Working Paper

The Highlands: A Shared Water Tower in a Changing Climate and Changing Asia

Xu Jianchu

Southeast Asia

World Agroforestry Centre
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Abstract

The highlands of Asia have an average altitude of 4000 masl; and they extend from an altitude of 3000masl to include the whole of the Tibetan Plateau and most parts of the Pamir Plateau. The highlands contain the most extensive areas of glaciers and permafrost outside high latitudes. The region is often referred to as the 'Asian water tower': the source of Asia's nine largest rivers the waters of which sustain over 1.3 billion people. The highlands of Asia have been ignored in comparison to other natural ecosystems, even though history has shown that, when ecological change takes place in the highlands, changes soon follow in the valleys and in the lowland plains. The impacts of climate change are superimposed on a variety of other environmental and social stresses in mountain ecosystems, and many of them have been recognized to be severe and cause uncertainty. Key impacts of climate change on the highlands include glacier retreat, shortage of fresh water, natural hazards, soil erosion, ecosystem degradation, and land desertification. The supply of fresh water, or the snow and ice meltwater component, in large river basins is projected to increase over the following decades as perennial snow and ice decrease. Later, however, most scenarios suggest a decrease, even of catastrophic proportions, by the 2050s.

The greatest challenge in the highlands of Asia is the very limited monitoring or understanding of the thresholds and cascades of climate change on the cryosphere, hydrosphere, biosphere, and on human society in the vertical dimension from highlands to uplands and from lowland plains to coastal areas. Impacts on water resources will differ depending upon the importance or influence of different sectors; and between forestry, agriculture, industry, ecosystems, or mitigation measures to reduce water-induced hazards. There are substantial variations within as well as between these sectors in different countries and valleys. Meanwhile, climate change is superimposed on a variety of other environmental and social stresses that cause uncertainty and lead to contradictory perceptions. Three practical suggestions are a) integrated research to understand highland complexities and reduce scientific uncertainty; b) promotion of regional cooperation and science-based dialogue to regulate blue, green, and virtual water flows; and c) building of social resilience and offsetting lack of knowledge of diverse human and ecological conditions by actively involving local communities; allowing their knowledge, innovations, practices, and concerns to inform understanding and help direct responses.

Keywords

Climate Change, Highlands, Water Tower, Ecosystem Services, Asia, Uncertainty

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Content

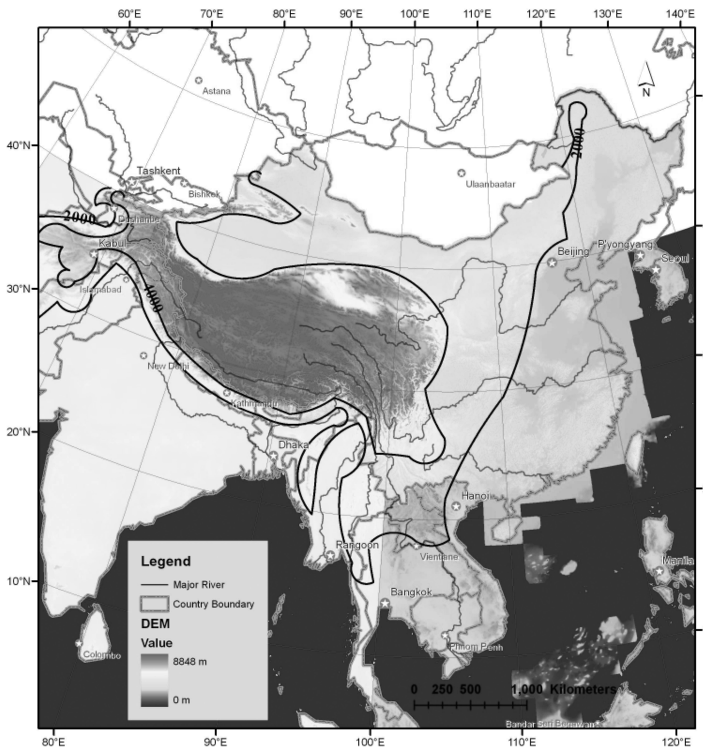
1. Introduction to the Highlands of Asia

The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) excludes the Himalayan region because of scientific uncertainty. The greater Himalayan region, or the highlands of Asia, called the 'Third Pole of the World', which include the inner and south Asian mountains, contain the most extensive and rugged high altitude areas on Earth and the most extensive areas of glaciers and permafrost outside high latitudes.   The highlands occupy about one-fourth of Asia's land surface, and although they provide a home for less than a tenth of the Asian population, the region is the source of nine of the largest rivers in Asia, the basins of which are home to over 1.3 million people (Xu et al. 2007). The highlands of Asia have been ignored in comparison to other natural ecosystems, even though history has shown that when ecological change takes place in the highlands, changes soon follow in the valleys and in the lowland plains (Eckholm 1975). The impacts of climate change are superimposed on a variety of other environmental and social stresses in mountain ecosystems, and many of them have been recognised as severe (Ives and Messerli 1989), causing uncertainty (Thompson and Warburton 1985).

