Global Change Impact Assessment for Himalayan Mountain Regions for Environmental Management and Sustainable Development

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Abstract

The Himalayas with their unique physical, biological and human systems provide environmental goods and services to almost one-tenth of the global population and affect in the long run the global environment. The Himalayan Mountains, however, because of their young and fragile nature coupled with sharp gradients, are particularly vulnerable to impacts of a rapidly changing climate often coupled with anthropogenic alteration of mountain landscapes due to population changes and economic activities. People in the regions have been long marginalized and have the fewest resources and capacities to adapt to these changes and hence are the most vulnerable.

The crucial aspects of global change impacts in the Himalayan mountain regions are ultimately about their potential effects on ecosystems and resources as well as on the societies that depend on them. As many of these effects are interactive with some specific thresholds, an understanding of the response of the system to global change and the associated vulnerabilities and potential adaptations, is crucial especially for preserving the natural resources and encouraging environmental management and sustainable development of mountain regions.

Some of the results of the research studies on global change impact assessment for the Himalayan mountain regions are presented and discussed in this paper. The observed climatic changes are briefly presented as are their impacts on water resources, food security and people's livelihoods. Likewise the effects of the process of globalization and economic liberalization on the Himalayan mountain communities are also briefly discussed.

Key words: environmental management, global change, Himalayan Mountains, impact assessment, sustainable development

1. Introduction

The Himalayan Mountains, the highest and most massive on earth, are home to over 100 million people, some of whom live at altitudes of over 5,000 m. These ranges trigger orographic precipitation and control the South Asian Monsoon; and they store water as snow and ice and constitute a water tower for almost one-tenth of the world's population living downstream in the Indo-Gangetic plains. Due to sharp ecological gradients, these mountains are rich in ecodiversity and biodiversity and are also the storehouse of unique gene pools and many valuable medicinal plants and herbs.

Mountains environments essential to the survival of the global ecosystem have drawn global attention and become a subject of global concern (Messerli & Ives, 1997), and mountain regions have also been referred to as 'water towers' (Mountain Agenda, 1998). Because of their young and fragile nature coupled with sharp gradients, however the Himalayan Mountains are particularly susceptible to impacts of a rapidly changing climate often coupled with anthropogenic alteration of mountain landscapes due to population changes and economic activities. The Third Assessment Report of the IPCC (IPCC, 2001) pointed out the critical role of Himalayas in the provision of water to continental monsoon Asia, and also clearly revealed their vulnerability to climate change in terms of their hydrology and water resources. Likewise, the IPCC Report on the Regional Impacts of Climate Change (IPCC, 1998) also highlighted the various vulnerabilities, based on some vulnerability assessments, related to impacts of climate change on the

Himalayan mountains, which provide goods and services essential for human survival to those living in the region and fundamental resources for tourism and economic development. Moreover, the mountain region's political and economic marginalization creates added vulnerability due to a reduced capacity to adapt to these changes. Thus natural and socio-economic systems in these mountain regions are at risk, in particular, regarding the impacts of global change and globalization.

Due to strong barriers to transportation, communication, trade and political integration, the mountain regions were traditionally well known for their pristine ecology. The mountain people in the past survived long with traditional resilience developed by adapting to the use of environmental resources in a sustainable manner. However, with rapidly growing populations and technological innovations in communication and transportation systems combined with linkages to a expanding market economy, use-intensification and over-exploitation of environmental resources are leading to high rates of environmental change in the fragile ecosystems thus turning the mountain regions into 'critical regions.' The incumbent global change, including climate change, is putting further stress on the system. Consequently, the traditional resilience is being rapidly breached, leading to growing dependence on external inputs and over-exploitation of selective resources, threatening their sustainability. Thus the landscapes and human groups in the mountain regions are being simultaneously affected by global, environmental and socio-economic threats and perturbations leading to a 'critical stage' as a result of global changes and globalization (Shrestha, 2001).

The important aspects of global change impacts are their potential effects on ecosystems and resources as well as on the societies that depend on them. As many of these effects are interactive with some specific thresholds, vulnerabilities and adaptations, an understanding of responses to global change is crucial, especially for preserving natural resources and promoting environmental management and sustainable development of mountain regions.

However, the vast majority of works to date do not seem to have been structured to facilitate an overall understanding of the interaction between climate, land surface processes and human activities, taking into account the specific conditions in mountain environments (BAHC, 1994; Becker & Bugmann, 1999). Global change impacts on and interaction between mountain hydrology and ecology, for instance, seem to be not well understood (Becker & Bugmann, 1997). No comprehensive and comparable data are available regarding the spatial dimensions of environmental and economic assets, which could illuminate priority issues where policy decisions are urgently needed to cope with global change issues in the mountains, in particular, those in the Himalayan Mountains.

Noting the uniqueness of Himalayan ecosystems and the regional significance and importance of studies regarding the impact of global change in the Himalayan Mountains, a collaborative research study, funded by the Asia Pacific Network for Global Change Research (APN), has been undertaken with the participation of researchers from Nepal, India and Pakistan. In the context of assessing the impacts of global change in particular on water resources and food security in the mountains as well as on the livelihood of the people living in the region, some of the results of the research study to ascertain ongoing climatic and socio-economic changes in the regions and their observed impacts are presented and discussed in the present paper. Particular references are made to the three selected watersheds in the three participating countries, viz. the Kali Gandaki basin (28° N, 83° E) in Nepal, the Alaknada basin (30° N, 79° E) in India and the Siran basin (34° N, 73° E) in Pakistan, chosen as representative mountain regions and basins draining different parts of the Himalayas. Glaciers and biodiversity, the two unique systems in Himalaya, in the context of recession of glaciers and threatening of biodiversity are also treated briefly and the impacts of globalization on the bio-resource of Himalaya in particular are also briefly discussed.

