Ecohydrological Investigations in the Himalayas

Jagdish Bahadur
Department of Science and Technology, Government of India,
New Delhi - 110 016

Introduction

The Himalayan mountain system is the tallest water tower on our planet and contains enormous renewable water reservoirs of perennial snow and ice at the highest elevations. In India we call it SARTAJ, i.e., a crowned head of water resources, the snow and ice caps forming the crown and head of the water resources of the mountain system. The whole system is held by Hindus in great reverence. The mountains are named after the gods and the rivers after the goddesses who have created and blessed the Indian land mass with the fertile Indo-Gangetic plains and provided perennial sources of water - the elixir of life.

We have to remember that the uplift of the Himalayas cooled the whole earth and modified atmospheric circulations, giving birth to the Indian monsoon -- one of the most obvious phenomena related to the ecohydrology of the region. The irregular topography of the mountain system influences weather on all time and space scales. The massif deflects air flow vertically and horizontally by retarding it near the surface and by providing elevated sources of sensible and latent heat. The intense freeze-thaw cycle combined with active tectonics and high slopes make the area prone to natural hazards, e.g., earthquakes, landslides, snow avalanches, mudflows, and glacial lake outburst floods, offering great challenges to managing the headwaters.

The nearness of the mountains to the sea in the eastern and north-eastern Himalayas triggers monsoon activity, which is held in check by the Tibetan plateau and the north-western glacier region. Unusually excessive Himalayan snow coverage delays the onset of the Indian monsoon and its activity.

Over a period of several million years, i.e., after the uplift of the Himalayas, the average annual precipitation in the northwestern region has been about 80 per cent in winter and 20 per cent in the summer season, creating arid to semi-arid conditions. This is just the opposite to the eastern and northeastern regions where 20 per cent of the precipitation is in winter and 80 per cent in summer, creating a humid to perhumid environment. In both the regions, micro-climates are altitudinally controlled, ranging from tropical below 900m to perpetually frozen above 4,800m.

The ecohydrology of the Himalayas includes all aspects of the hydrological cycle and the ecology - the science of plants and animals in relation to their environment. We shall, therefore, deal with some aspects of the atmosphere, geosphere, and biosphere to highlight the need for intensive international scientific studies of the apex system of the earth and for the establishment of meteorological and biogeo-databases to serve R&D efforts and modelling exercises for a better understanding of the massive Himalayan system and its various mesoclimatic regions. Improved knowledge of local, regional, and global effects on atmosphere will be useful in accurate weather forecasting and so reduce the effects of natural hazards and help understand and conserve the biodiversity, while increasing the productivity of flora and fauna in the various regions from west to east and in various altitude ranges.

Atmospheric Moisture, Cryosphere - Atmosphere Inter-Relationship

The fluctuations of the areal coverage of Himalayan snow and ice (including Tibet), from a maximum of over 1,000,000sq.km. in winter to 100,000sq.km in summer influence atmospheric processes throughout the year in a feedback loop subject to changes in albedo (varying from 95% for fresh dry snow to less than 40% for ripe snow-pack). These feedback processes operate on monthly, seasonal, and long-term scales, thereby providing clues for long-range weather prediction.

On smaller scales, the same feedback may prolong a cold spell or contribute to the continued steering of winter storms south of the extensive snow cover, yielding quasi-stationary atmospheric circulations.

The snowfall in the Himalayas begins in October and continues up to April and May, reaching its maximum in January and February. The maximum snow cover is registered after the establishment of maximum zonality, while the conditions for minimum snow cover are attained after a maximum of meridionality in air circulations. It has also been observed that the summer temperatures are negative at the firn line altitude in the north-western region due to radiation melting, while such temperatures are positive in the northeastern region due to advection and condensation heat transfer.

Several investigators have reported on the increase in snow precipitation with altitude (Bahadur 1993). The lack of a network of high-altitude observatories and continuous observations all along the length and breadth of the mountains makes it difficult to make definite water field estimates from different altitude ranges.