The Tibetan Plateau, located at the heart of the highlands of Asia, plays the role of an 'Asian water tower' as it supplies water and regulates the climate in upland and lowland areas of Asia adjacent to it. Geographically it covers the high altitude Qinghai-Tibetan Plateau as well as the Pamir Plateau, Yun-Gui Plateau, and Loess Plateau and other mountain ranges connected to it. The Tibetan Plateau plays a critical role in the cryosphere, hydrosphere, biosphere, and anthrosphere in the continent of Asia, and it also has an impact on the Asian monsoon. Despite the diversity and complexity of the mountains of Asia in terms of the land and peoples of three principal zones, viz., the highland Plateau, the upland watersheds, and the lowland plains[1] they present quite a uniform set of ecological and economic challenges. The upland watersheds include the mountains of central Asia, a narrow belt of the Himalayan Mountains, montane mainland Southeast Asia, the Yun-Gui Plateau, and the Loess Plateau of China at elevations of about 2000 masl. The lowland plains cover East China, lowland mainland Southeast Asia, and a large part of the Indian subcontinent below 1000 masl (see Map 1). The total land area of the Tibetan Plateau, the largest area of in the highlands, is around 2.5 million sq.km., accounting for about 26% of China's land mass. The total area of the Tibetan Plateau and its surrounding provinces in west China is about 6.4 million sq. km., accounting for 69% of China's land area, two thirds of the entire country, 56% of the runoff, and 95% of the hydropower potential of China (Table 1).

The highlands of Asia, the largest and most topographically complex ecosystem in the world, play a unique role in global climate and climate change processes. The highland climate is influenced by the Asian Monsoon, the Inner Asian high pressure system, and the winter westerlies. The Tibetan Plateau also has an important impact on climate circulation in the region and on the Asian monsoon. The area itself has several distinct climatic regions which are characterized by variations in rainfall. The eastern edge of the Tibetan Plateau is relatively humid, with rainfall of from 400-700 mm annually, the southern central area is semi-arid, and the western and northern parts of the Tibetan Plateau are arid with rainfall of less than 100 mm per year. Climate change is not new and can be catastrophic in the highlands since the climate is becoming much warmer than global average at increasing altitudes in the mountain region. Climate change is driven by natural, anthropogenic, biogeochemical, and biogeophysical processes. Human activities in the highlands and the surrounding mountain regions play a key role in biogeochemical cycling on earth through land-use practices and land-use changes, both physical and

[1]With an average altitude of 4000 masl, the high plateau extends from 3000masl and includes the whole of the Tibetan Plateau and most parts of the Pamir Plateau



Map 1: Tibetan Plateau, montane watersheds, and lowland plains of the Asian Continent

Table 1: Natural Resources of the West China (2005)

	Area ($10,000km^2$)	**Population (million)**	**Farmland (million hm^2)**	**Forest (million hm^2)**	**Rangeland (million hm^2)**	**Surface water resources (billion m^3)**	**Theoretical energy storage (x10000kw)**	**Exploitable (x10000kw)**
TAR	120	2.77	0.36	13.9	64.44	445.1	20,056	5,659.3
Xinjiang	167	20.10	3.99	4.84	51.16	91.1	3,355	853.5
Qinghai	72	5.43	0.69	3.17	40.36	85.8	2,337.5	2,099
Sichuan	48	82.12	9.17	14.64	13.72	292.1	14,269	10,346
Yunnan	38	44.5	6.42	15.6	0.78	184.6	15,000	9,166
Guizhou	18	37.3	4.90	4.2	1.61	83.5	1,874.5	1,683.3
Gansu	40	25.94	5.02	3	12.62	26	1,724	551
Shanxi	21	37.2	5.14	6.7	3.12	46.8	1,275	551
Ningxia	5	5.96	1.27	0.40	2.28	0.69	212	90.2
Guangxi	24	46.6	4.41	9.84	0.73	172.1	2,133	1,751
Inner Mongolia	115	23.86	8.20	20.51	65.72	33.9	482.5	238.7
Total	668	331.78	49.57	96.8	256.54	1,461.69	64,156.5	34,257
Account for China (%)	70.24	25.37	38.12	55.34	97.86	54.17	95	90.4

Source of data: China Statistical Yearbook 2006, National Bureau of Statistics of China socioeconomic. Land-use changes contribute directly to local and regional climate change, as well as to global climate warming. In turn, changing biogeochemical cycles strongly impact the human-environment system.

The highlands or the 'Asian Water Towers' are the source of the nine largest rivers in Asia. The major river basins of the region – west to south, to east and to north– are the Indus, Ganges, Brahmaputra, Irrawaddy, Salween, Mekong, Yangtze, Yellow, and Tarim. Unlike the polar regions, the highlands directly provide water-related environmental services to 1.3 billion people within nine river basins such as the east coastal area of China which is the Chinese economic engine, and mainland Southeast Asia, and South Asia, which together have the largest population globally in terms of size and density. Environmental degradation and widespread poverty in the headwaters of the mountain regions have led them to being identified as areas of emerging water crises as a result of climate change, rapid economic growth, deteriorating ecosystems, and increasing demand for water. There is an increasing need for integrated water resource management for human livelihoods, ecosystems, and economic development. One way forward is to move past realist frameworks of analysis and step forward to paradigms of 'sharing benefits, not just sharing water', 'sharing risk management,' and 'sharing costs to support ecosystem services' at local, national, and transnational level.