2. Himalayan Mountains and the Ecosystems

The Himalayan range extends over 2,400 km in a vast southerly arc from the bend of the Indus, marked by Nanga Parbat (8,125 m, 35°N, 74°E) on the west, to the Tsangpo-Dihang bend around Namche Barwa (7,755 m, 30°N, 95°E) in the east. The entire Himalayan range extends over an area of about 460,000 km^2. It is a complex of high mountains, elevated plateaus, deep gorges and extended valleys. The Himalayas, which are now considered to be the result of the largest continental collision on Earth, are estimated to have arisen over 45 million years ago between continental India and the Eurasian plate, compressing the crust by more than 2,000 km horizontally and producing a large region of highlands. They are the youngest, highest and most unstable mountain region in the world (Olschak *et al*., 1988). The Himalayas are the loftiest mountain complex, with ten of the fourteen world's peaks exceeding 8,000 m and 31 peaks exceeding 7,600 m in elevation. The series of narrow chains of high mountains with their crest-lines rarely falling below 5,500 m are breached by a number of trans-Himalayan rivers and their tributaries that play an active role in eroding and shaping the high mountains, producing deep valleys that wind between the peaks and cut deep gorges that accentuate the heights of the surrounding mountains, all adding to the grandeur of the Himalayas (Subba, 2001).

The numerous earthquakes in the region clearly indicate continuing active orogenic movement in the Himalayan region. Still being thrust upwards by massive tectonic forces, the Himalayan Mountains are thus inherently structurally unstable, leading to ongoing seismic activity and severe landslides. More than a dozen earthquakes with a magnitude of 7.5 or greater have been recorded over the last hundred years in the Himalayas. A physiographic section of the central Himalayas in Nepal with their various tectonic thrust lines is depicted in Fig.1a. Similarly, Fig. 1b shows NOAA satellite imagery of the central Himalayas with a white line sketch over it of a map of Nepal, which has a length of about 885 km (east to west) and a varying width of about 193 km (north to south). Fig. 1c depicts a typical landscape of the Himalayan mountain region.

Great differences in altitude, latitude and longitude have created vast variation in microhabitats throughout this range. Along the north-south section, for instance, the altitude in the central Himalayan region in Nepal varies from 60 m in the south at Terai (foothills of the Himalayas) to 8,848 m at Mount Everest in the north within a short distance of 90 to 120 km. As a result, variations in climate as well as vegetation types ranging from tropical and subtropical to alpine ones are to be found in a short spatial and altitudinal range. Similarly, while the eastern Himalayas are wet and hydrophytes constitute the dominant vegetation, xerophytes are the dominant vegetation in the drier western Himalayas. Due to such a sharp ecological

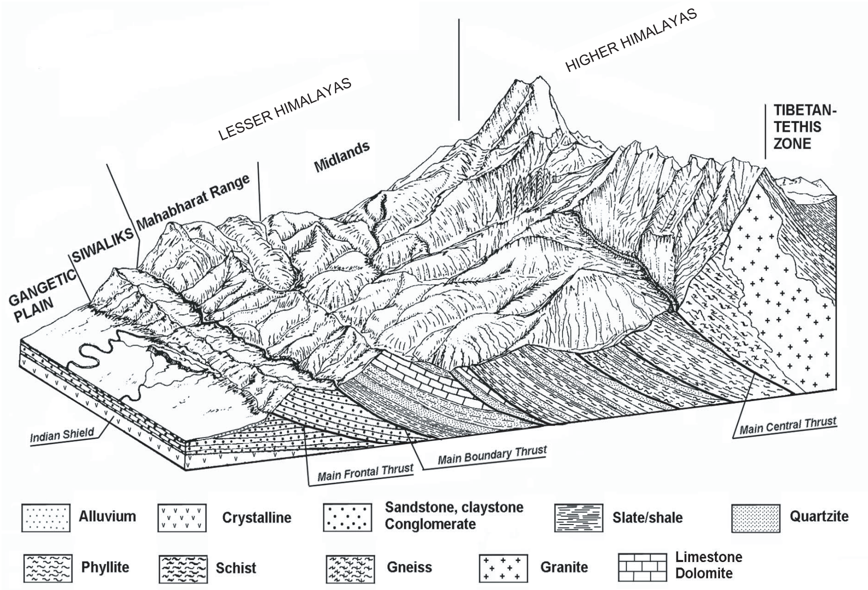

Fig. 1a Physiographic section of central Himalayas in Nepal, showing various ecological zones and geological structures.

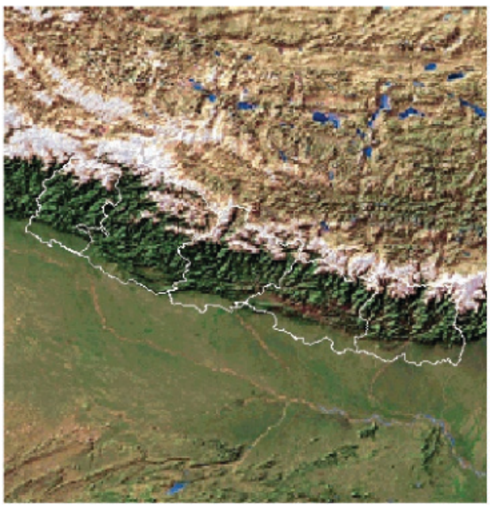

Fig. 1b NOAA satellite imagery of central Himalayan region.
(the white lines indicate a map of Nepal)

Fig. 1c A typical landscape of the Himalayan mountain region.

gradient, the Himalayan Mountains are thus very rich in biodiversity, which includes many valuable medicinal plants and herbs as well as wildlife. Longitudinal variations of some of the features along the Himalayas are briefly summarized in Table 1.

These Himalayan ranges trigger orographic precipitation and influence the South Asian Monsoon; store water as snow and ice and thus constitute a 'water tower' for almost one-tenth of the world's population living downstream in the Indo-Gangetic plains. These Mountains are not only the weather makers for the subcontinent, regulating the monsoon cycle and protecting the subcontinental plains from cold Central Asian air during winter, but in particular they provide water as a most valuable resource to the mountain people themselves and to the growing population living downstream. Three main river systems arise in the Himalayas, namely the Indus, the Ganges and the Brahmaputra systems. The estimated annual flow in billion cubic meters is 200 for Upper Indus, 450 for the Ganges, and 550 for the Brahmaputra River (Subba, 2001). These great rivers form the most important water source for South Asia, supporting almost half a billion people.

