Mountains of the World: Water Towers for the 21st Century

Foreword

Water is life. It is essential for all aspects of our livelihood, from basic drinking water to food production and health, from energy production to industrial development, from sustainable management of natural resources to conservation of the environment. Water is also a vital part of our religious and cultural values.

Unfortunately, water is becoming scarce in many areas and regions of our planet. The latest data from the World Water Council's *Report on Sustaining Water* show clearly how alarming the situation is. The report calls for immediate and effective action in order to maintain freshwater availability in the coming century. This is an endeavour of global proportions – a challenge which must be confronted by the whole of humankind.

In *Mountains of the World*, our contribution to the Commission on Sustainable Development and to the special session of the UN General Assembly in 1997, Rio Plus Five, we briefly showed the vital, global role mountains play in supplying water and in regulating river flows. This report also revealed the linkages between upstream and downstream developments.

The present publication, *Mountains of the World: Water Towers for the 21st Century,* elaborates further on the interrelationship between mountains and fresh water. Although many in-depth hydrological studies have been carried out, a global overview of the contribution mountains make to the supply of water to humankind has been notably absent. This publication presents a compilation of case studies, together with an overview of the important role of mountains in supplying fresh water to the world, and a summary of the main challenges to be faced in maintaining these water towers for the 21st century.

This report is a small contribution to Chapter 13 on mountains, and Chapter 18 on water in *Agenda 21*. It is intended to create a better understanding of the linkages between water and mountains and to foster the need for recognition of the important role mountains play in the water cycle. It highlights the necessity of strong stewardship by mountain populations as well as the responsibility of downstream communities and nations for the sustainable management of mountain water resources.

In addition, we sincerely hope that this report will promote the necessary initiatives and actions required to sustain water availability in the next century and to maintain and enhance the role of mountains as water towers for humanity.

Walter Fust

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Rationale

Several research programmes on mountain ecosystems were initiated in the 1970s, including UNESCO's MAB project No. 6, *Impact of Human Activities on Mountain Ecosystems* in 1973, and the UNU's programme on *Highland-Lowland Interactive Systems* in 1978. This was followed, in 1981, by the founding of the International Mountain Society, which produces the scientific periodical *Mountain Research and Development*. In 1992, during the UNCED Earth Summit in Rio de Janeiro, the world's mountains finally received some attention at the highest level. This was expressed formally with the inclusion of Chapter 13 in Agenda 21: "Managing Fragile Ecosystems – Sustainable Mountain Development."

After 1992, the UN Commission on Sustainable Development appointed the FAO as task manager for the mountain chapter. Through an unprecedented level of collaboration among UN agencies, national governments, international organizations, NGOs and research institutions – again with the support of the Swiss Agency for Development and Cooperation – a comprehensive report, *Mountains of the World: A Global Priority,* and a companion policy document, *Mountains of the World: Challenges for the 21st Century,* were presented to the special session of the UN General Assembly, Rio Plus Five, in 1997. In all these documents it was made very clear that mountains as water towers for humankind must receive highest priority in the 21st century and be given serious consideration by the Commission on Sustainable Development at its spring 1998 session on "Strategic Approaches to Freshwater Management".

The present document highlights the current and future importance of mountains in global freshwater supply. It is a contribution to the discussion on the role of mountains in the world. Due to a shortage of data from mountain regions, no global quantitative assessment is possible. However, case studies have been collected from different parts of the globe for this report, which presents a first global overview in the form of an illustrated map. In conclusion, the report highlights the challenges to be faced in maintaining the role of mountains as water towers.

Mountains of the World: Water Towers for the 21st Century is an initial global assessment of mountain freshwater resources. It aims to create the scientific interest and the increased political awareness necessary as a basis for concrete measures to promote sustainable management of mountain water resources.

Mountain water – a source of life. (Photo: H.P. Liniger)

Why focus on mountain waters?

All the major rivers in the world have their headwaters in mountains. More than half of humanity relies on the fresh water that accumulates in mountains – for drinking, domestic use, irrigation, hydropower, industry and transportation. Mountain areas constitute a relatively small proportion of river basins, yet they provide the greater part of the river flows downstream. These "water towers" are crucial to the welfare of humankind. As demand increases, the potential for conflict over the use of mountain water grows. Careful management of mountain water resources must therefore become a global priority in a world moving towards a water crisis in the next century.