This paper offers ideas in support of knowledge for action and cooperation. The assumptions underlying it are as follows: all stakeholders in the 'Asian Water Towers' witnessing changes in the mountain environment, relationships, economies, and in the climate. There may have been reasons for non-cooperation on some issues in the past, but there are now reasons to move forward and seek ways to cooperate considering the uncertainty of changes in the climate and the environment. All the stakeholders in the 'Asian Water Tower' can benefit from joint development if the 'Water Tower' is maintained and used carefully. There are many possibilities for shared benefits from cooperation, water being one, but there are also benefits beyond water.

2. The 'Asian Water Tower'

Mountains contribute a runoff of up to 60% of the total (Bandyopadhyay et al. 1997). Viviroli and Weingartner (2002) have shown that there is a big difference between the importance of mountain ranges in arid and semi-arid environments and mountains in humid and sub-humid areas. In arid and semi-arid areas the importance of mountain water is much more pronounced and it provides a lifeline for areas downstream (e.g., the Indus and Tarim rivers). According to Viviroli and Weingartner (2002) mountains in general provide a) disproportionately large amounts of discharge thanks to their high precipitation and low evaporation rates; b) seasonal retardation of discharge through the accumulation of snow and ice; c) highly reliable amounts of runoff thanks to the regularity of the melting process and the storage capacity of glaciers. Mountains provide a precipitation barrier which leads to orographic rainfall, and the cool temperatures at high elevations reduce evaporation rates. This often produces positive water balances in the mountains, i.e. water inputs are higher than water outputs and can therewith produce runoff. In the surrounding lowland areas, the inflow from rivers upstream is necessary to balance evaporation losses and produce an even water balance.

The Concept of the 'Asian Water Tower'

The criteria for the 'Asian water tower' are that it should be able to provide water-related services in terms of both quality and quantity across space and time for the large population of the Asian continent. In order to understand the concept of the highlands as Asian water towers, we analyze the function, productivity, and processes of water flow in four broad ecological zones that constitute river basins.

a)Highland 'Water Towers'

Highland 'water towers' refer to the highland plateaux and mountain ranges which cover a total area of 3,846, 131 sq.km. at elevations above 3000 masl (Li, et al, 2007). Water is often stored as glaciers, ice, and snow temporally and permanently. The area provides approximately 8.6 x 106 m^3 of water annually. It has been estimated that about 30% of the water resources of the eastern Himalayas are derived from the melting glaciers, snow, and ice: this proportion increases to nearly 50% in the Indus in the western Himalayas and becomes as high as 80% in the upper reaches of the Tarim Basin. The complexity and intensity of high altitude wetlands, lakes, and river network systems enable them to hold water for fairly long periods of time. Melting glaciers, ice, and snow replenish freshwaters significantly in early spring and summer. Highlands are often a combination of hilly and flat plateau areas covered with alpine vegetation, bush, and grassland, in many cases paradises for wildlife. Highland people are either nomads or agropastoralists like the Tibetans who have little access to social services such as health care and markets.

b) Upland Watersheds

Upland watersheds refer to the middle areas of large river basins between 1000 and 3000 masl where water is collected in small streams or sub-catchments that merge into larger ones and often flow into a reservoir or merge into major rivers. Upland watersheds are typically hilly and mountainous, originally forested or covered with perennial vegetation, and, in many cases. the location of protected areas or watershed conservation areas. People in upland watersheds, living in tribes or other minority groupings, are often shifting cultivators or composite swiddeners who practice a range of livelihood activities such as swidden-fallow agriculture, home gardening, and collection of non-timber forest products, but they are often poor because they have less assets than people living downstream.

c) Lowland 'Rice Bowls'

Lowland rice bowls, most productive rice producers in the world, are located in areas downstream from highland water towers and upland watersheds and upstream from coastal zones and exclude urban and peri-urban areas. They are often located at less than 1000masl and have alluvial and productive soil which renders products, from rice to vegetables, from cut-