But the Himalayan 'water tower' is obviously sensitive to the prevailing climate and environment in the mountains and thus vulnerable to climatic and environmental changes. Human pressure as well as climatic change and variability have a significant impact on the water availability, both in terms of quantity and quality, and also the feedback between mountains and climate. Changes in the snowfall pattern observed in the Himalayas (Verghese & Iyer, 1993), for instance, will have wider implications—from a marked impact on the monsoon regime to seasonal runoff and vegetation cover, including agriculture. Changes in the hydrological regime, likewise, will also trigger episodes of extreme events.

3. Socio-Economic Setting

The Himalayan range, including its directly adjacent areas that are home to about 100 million people, is the most populous mountain ranges in the world with some people living at altitudes of over 5,000 m. While the migration factor rather than the fertility rate has remained an important determinant in the population dynamics of the highland areas, there is now evidence of an increasing trend of population growth in the region.

The total population of Bhutan, Indian Himalayan states and highland Nepal alone comes to about 31.3 million. Aggregation of political territories into discrete sections of the Himalaya provides a more meaningful regional pattern. The area, population and population density of the different zones are presented in Table 2, treating the portion covered by Nepal as the Central Himalayan zone and the rest to the east and west as eastern and western zones of the Himalayas.

There is wide variation in population density with a progressively higher population density from the east to the west. While each square kilometer in the eastern Himalayas carries 19.4 persons, the same area

Table 1 Spatial variations in physical and socio-cultural parameters along the Himalayas.

Description	Western Himalayas	Central Himalayas	Eastern Himalayas
Latitude	37°N	28°N	28°N
Longitude	72°E	81°E	97°E
Snowline	4,800 m	5,000 m	3,500-4,900 m
Tree line	4,000 m	3,900 m	4,200 m
Predominant Species (lower elevations)	*Pinus* variety	*Shorea* to *Pinus*	*Shorea robusta*
Vegetation Regime	Xerophytic	Transitional	Hydrophytic
Annual Average Precipitation	700-2,000 mm	3,500 mm	Up to 10,000 mm
Main River System	Indus	Ganges	Brahmaputra
Drainage Area	1,263,000 km^2	1,075,000 km^2	940,000 km^2
Average Annual Runoff	3,850 m^3/s	15,000 m^3/s	20,000 m^3/s
Specific Runoff	3.05	13.95	21.28
Number of Languages	Indo Aryan: 11 Tibeto Burman: 9	Indo Aryan: 5 Tibeto Burman: 11	Tibeto-Burman: 11
Culture	Caucasoids	Mixed	Mongoloids

Table 2 Populations and population density distribution along the Himalayas.

By Zone	Area	%	Population	%	Density Persons/km^2
Western Himalayas	208,359	45.4	18,815,723	60.0	90.3
Central Himalayas	113,162	24.6	9,863,019	31.5	87.2
Eastern Himalayas	137,839	30.0	2,671,015	8.5	19.4
Himalayan Region	459,360	100.0	31,349,757	100.0	68.2

carries 87.2 persons in the central sector and 90.3 persons in the western sector. Thus the population density of the western and central Himalayas is about 4.5 to 4.7 times higher than that of the eastern Himalayas.

The verticality of the mountain landscape makes transport and communication difficult. While this isolation prevents access to many facilities, it has also acted as a barrier, preserving the diverse cultural and ethnic identities of the mountain people. The cultural and ethnic diversity of the region is thus remarkable, with each group of people adapting to the demands of the region in their own unique way. The Himalayas are wedged between the centers of two Asian civilizations, viz. the Caucasoid and the Mongoloid, and represent a cultural divide with the Caucasoids spreading over the entire western Himalayas and the Mongoloids being more numerous east of the Gandak basin.

People who live in the Himalayas are in general poor and face special difficulties. The rugged terrain makes road construction difficult, and landslides often damage roads once built, particularly during the monsoon season. Access to essential goods and services is in general difficult. Economic activities in the mountains are often hampered by lack of access to the well-organized market economy of the plains. Educational opportunities in the mountain regions are limited, and unemployment is a major issue.

The subsistence economy of the Himalayas varies from shifting cultivation and seasonal farming to nomadic herding, supplemented by petty trade. In some areas, increased road access and other transportation facilities in recent decades have facilitated the marketing of local products and crops/livestock with comparative advantages vis-à-vis the lowlands. There appears to be an increasing trend of crop diversification into cash crops, with increasing acreages under apple, citrus and vegetables.

In many mountain areas, the center of political and administrative power is located far from the population in the higher mountain ranges. Government policies are seldom created to reflect the realities and needs of the mountain people. Rather, mountain resources are stated to be systemically exploited for the benefit of those who live on the plains. This combination of factors creates a situation in which mountain people become progressively marginalized.

4. Climatic Changes

The climate of the Himalayan Mountain region is highly diverse. With a tropical climate in the foothills in the South, it changes with altitude and latitude to temperate and to alpine at the top of the high mountains. It also varies considerably with slope angle, aspect, and local relief, *e.g.* rain shadows caused by higher mountains. Thus the mountains have a mosaic of local 'topoclimates.' Nevertheless, analysis of long-term data for different parts of the Himalayas has revealed a general trend of increasing temperatures and changes in precipitation and precipitation patterns. Some of the results of such analyses are presented and discussed next.

4.1 Change in temperature

Trend analysis for the maximum, minimum and mean temperatures at seven meteorological stations in and around the Kali Gandaki river basin in the Nepalese Himalayas with available data for about 30 years from the 1970s have indicated a temporal variation with positive trends for six stations and a negative trend for one station. The observed mean trend values in the basin for maximum and minimum temperatures are 0.026 and 0.024^{o}C/year respectively, while the observed average trend for the mean temperature is 0.025^{o}C/year.

Earlier, analysis of maximum temperature data from 49 stations in Nepal for the period of 1971-1994 revealed warming trends after 1977 ranging from 0.06^{o} to 0.12^{o}C/year in the middle mountain and Himalayan regions while the southern plain regions showed a warming trends of less than 0.03^{o}C/year (Shrestha *et al.*, 1999). Likewise the analysis also revealed a greater temperature rise during winter in the Nepalese Himalayan regions.