There are many reasons why we need to focus on mountains. The most important are:

High precipitation levels

Mountains form a barrier to incoming air masses. Forced to rise, the air cools and precipitation is triggered. This phenomenon is known as the orographic effect. Rainfall thus generally increases with altitude (from 5 mm/100 m to 750 mm/100 m elevation, depending on the climatic zone), reaching maximum values between 1500 and 4000 m altitude. In semi-arid and arid regions, mountains are the only areas with sufficient precipitation to generate runoff and groundwater recharge. Colder temperatures at higher altitudes result in lower evapotranspiration rates so that the overall water balance in the mountains is positive. In the surrounding lowlands, with less precipitation and high evapotranspiration rates, the water balance is frequently negative. This imbalance is smoothed by rivers connecting the highlands with the lowlands.

Storage and distribution of water to the lowlands

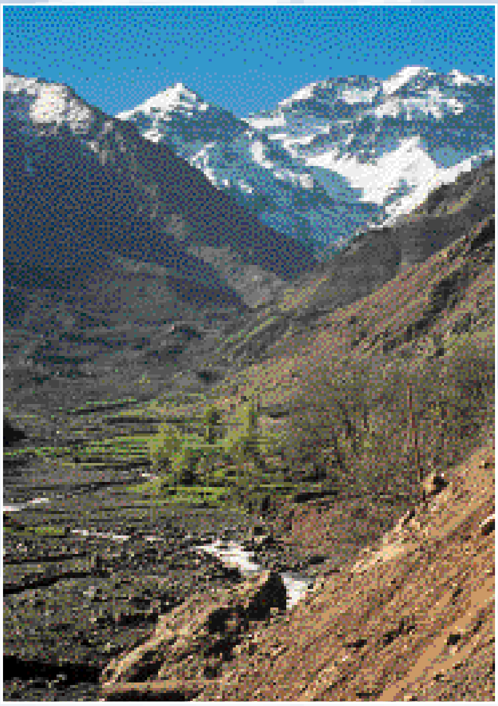
Mountain waters captured at high altitudes are carried under gravity via the stream network or groundwater aquifers to the lowlands, where the water demand from population centres, agriculture and industry is high. The distance covered can be hundreds to thousands of kilometres. Thus mountains naturally help to distribute water resources in space. In humid areas, the proportion of water generated in the mountains can comprise as much as 60% of the total fresh water available in the watershed, while in semi-arid and arid areas, this proportion is much higher (up to 95%).

With high elevation and cold temperatures, mountains have the capacity to store precipitation in solid form as snow and ice. During the summer or dry season, when temperatures rise, meltwater is released precisely at the time when precipitation is at a minimum and water demand, particularly for irrigation, is at a maximum. Therefore, the perennial flow of lowland rivers resulting from such seasonally delayed meltwater releases is indispensable. Although ice and snow in tropical, subtropical and mid-latitude mountains store

Mt. Parinacota and Laguna Chungará in the Chilean Andes. (Photo: M. Grosjean)

The Fedchenko Glacier in the Pamir Mountains provides water for irrigation in the Aral Sea Basin. (Photo: B. Messerli)

only 1% of the global freshwater resources (polar ice sheets store about 70%), this supply is vital because of its proximity to the areas of water demand. Mountains also store water in lakes and recharge groundwater bodies, similarly supporting lowland rivers in the dry season through delayed flow. Mountains thus help to distribute water not only in space, but also at the right time.



High Atlas, Morocco. Mountain waters from glaciers irrigate the semi-arid valleys downstream. (Photo: B. Messerli)

The life-sustaining role of water towers

Clean water is fundamental to human existence and health. Growing populations, intensifying agriculture and increasing urbanization and industrialization are leading to greater demands for water. Since 1940, global freshwater abstractions have more than quadrupled. Clean mountain water plays a major role in satisfying these growing demands. In some regions, however, the current demand for high-quality fresh water is already greater than existing supplies. If water resource development is restricted, a thorough management of demand (e.g. better water use efficiency) is required in order to avoid potential conflicts over the allocation of water between different users.