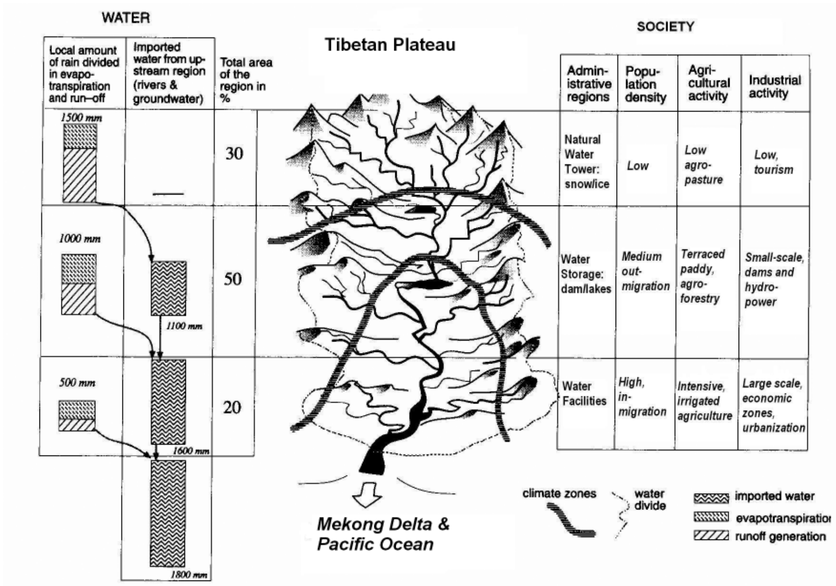


Figure 1: Highland-upland-lowland linkages of Asian water towers (after Falkenmark 1999)

ting flowers to fishes, that can be sold nationally or exported to other parts of the world. Lowland farmers engage in intensive agriculture, horticulture (orchards), and aquaculture. They have much better access to social services such as markets, extension services, and information.

d) Coastal Urban and Peri-urban Areas

Urban and peri-urban areas refer to those parts of the river basin in which population, land ,and water management are strongly affected by large concentrations of people. Asian mega-cities, lying at less than 300 masl, often have several million people if one includes the areas used for horticulture and animal husbandry surrounding them. Most of these cities are located in the coastal areas in the lower reaches of basins. They are completely dependent for water for domestic consumption and economic development on the upstream water towers, watersheds, and water tables. Figure 1 is a graphical representation of the zones.

Towards Integrated Water Tower Management

The four broad ecological zones described above are interconnected and therefore should not be considered in isolation. The following are suggestions about integrated water tower management (IWTM).

- More rainfall in highland areas is stored in the form of ice and snow by hours, days, months, years, and centuries than melts into high altitude wetlands, lakes, and rivers locally and downstream. The quality of water is in good condition because of low population density and, therefore, few human activities and also because of the alpine vegetation acts as a filter.
- Fresh water from melting glaciers, snow, and ice flows into the upland watershed zone though river systems and underground water. Rainfall dominated by the Asian monsoon produces substantial surface runoff and erosion. Water flow and quality in the watershed are influenced by soil conditions, land use, and land cover.
- Movement of plant nutrients generally from highland headwaters and upland watersheds to lowland plains to urban areas (as food) and the ocean (as pollutants and sediment). Since there are no mechanisms to ensure recycling to the place of origin, this process contributes substantially to nutrient depletion in marginal areas in watersheds, and on the plains and to pollution in cities and peri-urban areas.
- Landscapes in highland Asia are mosaics of forests, home gardens, wetlands, crop lands, and high pastures: a range of habitats for all life forms and a diversity of livelihoods and products, from dairy products in alpine areas to tea production in the mid mountains, from mushrooms and apples in temperate zones to mango and rubber in the tropics,

and from timber to non-timber forest products. Movement of food from alpine rangelands, upland watersheds and lowland rice bowls to urban areas is and important commercial activity in the region.

- Land-use decisions are also water decisions (Falkenmark et al. 1999). How land is used — whether it is dedicated to agriculture, forestry, rangelands, or urban areas; whether it is left barren and open to soil erosion, or whether it is subject to intensive crop management — will have substantial impact on both water use and the availability of water downstream. Land cover, whether land is managed or not, will have a great impact on runoff and infiltration as well as water consumption by biota. Land use and land cover, therefore, will influence both 'blue' (water visible in lakes and rivers) and 'green' water (water used by plants).
- The agricultural sector is the largest consumer of water. About 70% of the water available in the lowland plains is used for irrigated agriculture. This usually competes with water needed to sustain ecosystems and their services. A better understanding of the relationship of environmental flows and the health of the ecosystem must be achieved.
- Food transactions may also affect water consumption, if the use of water is more efficient at the site of export (often in wet and warm climates) than at the major importing areas. Interconnections through infrastructure: roads, channels, housing, dams, airports and recreational facilities can have positive effects by making key inputs available and at reasonable prices (e.g., fertilizer), by giving farmers different options for increasing income hence relieving the pressure on land (e.g., high-value vegetables, off-season production and livestock products, even forest and tree products), and by facilitating more commuting and off-farm activities.
- Over the centuries, people have used barter to exchange goods and services, maintaining genetic diversity and food security within the parameters of their traditional cultures. Merchants from Yunnan in the eastern Himalayas travelled the Tibetan plateau, South-east Asia, and South Asia for a thousand years. Caravans served as market structures and formed a sociocultural network among mountain and lowland communities. Mountains were as much pathways of migration and trade as barriers between highlands and lowlands.
- Movements of people, particularly the young generation, through permanent or temporary migration from the uplands to the lowland is a growing phenomenon as the rural poor seek new opportunities and new ways of life in transition to a market economy and regionalization. By using resources from a large, non contiguous area to produce food and the many other items they consume, they produce a massive 'ecological footprint'. Increasingly, however, it has been realized that new patterns of inter-and intra-basin connections are needed which also ensure food security and ecosystem services provided throughout the basin are protected.
- Human activities through land-use and land-cover changes generate both 'positive' benefits (increases in food and fibre production) and 'negative' costs (species' extinction, soil erosion, land degradation, water pollution, and global warming). The pace, magnitude, and spatial reach of land-cover and land-use changes have increased over the past three centuries, particularly over the last three decades, in Asia due to an increase in population and economic growth. Land use affects water resources, human health, and fauna and flora; contributes to local, regional, and global climate changes; and is the primary source of soil, water, and land degradation.