An analysis of climatic data for 1961-2000 from the Murree observatory in the Siran watershed, a representative site of the moist Himalayas in Pakistan, also indicated for maximum and minimum temperatures, rising trends of 0.02^{o}C/year and 0.01^{o}C/year, respectively. Other observatories representing low elevations of the moist Himalayas in Pakistan, meanwhile, indicated a declining trend in both maximum and minimum temperatures at rates of 0.01^{o}C/year and 0.02^{o}C/year respectively. In an earlier similar analysis, warming in the northernmost mountains of Pakistan was reported to have occurred in three later decades of the past century, with rises in mean temperatures ranging between 0.5^{o}C and 1.0^{o}C during 1961-1990 as compared to the preceding three decades of 1931-1960. Similarly, maximum temperatures showed warming of 0.8 to 1.2^{o}C, and minimum temperatures, an increase of 0.5 to 0.9^{o}C between the three decade periods compared (Elahi, M. & Study Team, 1998).

In the Alaknanda valley, the rate of temperature rise during 1994 to 2002 was noted to be 0.15^{o}C/year while, at another nearby Himalayan station at Nainital, the rate of temperature increase during 1987 to 1996 was found to be 0.03^{o}C/year.

Table 3 summarizes the above-observed trends in temperature variations in different parts of the Himalayas.

4.2 Changes in precipitation, precipitation patterns and extreme events

A large spatial variation in annual precipitation exists along the Himalayan range, ranging in magnitude from almost 10,000 mm in the east to less than 200 mm in the west. While the eastern region receives

Table 3 Observed trends in temperature variation in different parts of the Himalayas.

Country	Location	Year	Temp.	Variation °C / year
Nepal	Kali Gandaki	1970s-1990s	T_{max}	0.026
			T_{min}	0.024
			T_{mean}	0.025
	Nepal	1971-1994	T_{max}	0.06-0.12
				0.03 (Terai)
Pakistan	Siran	1961-2000	T_{max}	0.02
			T_{min}	0.01
	Northern Mountains of Pakistan	1931-1960	T_{max}	0.03-0.04
		1960-1990	T_{min}	0.02-0.03
India	Alaknanda	1994-2002	T_{mean}	0.15
	Nainital	1987-1996	T_{mean}	0.03

almost 80% of its total annual precipitation during the summer monsoon, this ratio decreases gradually to the western region, which receives less than 50% of its total annual. In the Far-Western regions, the westerlies in winter provide the bulk of the annual precipitation and this decreases towards the easterly regions.

An analysis of mean annual rainfall over Nepal suggests that, the middle mountains around central Nepal receive the highest amount of rainfall, on average over 5,000 mm per annum, while rainfall decreases northward and in the high mountains. Analyzing precipitation data from 1971 to 2000 at 11 stations in and around the Kali Gandaki basin, all the stations, except one at Jomsom, indicated increasing trends in monsoon precipitation ranging from 1.6 to 31 mm/year. The Jomsom station indicated a negative trend in monsoon precipitation of 0.4 mm/year. As the stations with positive trends were the ones that were already receiving higher rainfall, continuation of the trend would imply greater future vulnerability in these regions to floods and landslides due to increased precipitation.

By defining precipitation with values more or less than one standard deviation, $\pm 1\sigma$, of the time series for individual stations as precipitation anomalies, it was observed that in the Kali Gandaki basin, a deficit of extreme precipitation events (values less than -1σ) dominated during the decade of 1971-1980, while during the decade of 1991-2000, an excess of extreme events ($+\sigma$) dominated. The intervening decade of 1981-1990 exhibited no significant difference between excess and deficit of extreme events. Figure 2 depicts such anomalies both for annual as well as for monsoon precipitation at one of the stations, Lete. This again indicates an increasing tendency of excess rainfall in the later decades of the century.

In the Siran valley in Pakistan, an increase in annual precipitation by almost 40% was noted between 1981 and 1998. Likewise, precipitation increased by about 25% between 1961 and 1999 at the Murree station, a representative moist Himalayan area in Pakistan at a middle altitude of 2,100 m. At lower elevations of the moist Himalayas, the increase was moderate and in the sub-tropical mountains, a negative trend in rainfall of about 20% was noted between 1971 and 2000.

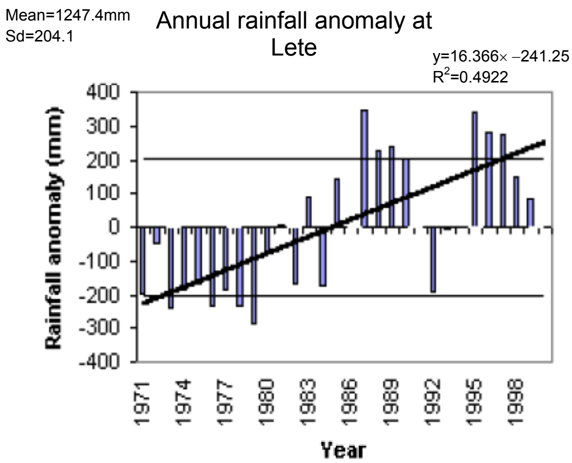

Fig. 2a Annual rainfall anomaly at Lete, Kali Gandaki Basin.

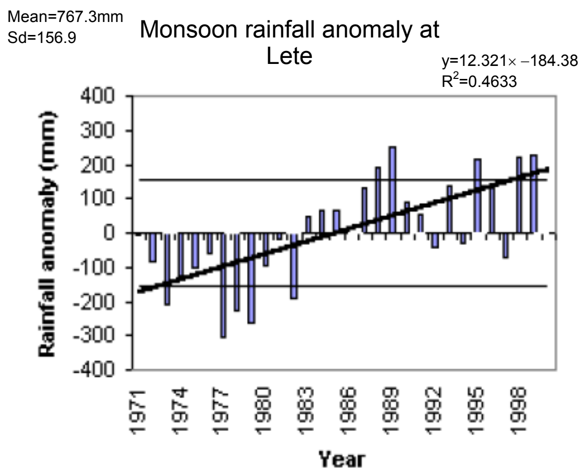

Fig. 2b Monsoon rainfall anomaly at Lete, Kali Gandaki Basin.

