face of reduced resources, such as water and food, social conflicts and unrest may rise or be exacerbated among nations, communities, and tribes. Water related disasters such as floods, droughts, landslides, GLOFs, and extreme weather events may increase or become more frequent due to climate change. This poses a huge threat to livelihoods and well being of the people of the region.