With 70% of total freshwater abstractions being made for irrigation, the dependency of world food production on mountain waters is evident. This is particularly important in the arid and semi-arid, monsoon (summer precipitation) and Mediterranean (winter precipitation) climates of the tropics and subtropics, where most of the developing countries and more than half of the world's population are located.

Water stored in mountain lakes and reservoirs has further economic value, given its potential as a source of hydroelectric power that can provide opportunities for the production of energy in a rapidly growing urbanized and industrialized world.

Mountain fresh water also sustains many natural habitats, both in the mountains and the lowlands, thus contributing to the conservation of biodiversity. Mountain parks and protected areas not only support the preservation of these habitats and their biodiversity, but also safeguard natural, undisturbed headwater catchments and thus the provision of clean, dependable water supplies.

Fragile ecosystems

Mountains are highly fragile ecosystems. High rainfall, steep slopes, and erodible soils can induce high surface runoff, soil erosion, and landslides. High-velocity rivers in headwater catchments can carry large amounts of sediment and deposit them downstream. Eroded sediments are the major pollutant of surface waters. Deforestation of mountain woodland, land use change, mining, construction of infrastructure, agriculture, and tourist activities in mountain areas may significantly affect the quantity and quality of river water. These human activities may increase surface runoff and lead to accelerated soil erosion and floods. Thus, careful management of the mountainous part of watersheds must have highest priority with regard to global freshwater resources.

Conflicts over water

Mountains deliver water to wide areas in the surrounding lowlands, where it often has to be shared between many communities or, in the larger basins, different countries. World-wide, 214 river basins, host to 40% of the world's population and covering more than 50% of the Earth's land surface, are shared by two or more countries. Transboundary water flows can create political tensions, as exemplified by the Nile, Jordan, Euphrates and Ganges rivers. The distribution of water from mountains was the cause of 14 international conflicts over water resources noted in 1995. Conflicts over water can also arise at a smaller scale, between regions or highlands and lowlands within national boundaries.

"Sacred water"

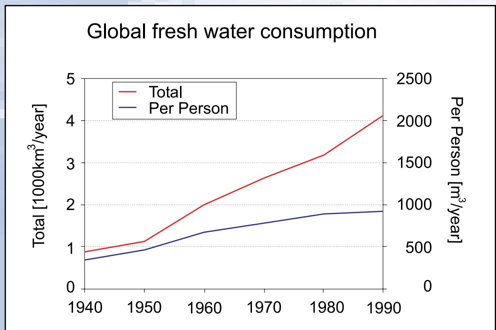
People throughout the world have always looked to mountains as the source of water, life, fertility, and general well-being. Mountains have been, and in some places still are, worshipped as the home of weather deities and as the source of clouds and rain that feeds springs, rivers and lakes on which societies may depend for their very existence. For example, in times of drought, the Kikuyu people faced Mount Kenya and asked the god Ngai for rain, while in China, villages traditionally had a temple dedicated to the local mountain deity responsible for clouds and rain.

The Kikuyu and Masai people living in the Mount Kenya area hold the traditional belief that God resides on the peaks of Mount Kenya, the sacred mountain of brightness. Special ceremonies were performed to ask the god Ngai for rain. (Photo: H.P. Liniger)

Inadequate resource management

In general, mountains to date have been treated as a resource to be used with little restriction. There has been inadequate hydrological monitoring and poor dissemination of the little data that do exist. This, together with an inadequate knowledge of mountain hydrology, insufficient consideration of highland-lowland interactions, and poor or lacking basin water resource management, can result in serious degradation of water quantity and quality. There is thus a great need to improve the current monitoring and management of mountain water resources.

It is estimated that in the year 2025, 35% of the global population is likely to suffer from water shortages.



Increase in global fresh water consumption (total and per person) from 1940 to 1990. In Europe, for example, this increase is a result of increasing individual consumption, whereas in Africa it is mainly due to population growth. (Data: World Resources Institute)

Case studies from Africa and the Middle East

The Nile Basin: an international challenge to mountain water management

In 1960, there were 60 million people living in the entire Nile Basin. By 1995, the total population increased to 140 million, and it is expected to reach 300 million by the year 2025. About half of the present population depends directly on irrigation. The lowland users, Egypt and Sudan, rely up to 97% and 77%, respectively, on the water resources generated in the headwaters of the nine upstream countries of the Nile Basin. This situation presents a major challenge to the international management of mountain waters.