Similarly, analysis of rainfall data from 1965 to 2001 at Nainital, a hill station in the western part of the Indian Himalayas indicated decreasing rate of rainfall of 15 mm/year. Other stations at higher altitudes did not have long-term data and the available short-term did not indicate any consistent trend.

4.3 Climatic variability and extreme events

The entire Himalayan region is vulnerable to hazards due to climatic variability and associated torrential rainfalls. Flash floods are generally caused by high intensity rainfall followed by debris flow or landslides, often resulting in blockages of river channels. The formation of temporary dams due to landslides and their subsequent breaching cause havoc and panic in the river valleys and downstream areas due to sudden rises in water level. The Alaknanda Valley has a long history with several examples of such bitter experiences. In course of the present study, the frequency of such cloudburst events was found to be increasing in the last two decades. Likewise, analyses of climatic data for over 70 years for Pakistan have indicated an increase in storm precipitation in the northern mountains in the decade of 1991-2000. Analysis of extreme events in Nepal has also indicated an increasing trend.

5. Hydrology and Water Resource

In mountain regions, hydrology is a function of topography and meteorology. River flow data of the mountain areas provide valuable information on the hydrology of the region.

An analysis of trends in discharge carried out for selected river basins in Nepal with more than 30 years of observed data has shown a decreasing trend in annual discharge in large basins like the Karnali and Koshi with no significant changes in the Narayani basin. Since all the major rivers in these basins originate from the high mountains in the Himalayas and their flows peak during the monsoon season carrying in general more than 10 times the flow during the dry period, it may be inferred that the declining trends are due to a trend of lower monsoon flows thereby implying less monsoon precipitation across the high mountains. Meanwhile, rivers that originate from the middle hills and flow east-west along the Siwalik Zone have increasing trend of mean annual discharge. This tends to suggest more monsoon precipitation in the middle hills, the origins of these rivers.

The discharge data for the Siran River shows an overall increasing trend of about 5.8 million m^3/year, which is about one percent of the average annual flow during the past 32 years from 1968 to 2000. Likewise, the observed discharge data for the Kali Gandaki River for 36 years from 1964 to 2000 exhibit an increasing trend of nearly 142 million m^3/year, which is again about 1% of the average annual flow. The observed maximum discharge data for the Alaknanda River from 1980 to 2000 also indicate an increasing trend of 1,767 million m^3/year (2.8% of the average annual flow). The observed variations in river flow of the three selected rivers are presented in Figs. 3a, 3b and 3c.

As climatic change and variability as well as human pressure have a significant impact on the Himalayan Mountains' role as a 'water tower,' the sensitivity of mountain waters to climatic and hydrological

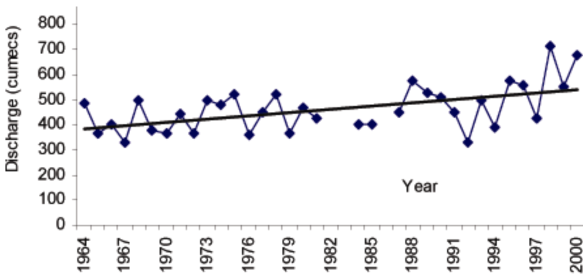

Fig. 3a Variations in annual flow of Kali Gandaki River at Kotagaon station.

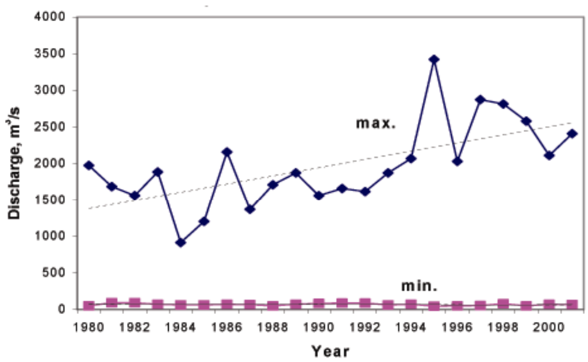

Fig. 3b Variations in annual flow of Alaknanda River.

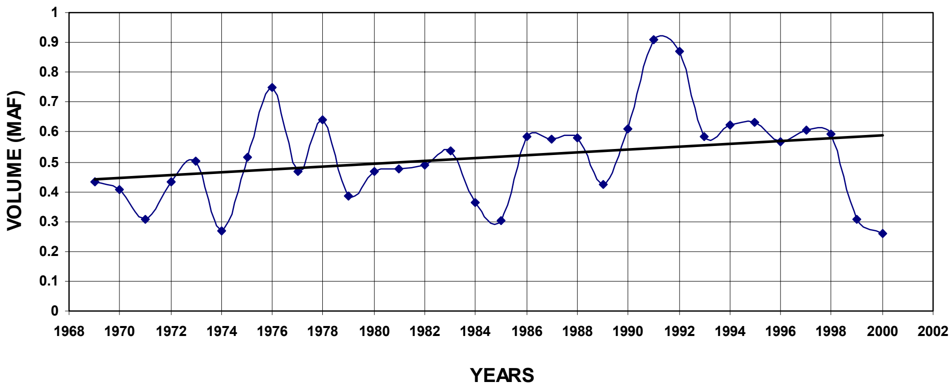

Fig. 3c Variations in annual flow of Siran River at Phulra station.

change in the context of changing environment needs yet to be understood well to assess the vulnerability of the Himalayan water tower.

6. Agriculture and Food Security

At present, more than 43% of the Himalayan region has a mean annual temperature of less than 5^oC and is therefore unsuitable for crop growth. Further, no more than 38% of the area has a growing period of more than 150 days and is suitable for agriculture. Subsistence agriculture is the mainstay of inhabitants of the mountainous region, which is characterized by small landholdings distributed in tiny crop fields over rugged terrain with a limited scope for irrigation. Areas above about 2,500 m elevation grow only one crop a year while two crops are generally grown in a year below this elevation. Humid and semi-humid mountain regions provide somewhat more favorable conditions for vegetative growth as compared to arid and semi-arid mountain regions.