Hydrometeorological Observations

Average annual and seasonal rainfall figures in different Himalayan meteorological sub-divisions are given in Table 1 with the percentage of the seasonal to the annual contribution.

Some salient hydrometerological observations for the Himalayan region of 431 stations by Chinese investigators made 20-30 years ago (Yang 1990) are as follow.

i) The annual precipitation could be from less than 20mm to greater than 5,000mm; its variation coefficient is about 20 per cent in the east; 20 per cent to 30 per cent in the north and 30 per cent to 70 per cent in the

Table 1: Average Annual and Seasonal Rainfall in Different Himalayan Meteorological Sub-divisions

	Subdivision	Average Annual rainfall (mm)	Seasonal Rainfall (mm) June-Sept	% of Annual Rainfall
1	Jammu and Kashmir	997	458	45.9
2	Himachal Pradesh	1,518	993	65.4
3	Hills of West Uttar Pradesh	1,750	1,409	80.5
4	Sub-Himalayan West Bengal	2,779	2,172	78.1
5	Assam and Meghalaya	2,497	1,624	65.0
6	Arunachal Pradesh	2,997	2,085	69.6
7	Nagaland, Manipur, Mizoram	2,314	2,092	90.4

Sources: Central Water Commission 1988
Note: The above figures do not include snowfall in the upper reaches

south. The high variation in the southern region is an indicator of the need to monitor the area whose drainage affects the Indo-Gangetic plains.

ii) The higher mountain belts have stable precipitation, with a maximum at about 5250m near the equilibrium line on glaciers.

iii) The annual evaporation in the glacier region varies from 70 to 120mm/yr.

iv) The snow-line elevations are higher in the east than in the west.

v) Negative temperatures on continental glaciers last over six months compared to three to four months on maritime glaciers.

vi) The glaciers in the southeastern region are subject to ablation at a rate of 3-6m/yr.

vii) Solar radiation is the main source of heat next to induced latent heat and accounts for less than five per cent.

viii) The hydrological year for continental glaciers is from September to October, while for maritime ones it is from January to December.

ix) The runoff modulus ranges from 25.5 to 195 $l/s/km^2$ for continental glaciers, while it fluctuates from 85 to 195 $l/s/km^2$ for maritime glaciers.

x) The annual glacier melt is about 50 per cent in the west and decreases to 10 per cent in the north-east;

xi) Rivers within large glacier areas are less susceptible to the effects of drought or excessive rain flooding, due to the self-regulating mechanism of glacier systems.

Water Contributions from Snowmelt and Glacier Melt

In a study of the snowmelt and glacier drainage of the Sutlej basin up to Bhakra Dam, qualitative snowfall data for 70 to 80 years, best correlated with longitude due to the strong westerly winds of winter circulation (Bahadur 1975). The snowmelt and glacier melt discharges were maximal from June to August in the upper reaches of the river (above 2,400m).

In another study, snow and glacier contributions were reported for Chenab River where meltwater yielded 2.18m for a region which was 71.6 per cent glaciated, suggesting that the glacier melt is around 3.45m for a 100 per cent glaciated region in this area. Based on 10 years of snow cover data provided by satellite images, the average snow and glacier melt contribution to the annual flow of the Chenab at Aknoor was found to be 49.1 per cent, while it was 28.68 per cent for the Ganga River at Deoprayag (Singh et al. 1994) Snowmelt runoff forecasting studies in the Himalayan basin have been initiated at the National Remote Sensing Agency (NRSA), Hyderabad. The snowmelt runoff model (SRM) is used for forecasting snowmelt runoff for the Beas and Parvati rivers (Kumar et al. 1993).