Case study 1

People in the highlands: at present, 70 million people, i.e. about half the current population of the Nile Basin, live in the Ethiopian Highlands and depend mainly on rainfed agriculture. Land degradation in the headwater catchments has a dramatic impact on sediment transport and life support systems in the entire basin.

Two major mountain rivers, the Blue Nile and the Atbarah in the Ethiopian Highlands, together provide 53% (44.5 km^3) of the total annual water inflow into Lake Nasser (Aswan Dam) on the border of Egypt, and about 90% of the total sediment load, although occupying only 10% of the watershed. Much of the remaining inflow comes from the White Nile, particularly the marshes of the As-Sudd, which are fed from the mountains of south-western Ethiopia and the highlands of Uganda, Tanzania, Kenya, Burundi, Rwanda, and Zaire.

Conflicts over access to mountain water

The water balance in Sudan and Egypt is highly negative throughout the year. Both countries thus depend totally on water resources from the mountains in the upper part of the Nile watershed where the water balance is highly positive. Since 1891, several treaties have been introduced to prevent conflicts over access to the waters of the Nile. Three Nile agreements focused on sharing the water among the main users, Sudan and Egypt. The most important one was signed in 1959, shortly before the construction of the Aswan Dam was completed. According to this agreement, Egypt is to obtain 55.5 km^3, and the Sudan 18.5 km^3 of the Nile's water annually. Because Sudan has been using less than its agreed share, Egypt has been able to satisfy its growing demand and also fill Lake Nasser (the full storage capacity of 132.5 km^3 was achieved in 1996). The Aswan Dam was a

Three Nile treaties (1906, 1929, and 1959) dealt with water use in the lowland countries alone, the most important being the agreement of 1959 between Egypt and the Sudan. The Sudan used less than 70% of the amount agreed on in 1959, thus helping to mitigate the potential water crisis in Egypt due to reduced discharge in recent years and growing demand. The other three treaties (1891, 1902, and 1925) involved parties with interests in the highlands.

Major Nile Treaties

Year	Parties involved	River
1891	Britain, Italy	Atbarah
1902	Britain, Ethiopia	Blue Nile
1906	Britain, France, Italy	Blue Nile
1925	Britain, Italy	Blue Nile
1929	Britain, Egypt	Nile
1959	Egypt, Sudan	Nile

major achievement in the 1960s, allowing Egypt to retain a larger portion of the summer floods from Ethiopia, and use it over an extended period, instead of "losing" it to the Mediterranean Sea. Major concerns have been raised relating to the life-span of the reservoir, to environmental and development problems, and most recently, to the dam's impact on the regional climate.

Another three Nile agreements focused on highland-lowland dependency. Since these treaties, the highland countries have developed plans for the increased use of water resources in the mountains which, to date, have been under-utilized. Whereas small-scale irrigation schemes pose little threat to downstream users, larger projects must be carefully assessed with regard to water resources, mountain hydrology, and sediment transport. Large projects are thus observed with great concern by the governments of Sudan and Egypt.

> **"The next war in our region will be over the waters of the Nile, not over politics…"**
>
> **Boutros Boutros-Ghali, former foreign minister of Egypt and former UN Secretary General. (Quoted in: International Fresh Water Resources, 1997)**

The toll of land degradation on the Ethiopian headwaters

Any land use changes in the headwaters of the Nile Basin are of paramount importance to downstream irrigation. For example, land degradation in the mountains of Ethiopia has increased significantly in recent years due to expansion of agriculture, overgrazing, and subsequent soil erosion. This threatens both the local land users, through a reduction in soil productivity, and those living downstream in the lowlands, through sedimentation which has increased rapidly since the late 1960s. On average, sediment concentration in the Atbarah increased by 60% within 20 years, from 5 g/l in 1969/70 to 8 g/l in 1989/90. This will significantly reduce the original life-span of Lake Nasser.

Mountain sensitivity to climate change

Rainfall in the headwaters of the Blue Nile and the Atbarah River in the Ethiopian mountains decreased by 9% between a first observation period from 1945 to 1964, and a second period from 1965 to 1984. At the same time, runoff decreased by 25% due to changes in the water balance. The consequences for water availability are manifold, both in the mountains and in the lowlands. These changes may be more a phenomenon of climate oscillation and land use dynamics than an effect of climate change. However, it has been noted that mountains are very sensitive to short-term and long-term climatic changes. For example, Lake Victoria, in the headwaters of the White Nile, was completely dry during the last ice age, until 13,000 years ago.