The mountain farming system is in general found to be very complex and diverse, characterized by strong linkages between the three spheres of crop production, livestock ranching and forestry. Field surveys conducted in selected mountain areas in the Himalayas indicate that crop production in general supplies about 3-9 months of the annual household food demand and mountain households in general are left with little marketable surplus. Almost each household seems to keep small numbers of livestock for domestic needs and for some extra income. Certain groups of people in highlands in proximity to pastureland still engage in transhumance. Transhumance is more prevalent in the western Himalayan regions. Forests are utilized for domestic, agricultural and commercial purposes. Off-farm employment opportunities are limited locally. On average, most of the households have some of their members engaged in temporal migration. A high rate of labour migration indicates low local income opportunities and suggests that labour remittances are an important source of income for local households. Marginal and rain fed crop fields are being abandoned by the people, as further fragmentation of landholdings is not possible and young people are migrating out of the region for jobs elsewhere. Such incidences are now becoming more common.

Enhancing economic viability and the potential for increasing food and income from small and marginal farms in the mountains with declining productivity is a challenge being faced in the mountain areas. Realizing that subsistence farming, which focuses on cultivation of cereals, is no longer economically viable as the income from crop production is very low and the soil erosion rate is high, there is now a growing tendency to supplement/replace cereal crops with horticultural and vegetable crops. Nevertheless, the overall trend of declining fertility and productivity, increasing soil erosion, reduced cropping intensity, increased mono-cropping, and increased use of chemical inputs have raised concern for long-term sustainability of the farming system in the mountain regions.

Global change includes climate change and increasing atmospheric CO_2 concentration, so it appears that agriculture in the Himalayan mountain regions will bear mixed impacts. Certain crops have already been found in the Mustang area in Nepal to have crossed their earlier crop growing elevation limits and moved higher up. A spatial shift of cultivated areas to higher elevations is apparent, thereby increasing cultivated areas as well as production and productivity of certain crops. However, it is likely that other effects like increased water requirements of crops, pest problems, crop diseases, extreme climatic events, etc., may counteract the positive effects.

7. Threatened Unique Systems

Himalayan glaciers and biodiversity constitute unique systems being threatened by global change, including globalization. The threatened systems are briefly discussed next along with the consequences of these impacts.

7.1 Glaciers, glacial lakes and glacial lake outburst flooding

It is estimated that the Himalayas have nearly 1,500 glaciers covering an area of about 33,000 km^2 (Dyurgerov & Meier, 1997). Some other estimates have put the area covered by Himalayan glaciers at around 100,000 km^2, with maximum seasonal snow cover as high as 1.5×10^6 km^2 and the amount of water in the glaciers and snow cover to be around 12,000 km^3 (Bahadur, 1998). The Himalayan glaciers lie astride the boundary zone between monsoonal and westerly atmospheric influences, strongly affecting precipitation (in the form of rain and snow) and hydrological runoff conditions in the region. These enormous snow and ice fields have a significant cooling effect on the immediate vicinity and the region as a whole. The icy conditions in the Himalayas rival those existing in the polar regions and therefore they are sometimes referred to as a 'third pole.' Thus, the extensive Himalayan snow and ice fields act as a great refrigerator, cooling the earth's environment. The meltwater contributions from the mountains apparently lead even to reorganization of oceanic circulations.

Snow cover, glaciers and permafrost contribute significant amounts of meltwater to perennial Himalayan rivers like the Indus, Ganges and Brahmaputra as well as their tributaries. The Himalayan rivers supply an estimated 8,500 km^3 of water annually. Roughly 10% of this volume of water comes from meltwater contributions. The remaining amount is generated from rainfall. The glaciers act as buffers and regulate the runoff water supply from the high mountains to the plains during both dry and wet spells

(Bahadur, 1998). These rivers are in turn the lifelines of nearly half a billion people living in the river basins, which provide them fresh water just when it is most needed in the dry hot season before the monsoon.

The Himalayan glaciers constitute a unique system according to the definition of IPCC (IPCC, 2001) and are sensitive to environmental variables including climate. Being potentially vulnerable to climate change and variability, they also serve as good indicators of climate change and variability.

7.1.1 Recession of glaciers

Glaciers in the Himalayas are receding faster than in any other part of the world. The mean equilibrium-line altitude at which snow accumulation is equal to snow ablation for the glaciers is estimated to be about 50-80 m higher than during the first half of the 19th century (Pender, 1995).

The 26-kilometer long Gangotri glacier in India, for instance, has been reported to be retreating fast. From observations dating back to 1842, the rate of recession of the snout (the point at which the glacier ends) has been found to increase more than two-and-a-half fold per year. Between 1842 and 1935, the glacier was receding at an average rate of 7.3 m every year, whereas between 1935 and 1990, the rate of recession had gone up to 18 m a year. Available records suggest that the Gangotri glacier is currently retreating by about 30 m yr^{-1}. The average rates of retreat of some of the Glaciers in the Indian Himalayas as reported in various literatures are presented in Table 4.

Likewise, various field studies including those carried out between 1994 to 1996 in the Nepalese Himalayas and Tibetan Plateau to obtain basic knowledge on retreating glaciers and assess the impact of recent global warming on the Himalayas found almost all the glaciers in the area to be shrinking fast (Nakao *et al*., 1997). The follow-up field study carried out between 1997 and 1999 further verified the rapid shrinking of the glaciers as well as accelerated rates of their shrinkage (Ageta *et al*., 2001). Table 5 gives the rates of retreat of some of the studied glaciers (IHAS, 2001) in the Nepalese Himalayas.

Glacial retreat has immediate implications for downstream river flows. In rivers fed by glaciers, the river flows first increase, including the dry period flows that are supported by glacier melt, as more water is released due to melting of snow in long-term storage due to global warming. As the glacier gets smaller and the volume of meltwater reduces, dry period flows will no longer be supported and river flows will decline to well below present levels. The duration of the period of increased flows will depend

Table 4 Rates of retreat of some of the Glaciers in the Indian Himalayas.