In the absence of records of areal snow cover, its depth, and water equivalent and the ever-changing properties of snow cover, it is difficult to assess the snowmelt runoff. The area of maximum snow cover changes year after year, but it ranges from more than 10^6 km^2 to less than; $2x10^6$ km^2 in the Himalayan region (including Tibet), and, assuming an areal precipitation of 500mm/yr over the whole region, an average annual melt runoff ranging from 500 to 1,000km^3/yr is obtained. As the total area of glaciers in the Himalayas is about 100,000sq.km. and annual water yield ranges from 3 to 6m/yr, the glacier melt comes to 300 to 600km^3/yr, and at least half this amount, i.e., 400-800km^2/yr, flows down the Indus Ganga, and Brahmaputra rivers rather than the earlier conservative estimates of 500km^3/yr (Bahadur and Dutta 1989) and 200km^2/yr (Upadhyay 1995).

Status of Water Storage Reservoirs

Both fresh- and saltwater natural lakes exist in the high Himalayas. The lake water originates from snow and glacier melt contributions. These lakes occur at altitudes between 3,500 to 5,000m and have depths ranging from a few metres to about 100m. Their areal extent varies from less than a hectare to several hundred hectares. These lakes are formed across drainage land by avalanche debris from side slopes or by the advance of a side glacier with its lateral moraines. The lakes formed by glaciers disappear totally during the dry season and, in springtime, are refilled during the summer months from June to August.

The average annual streamflows of the Indus, Ganga, from and Brahmaputra river systems are 206, 488, and 510km^3/yr, respectively, and probably more or less half of this water comes from snow and glacier melt (Bahadur et al. 1978). There is no major water storage system along the Brahmaputra; Table 2 shows the major man-made water storage reservoirs along the Himalayan streams.

Table 2 Dams on Himalayan Rivers (> 100m)

Dam	River	Height (m)	Reservoir Capacity ($10^6 m^3$)
Bhakara	Satlu	226	9,868
Pomdob	Beas	116	8,141
Kalagarh	Ramganga	126	2,369
Pog	Beas	133	8,570
Thein	Ravi	147	3,300
Kothar	Kosi	155	4,080
Kishau	Tons	253	2,400
Tarbela	Sindhu	143	1,367
Mangla	Jhelum	118	7,250
Tehri*	Bhagirathi	261	3,539
Lakhwar	Yamuna	192	580

From the above table, it can be seen that the meltwater contributions in the arid Indus River system have been utilised to a large extent. The humid Ganga system is the second river basin in which artificial reservoirs are being created, but the water resources of the perhumid Brahmaputra have yet to be exploited in a big way. More imaginative, bolder, and coordinated steps have to be taken at the political and technical levels to create larger storage areas along the Ganga and Brahmaputra multipurpose water storage projects that make fuller use of water resources from the high-altitude environment in order to reduce the overland runoff and losses of valuable soil resources. One can harness the water resources in the upper reaches to meet the demands of environmental regeneration, etc.

Some Case Studies of Ecohydrological Investigations in India

Rainfall Trend at Barapani (Maghalaya)

Statistical analyses of the rainfall data for 31 years (1957-87) from Barapani indicate that the rainfall trend remained unchanged. The data show that 88 per cent of the average annual rainfall occurs during the period from May-October; 89 per cent of these months were categorised as normal months (Satpathy 1991). The coefficient of variation of annual rainfall is 23 per cent. The prediction of monthly rainfall at probabilities of 80, 50, 40, and 20 per cent has been presented to allow decision-making for different agricultural operations. The percentages of total months under the categories normal, abnormal, and drought were found to be 66.93, 7.53 and 25.53, respectively.

Water Harvesting in the Northeastern Hill Region

Research experience with work related to *in situ* retention of rainfall, namely, the embanked dug-out type of pond that harvests springs, is discussed by Singh et al. (1991). Watershed-based land-use systems for *in situ* harvesting of rainfall resulted in retention of 80 to 100 per cent of annual rainfall. The contribution to water stored in seasonal ponds and located in well-managed watersheds from direct rain, surface runoff, and sub-surface flow was 16.8, 3.2, and 80 per cent respectively. The effect of low density polyethylene (LDPE) lining against seepage losses was found to be ineffective due to the base flow in pond beds/sides. The experience with perennial springs was economic and encouraging. The authors concluded that watershed-based land-use systems should be adopted wherever feasible, fish farming encouraged, and the relationship between the catchment area and water impounded area be evaluated so as to improve traditional water-use systems and to standardise earth dam sections for different storage depth situations.