Table 2 summarises the structure, function, and socioecological challenges of the Asian water tower.

Table 2: Characteristics of Critical Zones of the Asian Water Tower

Altitude (masl)	Function	Ecosystem	Livelihood/land use	Natural hazards	Population density	Environmental issues	Socioeconomic issues	Opportunities	Niche products
Above 3000	Highland water tower	Alpine ecosystem	Agropasture	Glacial lake outburst floods	Low	Overgrazing and climate change	Malnutrition, poverty, access to services	Tourism, niche products	Dairy products
1000-3000	Upland watershed	Montane forest ecosystem	Agroforestry	Cloudburst, flash floods/landslides and mudflows	Medium, out-migration	Agricultural intensification and pollution	Economic polarization, lack of alternative livelihoods	Niche products, watershed conservation	Opium before, tea, at present
300-1000	Lowland rice bowl	Lowland plain	Intensive agriculture and horticulture	Riverine floods and soil erosion	High, in-migration	Water pollution, eutrophication	Water conflicts	Payment for environmental services	Rubber, rice
Below 300	Urban & peri-urban	Flood plain	Horticulture, animal husbandry, aquaculture	Cyclonic storms, Tsunami, rise in sea levels, waste disposal	Communities that migrate frequently	Salinity, water sanitation and scarcity, overextraction of groundwater	Urban poor	Information services and market chains	Rice, fish/shrimps

Regional River Basins

Highland glaciers, ice, and snow, which represent major natural reservoirs of frozen water, feed the wetlands at high altitude and nine of Asia's great rivers. The Yellow and Yangtze Rivers flow to the coastal areas of China; the Mekong, Irrawaddy and Salween flow to Southeast Asia, and the Indus and Brahmaputra are major South Asian river systems. The water tower (natural reservoirs of frozen water and wetlands) serves as a buffer to local climate variation. It compensates for the deficit of rainfall and snowmelt during dry and drought years and stores water from cloudy skies to reduce melting during wet years. Thus stream flows and discharge are stabilized with recharged melting water from upstream, which is crucial for local agriculture and livelihoods. Table 3 gives indicators of the importance of water resources in the region. In particular, it shows that, in some river systems, glacial melt is an important source of water for big populations downstream. In the long term, glaciers are predicted to melt and disappear, with major consequences for the availability of water in these river basins. Climate change will also have other impacts on the interannual and seasonal flows of these rivers, so even where the total availability of water is not limited, climate change will cause other impacts such as floods and changes in the seasonality of water flows. For example, 49% of the total discharge of the Yellow River is from the Tibetan Plateau, 25% of the discharge of the Yangtze River, and 10% of the discharge of the Mekong: water resources from the Tibetan Plateau account for 20.23% of China's total availability of water with a production of $22.55x10^4/km^2$ (Lu et al. 2004, An et al 2007). It is estimated that glacial melt is the principal source of water in the dry season for 23% of the population of western China. Changes in glacial water flows will have impacts on the availability of water in this critical season. As a high-altitude area, the highlands have several other cryogenic features of importance for water resources such as perennial ice and snow cover, snowfall, rainfall, evaporation, and permafrost. Thus the impacts of climate change on the highlands will have major impacts on water resources and on the ecology, human health, and economic activities not only in the highlands but also in the river basins dependant on water flows from the highlands.

Four critical ecological zones directly benefit from the Asian water tower as well as from the great river basins and they are the a) east coastal areas of China; b) drylands of northwest China; c) mainland Southeast Asia; and d) Himalayan areas of South Asia. The water tower and its river basins straddle some of the world's poorest regions, densely populated human settlements, and rapidly growing economies, particularly China and India. Within these populations and communities, the impacts of climate change are not evenly distributed, in either intensity within the region or among different sectors of society. The more fragile the ecosystem and the poorer and more marginalised the people, the earlier and greater the impact. This is inevitable unless concerted and effective action is taken to engage and assist them to cope with the changes.

Continuing climate change is predicted to lead to major changes in the strength and timing of the Asian monsoon, inner Asian high pressure systems, and winter westerlies, the main systems affecting the highland climate. The impacts on river flows, natural hazards, and the ecosystem, as well as on people and their livelihoods, are likely to be dramatic, although not the same in rate, intensity, or direction in all parts of the region. Given the current state of knowledge, determining the diversity of impacts is a challenge to researchers and risk assessment is needed to guide future actions.