Glacier	Observation Period	Retreat of Snout (m)	Average Retreat of Glacier (m/year)
Triloknath Glacier (Himachal Pradesh)	1969-1995	400	15.4
Pindari Glacier (Uttar Pradesh)	1845-1966	2,840	135.2
Milam Glacier (Uttar Pradesh)	1849-1957	1,350	12.5
	1909-1984	990	13.2
Ponting Glacier (Uttar Pradesh)	1906-1957	262	5.1
Chota Shigri Glacier (Himachal Pradesh)	1986-1995	60	6.7
Bara Shigri Glacier (Himachal Pradesh)	1977-1995	650	36.1
Gangotri Glacier (Uttar Pradesh)	1935-1976	600	14.6
	1977-1990	364	28
Zemu Glacier (Sikkim)	1909-1965	44	0.2
	1977-1984	194	27.7
Shankulpa	1881-1957	518	6.8

Table 5 Rate of retreat of some of the glaciers in the Nepalese Himalayas.

Glacier	Observation Period	Retreat of Snout (m)	Average Rate of Retreat (m/year)
Rikha Shamba (Western Nepal)	1974-1994	215.8	10.8
	1994-1998	72.8	18.2
	1998-1999	11.5	11.5
Yala (Central Nepal)	1982-1987		–0.5
	1987-1989		3.4
	1989-1994		3.9
	1994-1996		4.3
AX 010 (Eastern Nepal)	1978-1989	30	2.7
	1989-1991	28	14.0
	1991-1995	12	3.0
	1995-1996	0	0
	1996-1997	26	25.9
	1997-1998	13	13.5
	1998-1999	51	50.9

on glacier size and the rate at which the glacier melts; the smaller the glacier, the shorter lived the increase in flows and the sooner the onset of reduction in flows.

7.1.2 Observed changes in flows of snow fed rivers

The measured annual flows of the River Indus at two gauging stations have been exhibiting a continuous increase (Figs. 4a & 4b).

The station at Pratap bridge, which is at a higher altitude than that at Qila Bisham shows an annual increasing trend of about 7.6 m^3/s, while the station at Qila Bisham shows one of about 3.8 m^3/s. Almost all of the river's inflow comes from snow and glacial melt at these stations. Likewise, the annual flow of the Kali Gandaki River showed an increasing trend between 1964 and 2000 of about 4.5 m^3/s and the Alaknanda River also exhibited an increasing trend in its annual flow of about 56.06 m^3/s between 1980 and 2001. Similarly, glacial discharge of the Ganga's headwaters (Fig. 5) indicated a sharp increase in summer flow during August and September with an average increasing trend of 5.3 m^3/s between 1994 and 2000 (Hasnain *et al.*, 2002).

All these observed increases in flow of snow fed rivers apparently indicate the impact of global warming in enhancing flows due to increased melting of snow in long-term storage. However there is a need to study in further detail the relation between snow melt and river flows with good data spread over a longer period in order to assess the impact and develop scenarios for future flows.

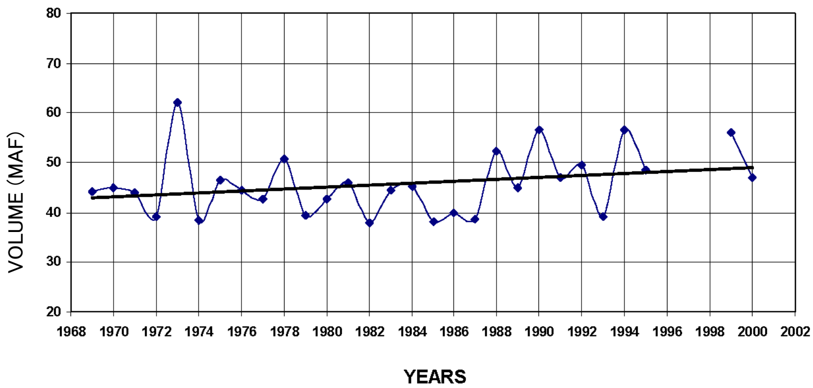

Fig. 4a Variations in annual flow of Indus River at Pratapgarh Bridge.

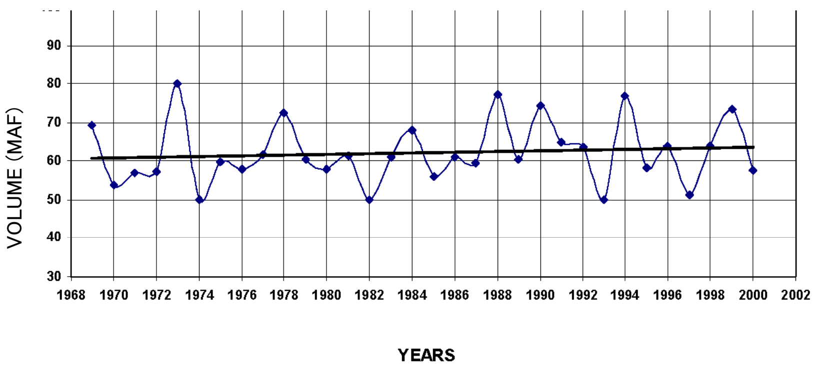

Fig. 4b Variations in annual flow of Indus River at Qila Bisham.

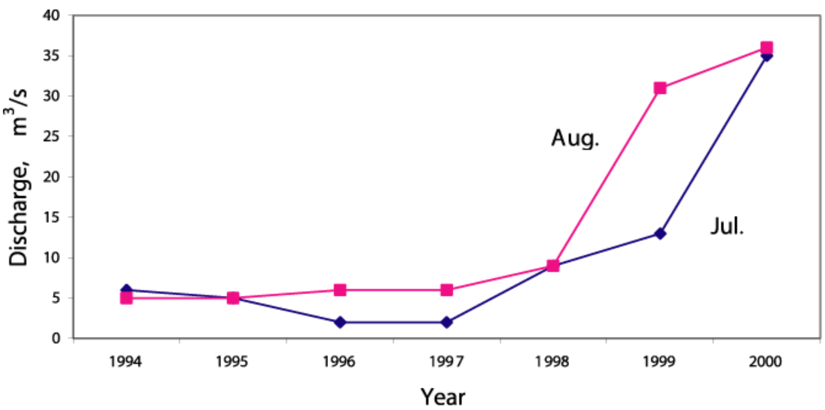

Fig. 5 Variations in glacial discharge of Ganga Headwaters.