Due to intensive agriculture and land degradation on the steep mountain slopes of Ethiopia, immense sediment loads are transported from the source of the Blue Nile to the lowlands.

In 1990, a planned African Development Bank loan to Ethiopia for a water development project which could have reduced the downstream flow was dropped due to disagreement between highland and lowland users.

People in the lowlands: about 70 million people depend on irrigated agriculture in the lower part of the Nile Basin, shown here at the confluence of the Blue and the White Nile near Khartoum. This number of water users will double by 2025. (Photos: H. Hurni)

Mount Kenya: a vital water tower in a semi-arid region

Mount Kenya (5199 m a.s.l.), the second highest mountain in Africa, located on the equator, provides water to over 2 million people. Increased water abstractions for irrigation in the highlands are reducing the amount of water flowing downstream to the pastoralists, ranchers and wildlife parks of the semi-arid lowlands, whose survival depends on this mountain water. Conflicts are increasing and there is an urgent need for management solutions.

Case study 2j

Rivers originating from the glaciers of Mount Kenya flow through the moorland to the forest belt, where rainfall is highest, and rivers and groundwater aquifers are recharged. 90% of the dry season flow of the Ewaso Ng'iro River is produced in the alpine zone, the moorland, and the montane forest belt (above 2400 m) of Mount Kenya. On the lower mountain slopes and in the foot zone, both the population and the cultivated area have more than tripled over the last 20 years and river water abstractions for irrigation have dramatically increased. Currently, 60% of the population of the Ewaso Ng'iro basin live in this area. The remaining 40% live downstream on the semi-arid plains and their livelihood depends on the use of water upstream.

Decreasing dry season river flows

The average flow of the Ewaso Ng'iro River (including tributaries from the Aberdare Mountains) during the dry season decreased from 9 m^3/s in the 1960s to 1.2 m^3/s in the 1980s, as ten times more water was abstracted for irrigation than was legally permitted. Consequently, the unique wildlife ecosystems of the Samburu and Buffalo Springs game reserves in the lowlands suffer during the drought period, as the river now dries up. This has a negative impact on tourism, the primary source of foreign exchange in the region. Nomadic pastoralists and their livestock, and the wildlife living in the lowlands, are drastically affected by the resultant water shortage. They are forced to move upstream in the search for water and grazing land. As a result, conflicts with farmers are increasing.

Changes in land use also have an impact on river flow and the quality of water. Removal of vegetation cover and intensified land use on the slopes of Mount Kenya have led to increased surface runoff during heavy storms, causing erosion and pollution of the surface water. Previously unknown flash floods have been recorded in recent years, flooding old farm houses and tourist lodges. As a result, there is less water stored in the mountains to feed the rivers during the dry seasons.

Left: Mt. Kenya: a forest belt and the semi-arid north-western slopes with irrigation fields.

Right: Searching for water and food for survival, elephants leave the national parks and move upstream, destroying crops and threatening people.

Monitoring rivers from the glacial and alpine zone of Mt. Kenya at 4200 m a.s.l. (Photos: H.P. Liniger)

Solutions

Monitoring of natural resources and their use, and assessment of the impact of land use change in the highlands on the availability and quality of water in the lowlands are the first steps towards successful water resource management. Another challenging step is to develop management tools which allow prediction of the impacts of future human activities upstream on the availability and use of resources downstream. Dissemination of the information gathered, together with the creation of awareness of water resource issues and the involvement of the different upstream and downstream users in water resource management, are prerequisites for improvement. The main challenges are the search for efficient use of the mountain water resources, equitable distribution of the scarce water, and effective water and land management and policing of water use to secure a stable water supply for the downstream users.