Hydrological Behaviour of a Mini-agricultural Watershed

A 26-hectare watershed (isolated from the surrounding area) having a general slope of 1-10 per cent located at Palampur, Himachal Pradesh, at an altitude of 1,300m was used as an experimental area for the development of agriculture. The area falls within the mid-hills sub-humid agroclimatic zone. Annual average rainfall is about 3,000mm, of which about 80 per cent is received during the monsoon season (from June to the end of September). Effective soil and water conservation methods for watershed management resulted in a decline of runoff from 65 to 30-34 per cent, and soil losses from 22.5t/ha to 3-3.4 t/ha, in a period of ten years (1979-88). No reduction in nutrient losses was observed (Table 3).

Small storage works are very effective in reducing sediment yield, preventing gullying, restoring degraded land, and creating mini-commands easy to manage.

Table 3: Runoff and Soil and Nutrient Losses from a Mini-agricultural Watershed (Jun-Sept)

Year	Rainfall (mm)	Runoff (%)	Runoff duration (hrs)	Soil loss t/ha	Nitrogen loss kg/ha
1979	1,536.6	65.0	624	22.50	3.80
1980	1,923.8	60.2	740	18.45	4.00
1981	1,943.0	53.4	775	6.65	4.20
1982	1,270.0	47.7	240	3.08	2.25
1983	1,613.5	43.5	818	4.74	3.10
1984	1,397.6	43.0	543	4.50	4.00
1985	2,023.3	38.6	231	4.63	4.10
1986	2,196.3	33.2	891	4.27	4.00
1987	992.2	30.8	334	3.62	3.56
1988	2,740.1	34.3	1,293	4.32	4.12

Temporal Variation of Rainfall and Temperature in the Ganga Basin

Rainfall and temperature data at three stations, viz., Agra, Delhi, and Dehradun, were studied for the period from 1901 to 1989 with the following changes in the statistics of the time series (Kolhyari and Singh 1992). The total monsoon rainfall has shown a declining, and the annual maximum temperature an increasing, trend (Table 4).

Table 4 Changes in Statistics of the Time Series

Station	Average rate of decrease of monsoon rainfall amount (mm/100yrs)	Mean monsoon rainfall (mm)		Rainfall amount (mm)					
		Based on data from 1901-65	Based on data from 1901-89	Data series 1901-64			Data series 1965-89		
				Frequency			Fequency		
				50%	75%	90%	50%	75%	90%
Agra	120	609	580	591	433	316	531	387	276
New Delhi	145	630	610	613	457	397	571	410	285
Dehradun	206	2,063	2,003	1,970	1,830	1,817	1,895	1,382	1,200

The above changes are typified by dramatic shifts towards crops that are new to the Agra region. Previously, sugarcane, peas, grams, and wheat were dominant crops. Nowadays mustard and wheat are dominant. Among other possible reasons for this is the large-scale deforestation for construction of roads, and subsequent large-scale urbanisation. However, it is difficult to prove that the changes are due to the accumulation of CO_2 and other greenhouse gases.

In a recent study (Kelly and Hulme 1993) on climatic scenarios for the Indian sub-continent utilising seven recent global climatic models up to 2100 A.D., it was concluded that the annual average temperature shows warming over the central part, close to the warming affecting the global mean temperature. Warming will be greater in the north than in the south, where the likely projection is about 1°C.