Hydroclimatological Conditions

Hydroclimatological conditions vary more sharply with elevation in the highlands and over shorter distances than they do with latitude and longitude. The average total annual precipitation on the highland Tibetan Plateau is about $8{,}498x10^8m^3$, more than 80% concentrated in elevations between 3500-5000masl (see table 4).

Mean temperatures, for example, decline about 1^oC per 160m of elevation, compared with about 1^oC per 150 km by latitude (Hartman 1994). Precipitation in

Table 3: Principal Rivers of Highland Asia – Basic Statistics

	River		River basin			
	Mean discharge (m^3/s)	**Glacial melt in river flow** (%)	**Area** (sq.km.)	**Population** x1000	**Population density**	**Water per person** (m^3/year)
Indus	3,850	44.8	1,263,000	178,483	165	830
Ganges	15,000	9.1	1,075,000	407,466	401	~2,500
Brahmaputra	19,824	12.3	940,000	118,543	182	~2,500
Irrawaddy	13,565	Small	413,710	33,097	80	18,614
Salween	1,494	8.8	271,914	5,982	22	23,796
Mekong	15,948	6.6	805,604	57,198	71	8,934
Yangtze	35,000	18.5	1,970,000	368,549	214	2,265
Yellow	1,365	1.3	944,970	147,415	156	361
Tarim	146	40.2	1,152,448	8,067	7	754
Total				**1,324,800**		

Source: adapted from Xu et al. (2007) based on IUCN/IWMI, 2002; Chalise and Khanal 2001; Merz 2004.

Table 4: Precipitation distribution with elevation on the highland Tibetan Plateau

Elevation (masl)	**Annual rainfall ($10^8 m^3$)**	**Per cent (%)**	**Energy potential (10^4J)**
Above 5,000	485.9	5.72	2,035.8~2,274.4
4,500~5,000	3,790	44.6	12,999~14,857
4,000~4,500	543	6.39	1,596~1,863
3,500~4,000	2,480	29.2	6,076~7,291
3,000~3,500	294	3.47	576~720
Below 3,000	905	10.65	1,115~1,559
Total	8,497.9	100	

Source: Lu et al. 2004

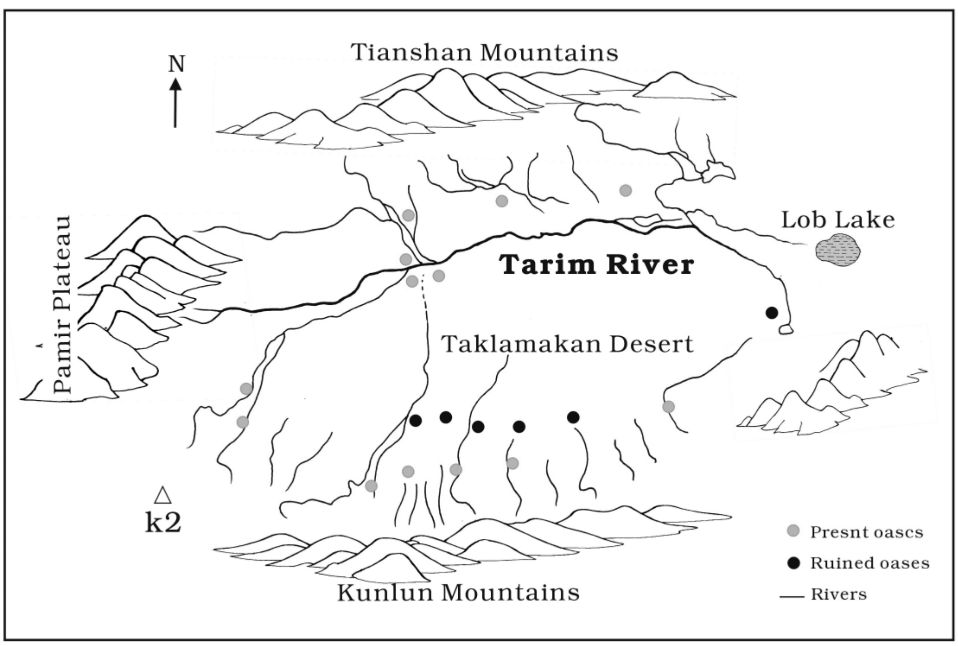
highland Asia shows an east-west and north-south variation on the macroscale. The east-west variation is based on the dominance of different weather systems. In the western Tibetan Plateau air masses connected to the westerlies bring moisture during winter leading to a winter peak in rainfall. The eastern highland is influenced by the southwest monsoon with a dominant maximum during summer. The maximum rainfall in the area and globally is measured in Cherapunjee, northeast India with annual maxima of more than 10,000mm. The monsoon rainfall is mainly orographic in nature, which causes distinct variations in rainfall with elevation and distinct differences between the southern rim and the rain shadow areas of the Tibetan Plateau behind the main mountain range. Alford (1992) identified the lower and intermediate altitudes as the main sources of precipitation suggesting that there is an increasing trend with altitude up to about 3500 m after which rainfall again decreases. On the mesoscale, climatic effects are driven mainly by local topographic characteristics such as ridges, slopes, valleys, and plateaux (Chalise 2001). According to Domroes (1978) the valley bottoms of the deep inner valleys in the highlands receive much less rainfall than the adjacent mountain slopes. This would suggest that the current rainfall measurements, which are based mainly on measurements in the valley bottom, are not representative for the area and major underestimations result from the use of these data. The impacts of climate change, therefore, are expected to intensify in mountain areas, and they are considered to be unique areas for detection of climate change and related impacts (Beniston 2003), but with an uncertainty due to limited numbers and poorly represented geographical locations. The broad predictions of global climate change, especially the emphasis on shifts in mean temperature, do not take into account important regional complexities related to the effects of topography and elevation in the mountains. If climate change mainly involves vertical shifts in precipitation and thermal conditions, ruggedness, elevation, and orientation will also modify the significance of regional climate changes. The highest mountains, or those facing or funnelling the prevailing winds, may retain a substantial, if diminished, glacial cover, whereas lower watersheds or those less favourably oriented may lose theirs.