The moorland and forest belts receive the highest rainfall and have the lowest evaporation, resulting in a surplus of water. Thus, they provide the greatest contribution to river flow and groundwater recharge.
On the semi-arid plateau and in the arid lowlands where water resources are critically scarce during the dry season (water deficit), 90% of the Ewaso Ng'iro River flow comes from the montane belt (above 2400 m) of Mount Kenya. Due to excessive water abstractions upstream and high evaporation rates in the semi-arid lowlands, the rivers dry up and no longer reach the lower end of the basin in the dry season. (Figure: H.P. Liniger)

The Jordan River Basin and the West Bank aquifer: sharing mountain water resources in a politically sensitive arena

The Arab-Israeli conflict is primarily a security and territorial dispute. However, the issue of freshwater resources is traceable back to the beginning of the conflict and remains a major challenge to its resolution.

Case study 3j

In the arid Middle East, immense amounts of water are needed for irrigation. Throughout the region, between 60 and 90% of the fresh water is used in agriculture. Major areas of water recharge are (1) the Anti-Lebanon mountains, Mt. Hermon and the Golan Heights, where the headwaters of the Jordan and Yarmuk rivers rise, and (2) southern Lebanon and the hills of the West Bank, which form the recharge area of the most significant aquifer in the region. Of Israel's total water consumption, about 65% is supplied from these mountainous regions.

Control over the Jordan River's headwaters

Although the Jordan River measures only 230 km in length, it is shared by five parties, namely Lebanon, Syria, Israel, Jordan, and the Palestinians. Total discharge averages approximately 1.25 km^3 per year. This is divided almost equally between the upper Jordan Valley and the southern basin (including the Yarmuk River). Nearly all of the water in the northern basin (around 0.55 km^3 per year) is presently utilized by Israel. The southern basin water resources are shared unevenly between Syria, Jordan, and Israel. A lengthy dispute between Israel and Jordan over the water resources of this basin was settled in the 1994 bilateral peace treaty. This treaty entitles Israel to use the main flow of the upper Jordan River, and Jordan to use the Yarmuk River, and it identifies a number of common water projects. Meanwhile, conflicts persist between Israel, Syria, and Lebanon regarding control of the headwaters of the Jordan. Southern Lebanon and the Golan Heights, where two of the three headwater streams feeding the Jordan originate, remain disputed lands. The hydro-strategic importance of these mountainous areas is clear.

Use of the West Bank aquifer

A second water dispute concerns the aquifer underlying the West Bank. Precipitation over this hilly region is significantly higher than in the surrounding lowlands. The aquifer, which is bisected by the 1949 Armistice Demarcation Line, today primarily supplies both the adjacent Israeli lowlands and the Jewish settlements in the West Bank. According to figures prepared for the 1995 Oslo II Agreement, total Israeli abstractions average 0.483 km^3 per year, which corresponds to 71% of the aquifer's average yield, while Palestinian use averages 0.118 km^3 per year (17%), and 0.078 km^3 per year (12%) remains unutilized. The Oslo Agreements did not change this distribution, as discussion of water rights was postponed to a later stage of negotiation.

Sovereignty over the West Bank is a major political issue at the core of the unresolved Palestinian question. A settlement of the water dispute is certainly not the only condition for a resolution of the historical conflict, but it is nevertheless a fundamental one.

Left: Israel's National Water Carrier conveys most of the upper Jordan's waters to the population centres and agricultural projects in the south.

Right: The Jordan River, south of Lake Tiberias, upstream of the confluence with the Yarmuk. Following the abstraction of 90% of its natural flow, only a small stream remains.
(Photos: S. Libiszewski)

Case studies from Central Asia and Europe

Case study 4

The Aral Sea Basin: overuse of mountain water resources

In the 1960s, the Aral Sea in Central Asia, fed by the Tien Shan and Pamir mountains, was the fourth largest inland lake on earth. Today, the lake surface has been reduced to 50% of its former size. The "Aral Sea Crisis" is an ecological disaster that resulted from human-induced changes to the water cycle in the lowlands without adequate consideration of the impacts.

The mountain water resources

In Central Asia, the mountains receive significantly more rainfall (600 to 2000 mm) than the desert lowlands (below 100 mm/yr). The Tien Shan and the Pamir mountains provide 95% of the inflow to the Aral Sea, yet they occupy only 38% of the Syr Darya catchment and 69% of the Amu Darya catchment respectively. These mountain areas store large quantities of snow during the winter months, and later release meltwater to the lowlands during the summer. This hydrological regime supports agriculture in a dry area; today there are 32 million people living in the basin. The meltwater peak during summer coincides with the growing period of cotton (the main crop). Thus storage capacity and seasonal regulation of streamflow in the mountains are vital for the ecological and socio-economic welfare of the downstream users.