7.1.3 Glacial lakes and GLOFs

Moreover, as glaciers retreat, glacial lakes form behind some of the already exposed terminal moraines (Fig. 6). Rapid accumulation of water in glacial lakes, particularly in those adjacent to receding glaciers, at times lead to a sudden breaching of the unstable 'dam' behind which they have formed. The resultant discharges of huge amounts of water and debris cause Glacial Lake Outburst Floods (GLOFs). There have already been several such instances of GLOFs that have had catastrophic effects downstream, leading to huge losses of life, property and public infrastructure.

Table 6 shows some of the estimated numbers of glaciers, glacial lakes and potential GLOFs in Nepal and Bhutan based on recent studies using satellite imagery and aerial survey data.

7.2 Threatened Biodiversity

One-tenth of the world's known species of higher altitude plants and animals occur in the Himalayas. The sharp variations in mountain environment with altitude result in a vast number of microhabitats, one reason for the extraordinary biodiversity of the region.

Apparently the geographic isolation, glaciations and a varied history of species migration and/or evolution all together have led to high degrees of biodiversity in the alpine environment of the Himalayas. As a reservoir of genetic resources, the Himalayas are one of the most important areas of the world. The eastern regions are in particular exceptionally rich in biodiversity. In addition, they are important sources of genes for the wild relatives of important plants, trees and crops.

Biodiversity is being lost in these regions because of human activities, especially land degradation and the overuse of resources. In 1995, approximately 10% of known species in the Himalayas were listed as threatened, and the number of species on the verge of extinction has increased since then (IPCC, 2001). Additionally, global warming is rapidly changing the Himalayas' unique and diverse mountain habitats. The accumulated stresses of climate change are disrupting the ecology of mountain and highland systems, and the plants and animals that are dependent on them are already facing a survival crisis.

8. Globalization and Its Impact on Himalayan Resources

The Himalayan Mountains are faced with a range of new problems in the context of rapid globalization and economic liberalization. Globalization through its driving market forces, such as short-term profitability and external demands, has promoted selectivity and narrow specialization in the choice of production activities and encouraged intense and indiscriminate resource use leading to overexploitation of niche opportunities and resources with little concern for environmental consequences. The negative impacts of globalization and new trade policies on local production systems are already visible in many parts of the Hindu Kush-Himalayan region (Jodha, 2000). Narrow specializations in cash crops, including selected horticulture with intense use of chemical inputs, a focus on monocultures, and reduced diversification at the farm level are now all apparent along with over-extraction of niche resources with accompanying negative impacts at the local level.

The key challenge for ensuring the prosperity of mountain regions is to promote awareness of the impacts of globalization, particularly at the micro- and

Fig. 6 A Glacier with Glacial Lake.

Table 6 Glaciers, glacial lakes and potential GLOFs in Nepal and Bhutan.

Country	Glaciers			Glacial Lakes		Potential GLOFs (Number) (2001)
	Number	Area (km^2)	Ice Reserves (km^3)	Number	Area (km^2)	
Nepal	3,252	5,323.89	481.23	2,323	75.70	20
Bhutan	677	1,316.71	127.25	2,674	106.77	24

Source: Mool *et al*., 2001a & b

meso-level, and to strengthen traditional niche markets while identifying new opportunities through institutional and infrastructural support as well as through local participation and partnership with the private sector.

Recent research conducted to assess the impacts of globalization and trade liberalization on the livelihood of mountain farmers in South Asia have clearly converged on the point that rapid trade liberalization and globalization may erode their sustainable livelihood options, unless specific measures are taken up to ensure sustainable livelihoods, especially to the mountain farmers, as they cannot bear the brunt of rapid globalization and trade liberalization (Munir & Adhikari, 2003).

9. Conclusions

Himalayan mountain ecosystems, which provide valuable resources and services to those living in the regions as well as to populations in the lowlands, are being threatened by increasing global change impacts on the Earth, most of which are human-induced and global in scale.

Analysis of some of the available meteorological data for selected regions of the Himalayan mountain regions has clearly indicated a warming trend in most of the regions as well as a changing pattern of precipitation, with the monsoon rainfall being reduced in the high mountains and enhanced in the medium altitude mountains.

A clear consequence and important indicator of this is the observed retreat of Himalayan glaciers, which highlights the impact of global climate change at high elevations and the consequences for lowland agriculture, hydroelectric power, ecotourism and society in general. Changes in snowmelt as well as the biological community covering the mountain watershed equally affect water storage and water yield to the downstream regions as well.

The rapidly growing population and greater physical, administrative and market integration of mountain and upland agriculture with mainstream systems have fundamentally altered local resource management practices leading to resource use intensification and overexploitation. Thus the landscapes and communities in the mountain regions are being simultaneously affected by environmental and socio-economic threats and perturbations.

Himalayan mountain systems are thus moving along a trajectory that fits clearly within the rubric of critically affected regions where high rates of environmental change are manifest in fragile ecosystems coupled with economies strongly dependent on local environmental resources and limited response capability.

The major challenges in research in the Himalayan Mountain region are to understand, describe and model better the impacts of ongoing global change processes in the region and their complex interrelations and interaction, and to use the required integrated models (model systems), after their verification and validation with reference to recent and past observations and monitoring programmes, for scenario-based simulations into the future. Based on such future projections of environmental and socio-economic conditions in the fragile Himalayan Mountain ecosystems, proper and efficient participatory methodologies, policies, strategies and action programmes need to be developed to help to ensure sustainable development and break the prevalent cycle of poverty, migration and environmental degradation. This includes intensified and more comprehensive studies of extreme events, such as droughts, floods, landslides, debris flows, GLOFs and the like, which are expected to increase in frequency and scale. Better preparedness of threatened communities for such events and measures for improved disaster prevention are required in order to avoid or mitigate as far as possible potential damages and losses.

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