Water Storage in the Highlands

Seventy per cent of the world's fresh water is frozen in glaciers. Highland Asia has the largest concentration of glaciers outside the polar caps. Several of the largest concentrations of glaciers are found at middle and low latitudes, covering a total area of 112,767 sq.km. (Xu et al 2007). Mountains and plateaux often have greater precipitation and water storage capacity in terms of glaciers, ice, and snow as well as large proportions of lakes and wetlands. Mountains provide a proportion of 20-50% of total discharge in the humid areas, while in arid areas, the contribution of the mountains, particularly from melting glaciers, to total discharge amounts to from 50-90% with extremes of over 95% (Viriroli and Weingartner 2002). Melting glaciers provide 40. 2% the river flow in the Tarim Basin, up to 50-80% in the upstream catchment (Yan et al. 2007, Chen et al. 2003) (see map 2). The highly glaciated Tarim Basin supplies about 137.7x10^{8}m^3 of fresh water from melting glaciers to areas downstream each summer (Yao et al. 2004). The discharge from highland Asia is an extremely reliable water resource and causes a significant reduction in the variability of total discharge.

Glaciers, Snow, and Ice

In the highlands, a substantial proportion of the annual precipitation falls as snow. Snowfall builds up from year to year to form glaciers that provide long-term



Map 2: Melting glaciers provide vital fresh water for people and ecosystems along the Tarim River in Xinjiang, the most arid basin in Asia (Illustrated by Yang Jiankun)

reservoirs of water stored as ice and function as regulators for stream and river runoff from mountain watersheds. Most commonly glaciers are thought to delay runoff by preventing precipitation from running off directly. Such storage occurs on a sub-seasonal and sub-daily basis and involves both factors associated with snow accumulation and melt on the glacier and the water-storing capacity and characteristics of the glacier (Jansson et al. 2003). Storage and release of water from glaciers are important for ecosystems, food production, and industrial development (e.g., hydroelectricity) irrigation; flood forecasting, sea-level fluctuations, glacial dynamics, sediment transport, and formation of landforms. The Asian highlands have a large concentration of glaciers with coverage of 112, 767 sq. km. (Dyurgerov and Meier 2005, Xu et al. 2007), with wetland coverage of 107,948 sq. km. (Li et al. 2007). China's glaciers cover a total area of 59, 406 sq.km., the fourth largest coverage in the world after Canada, Russia and United States; of them, 48% are located within the Tibetan Autonomous Region (TAR), including 21% of China's total glacier located inside of upper Brahmaputra River Basin, Tarim Basin in Xinjiang has 33.5% of total China's glacier (Wang and Liu, 2001). It has a total water storage capacity of 559 billion cubic km., which provides an average of 56.3 billion cubic km. of fresh water from melting glacial waters (glacial melt) annually. The annual amount of fresh water from melting glacial waters from the Tibetan Autonomous Region (TAR) accounts for 60% of the total for China (Yao et al, 2004, Shi, 2001).

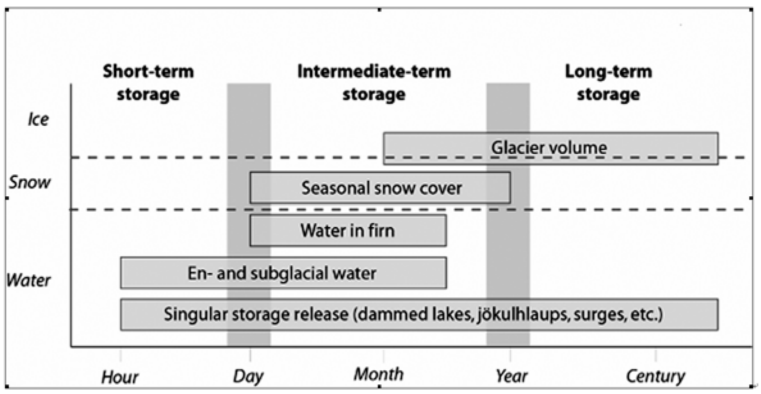


Figure 2: Glacial water storage (after Jansson et al. 2003)