The crisis

Large diversion projects introduced after World War II aimed to promote irrigated crops, particularly cotton, for export. Today, 8 million hectares (90% of the cultivated land) are irrigated, and the storage capacity of artificial reservoirs in the upper course of the Amu Darya and Syr Darya rivers amounts to 117 km^3 (about 10% of the 1960 volume of the Aral Sea). In 1985, direct water flow from the two mountain rivers into the Aral Sea ceased for the first time. The impact of the immense water diversions has been devastating. Today, the inflow to the Aral Sea has been reduced to 6% of its former rate, the lake surface has decreased to 50% of its former area, and the volume of water to 44% of its previous level. 266 invertebrates, 24 fish species, and 94 plant species have become extinct, the salinization of irrigated land has caused massive reductions in yields, wind erosion has contaminated the atmosphere and covered cropland with lake sediments, and agricultural pesticides have polluted the potable water supply. As a result, in some locations, the human mortality rate increased by a factor of 15, while around the lake, thousands of jobs were lost.

In 1908, Wojekow, a noted scientist, predicted that the expansion of irrigated land would, from a financial point of view, more than compensate for the disappearance of the Aral Sea.

Left: 95% of the freshwater resources in the Aral Sea watershed are generated in mountains. The mountains store winter precipitation in large glaciers, and release meltwater in the dry summer season. Monitoring of mountain hydrology in remote places, such as at this station on the Fedchenko Glacier at 4300 m (Pamir Mountains), is extremely costly, but of crucial importance when mountain water resources are used. The network of monitoring stations in mountains world-wide is inadequate. (Photo: B. Messerli)

Right: Massive abstraction of river water for irrigation over the last 35 years has resulted in a significant reduction of inflow to the Aral Sea and consequently in a reduction of the lake's surface area. (Photo: M. Spreafico)

The Alps: the water tower of Europe

The Swiss alpine section of the Rhine River (to Basel) covers only 23% of the total catchment area (160,000 km²), but contributes on average 50% (1000 m³/s) of the total discharge to the North Sea. Switzerland thus has a great responsibility to ensure the passage of high-quality water to the countries downstream.

Case study 5j

The water resources

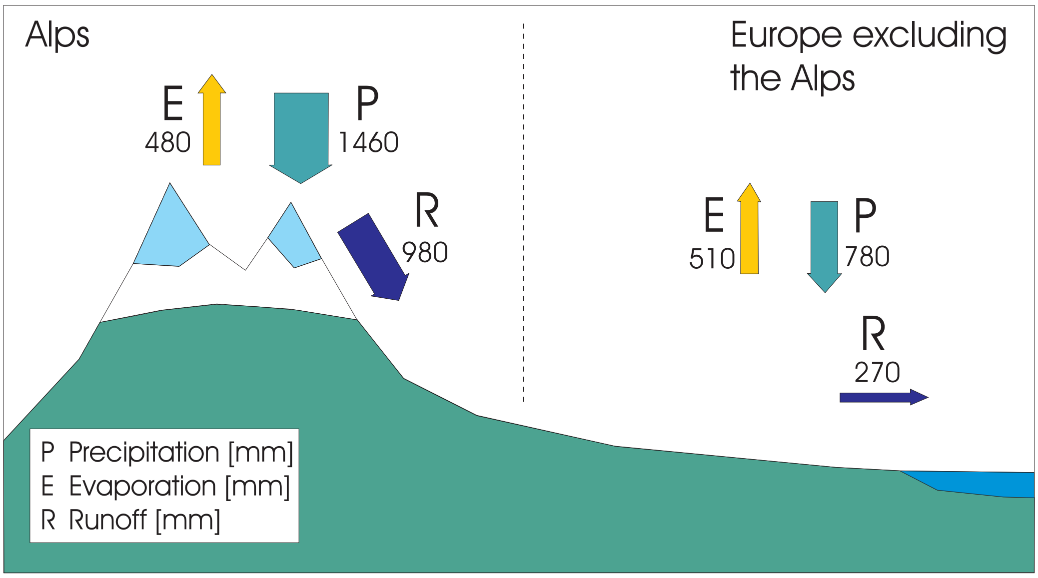
The contribution of Swiss mountains to the flow of the Rhine in the Netherlands is disproportionally large, varying seasonally from 30% in winter to 70% during summer, when streamflow is minimal in the lowland rivers, but high in the alpine rivers due to snow- and icemelt. Similarly large contributions to the annual flow are observed in the Rhone River (32% of the mountain area contributes 47% to the lowland flow) and the River Po (32% of the mountain area contributes 56% to the lowland flow).