For Himachal Pradesh in the Western Himalayas, the projected temperature changes are an annual temperature rise of about 3°C; a winter temperature rise of about 3°C; a spring temperature rise greater than 3°C; and a summer temperature rise of about 4°C. The annual precipitation will rise 20 per cent, winter change +20 to -15 per cent; spring change + 30 to 40 per cent; summer change +30 to -20 per cent; and autumn change + 15 to -15 per cent. These estimates have a wide range of uncertainty and should be taken as only likely to happen.

In the Himalayan context, there are no long-term climatic records, nor are exact records of past vegetational patterns available. The day and night fluctuations in air temperature are greater in the Himalayan region than those reported for other mountain zones. Even today, the CO_2 concentration in the mountains at about 3,000m is that of the pre-industrial period (270ppm), whereas in valleys at about 500m, CO_2 is around 330ppm, which is almost identical to the present-day concentration of CO_2 on the global level (Purohit 1991).The effect of global warming is apparent from the permanent snow-line and the recession of glaciers in the high mountains.

How quickly we can predict the possible impact on the basis of authentic data will depend on how soon we can identify the systems most sensitive to climatic change. Given that the Himalayas are the most sensitive zone to global climate change, and that their sensitivity increases with the increase of altitude, the ecophysiology of the flora and fauna of this region offers interesting opportunities to develop predictive models. Studies analysing the soil-vegetation-atmosphere complex, water and energy fluxes, species spread and turnover, the landscape, and agricultural and crop productivity under natural environmental conditions along the altitudinal gradient, supported with data reported from experiments on CO_2-temperature-water interactions to plan development processes, will be helpful in formulating the desired ecosystem model. For such studies, the data generated from the continuous monitoring of geomorphological processes along the altitudinal gradient will increase the reliability of simulated parameter values of the model. For studies of vegetation-free areas, land-ice-snow-atmosphere interactions have much to say about weather changes that affect the climate and the earth's life system. In a recent study on the biodiversity of Himalayan hill streams (Ormerod et al. 1995), the authors have concluded that there is a need to develop surveillance and monitoring strategies, particularly in view of the large array of potential changes facing Himalayan rivers from agriculture, varying forest cover, urbanisation, pollution, and tourism.

Need for an Improved Understanding of Ecohydrology of the Himalayan System

From what is stated in the previous pages, it is apparent that freshwater from the highlands poses several special problems for eco-management. Retention of water on high slopes is needed, and this can be achieved by keeping forests healthy, adopting appropriate soil/water conservation measures, and developing man-made water storage systems consisting of tanks, ponds, small dams and reservoirs, and artificial/natural lakes at different altitudes, with an elaborate system of canals guarded by weirs and sluice gates to carry clean water to all elevations.

As the sustenance of life is controlled by the water cycle, the hydrology of the Himalayas, the world's tallest water tower, needs serious consideration from the international scientific community. It is melt contributions from snow and glacier fields at higher altitudes that generate the perennial streams, but the amount of meltwater discharge is largely dependent on meteorological conditions, so we need to understand the role of mountain weather and climate more or less across the board. For this reason accurate weather forecasting assumes special significance. We have to develop such a system to meet the demands of all forms of life among the great biogenetic diversity in the Himalayas.

The success of planned land-atmospheric experiments, e.g., the Alpine Experiment (ALPEX-82) and Pyrennees Experiment (PYREX-90), has improved understanding of the mountain enviroment and resulted in accurate weather forecasting. The Himalayan Experiment (HIMEX) is being proposed to generate a better understanding of the physical processes controlling atmospheric circulations in the tropical to permafrost conditions existing in the region.

The framework of a long-term and meso-scale measurement network to be established for land surface experiments in different biomes includes the following.

i) Meso-meteorological measurements, among other means by radio-sounding
ii) Long-term flux measurements at individual sites combined with hydrological and vegetation studies
iii) Satellite data aquisition and the development of a snow-cover analysis system
iv) Rain-radar data aquisition
v) Sub-sites for intensive field activities

It is hoped that accurate weather forecasts will help reduce the frequency and intensity of weather-based natural hazards in the region and provide a better quality of life for its people.

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