Climate controls river flow and glacial mass balance in the Asian water tower, and these vary considerably from west to east. The monsoon from the Bay of Bengal, further developed in the Indian subcontinent, produces heavy precipitation; and this is predominantly in the southeast of the Tibetan Plateau. The monsoon weakens from east to west of the highlands, penetrating northwards along the Brahmaputra River into the southeast Tibetan Plateau, rarely penetrating as far as the Karakoram (Hofer and Messerli 2006, Rees and Collins 2006). Water from both permanent snow and ice and seasonal snow packs is released by melting, giving a distinct seasonal rhythm to annual stream flow regimes. Glaciers undergo winter accumulation and summer ablation in the west, but predominantly synchronous summer accumulation and summer melt in the east. The main melting occurs in high summer but, when this coincides with the monsoon, it may not be as critical for water supply as when the melting occurs in the shoulder seasons: spring and autumn. When the monsoon is weak, delayed, or fails, melt water from snow and ice may limit or avert catastrophic drought.

The contribution of snow and glacial melt to the major rivers in the region ranges from less than 5 to more than 45% of the average flow (see table 1). The rivers of Nepal that originate in the highland Tibetan Plateau contribute about 40% of the average annual flow of the Ganges Basin. More importantly, they contribute about 71% of the flow in the dry season (Alford 1992). Melting snow and ice contribute about 70% of the summer flow of the main Ganges, Indus, and Kabul rivers in the 'shoulder seasons' before and after precipitation from the summer monsoon (Kattelmann 1987, Singh and Bengtsson 2004, Barnett et al. 2005). The contribution to inner Asian rivers, such as the Tarim, is even greater, more than 40%. The Indus Irrigation Scheme in Pakistan depends on approximately 50% of its run-off originating from snowmelt and glacial melt from the eastern Hindu Kush, Karakoram, and western Himalayas (Winiger et al. 2005). Glacial melt provides the principal water source in dry season for 23% of the population living in western China (Gao and Shi 1992). The contribution to the Mekong and Salween is less than 10% in the eastern highland region, the monsoon predominant sub-tropics, and the tropics.

High Altitude Wetland

Highland Asia has a wide variety and coverage of wetlands; and these include peat lands, lakes, and river systems. They are an important feature of the Asian water tower and provide water resources, maintain hydrological cycles, and serve as carbon sinks. Ruoergain Peatland, situated at the headwaters of Yellow, Yangtze and Mekong, is the largest peat land in China and stores several billion metric tons of carbon. Little effort has been made, however, to understand wetland ecological dynamics and their hydrological processes and carbon cycling locally and regionally. Melting glaciers increase water levels and expand the wetland in the short term, and eventually cause the loss of wetlands and small lakes in the long term. The water level of Qinghai Lake has decreased at the rate of 0.769 metres per decade during the last 42 years (1961-2002). Some small lakes will eventually disappear as a result of high rates of evaporation and a decrease in rainfall, particularly on the western Tibetan Plateau. There is increasing global and regional concern about the vulnerability of high altitude wetlands to climate change and human activities. There are not only many examples of wetlands disappearing and decreasing water levels, but also there are examples of wetlands evolving and expanding which have brought significant changes to hydrological processes such as buffers for floods, groundwater recharge, and river flow. High-altitude wetlands have, therefore, become important elements in conservation and water management at national, regional, and international levels with good examples of Himalayan initiatives. According to a Chinese government inventory of high-altitude wetlands in China, there is a total area of 92,466 sq.km. of wetland at altitudes above 3000 masl, and these are found mostly in the Tibetan Autonomous Region, Qinghai, Xinjiang, Gansu, Sichuan, and Yunnan (table 5). The high-altitude lakes, situated mainly between 4000-5000 masl, cover a total area of 38,727 sq.km. and have a storage capacity of $5,46010^8 m^3$, accounting for 73% of the total for China (Lu et al. 2004).

Table 5: High-altitude Wetland in China (over 3000 masl)

Wetland type	**Area （sq. km.）**						**Total area of high altitude wetland**
	Tibet	Qinghai	Xinjiang	Gansu	Sichuan	Yunnan	
Freshwater lake	5,693	2,486.75	380. 50	90	64.42	34.20	8,748.87
Saltwater lake	19,424.37	8,746.29	1,807.18				29,977.84
Marsh	5,404		275. 05	4,100	3,415.19		13,194.24
Swampy meadow & peat lands	16,814	19,014		250		4.10	36,082.10
Inland salt marsh	2,399						2,399
River wetland	11	1,012.46		1,040			2,063.46
Total	49,745.37	31,259.50	2,462.73	5,480	3,479.61	38.30	92,465.51

Source: Ramsar Convention Implementing Office State Forestry Administration, China, 2005