With regard to water resources, the importance of the alpine region is primarily based on enhanced precipitation due to the orographic effect. A large proportion of the precipitation falls as snow at higher altitudes, and may form glaciers, which are key features of mountain hydrology. Due to these conditions, alpine catchments are characterized by much higher annual mean discharge per area (more than 30 l/s per km²) compared to catchments in the Central European lowlands (about 10 l/s per km²).

Water quality

A reliable and steady supply of high-quality fresh water is a matter of concern for the eight countries in the Rhine basin, particularly for the downstream users. In 1963, the International Commission for Protection of the Rhine against Pollution (ICPRP) was established, to assess the water quality of the basin and to promote technical and scientific collaboration and integrated political solutions to reduce pollution and improve the water quality of the river. The members of the ICPRP signed the "Convention for the Protection of the Rhine against Chemical Pollution" in 1976, and agreed to the "Rhine Action Programme" in 1987.

Switzerland, as the mainstay of the alpine water tower, with a dominant influence on the Rhine and thus a great responsibility to ensure the passage of high-quality water downstream of its borders, embarked on a series of restorative measures. A programme of water treatment works construction initiated in the 1960s stopped the trend toward deterioration in the water quality of the Rhine and improvement followed. In 1986, a ban on the use of phosphate-based washing powders had a dramatic impact on the phos-



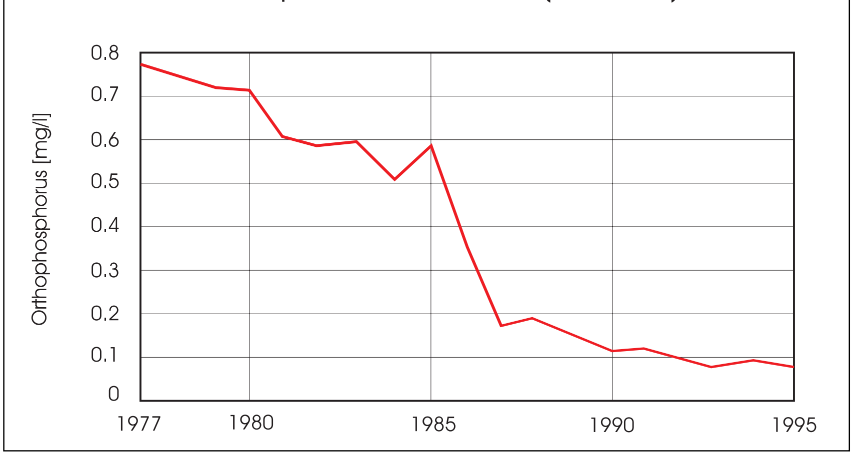
Annual water balance of Europe, showing the dominant influence of the Alps in producing runoff. (Data: A. Baumgartner et al.)

Within Switzerland, 136 km³ of water is stored in lakes and reservoirs, and another 74 km³ in alpine glaciers. Altogether, this storage is five times the total annual river outflow from Switzerland. (Photo: M. Grosjean)

phate content of the Rhine water leaving Switzerland, further improving the quality of river water.

Demands on the Rhine

Many population centres in the Rhine basin depend on the Rhine for their water supply. For example, the 4 million inhabitants of the German state of Baden-Württemberg abstract 4.4 m^3/s for domestic purposes from Lake Constance, a high-quality source fed by the alpine Rhine. Such a demand can be easily met from a mean Rhine discharge of 360 m^3/s. However, hypothetically, the Lake Constance distribution network could be extended to serve an area of about 100 million people in Central Europe (including those already abstracting from the poorer quality downstream Rhine), for which water abstractions of approximately 110 m^3/s would be needed. Depending on the season, this amounts to between 18 and 50% of the mean monthly flow of the alpine Rhine. At first glance, the huge potential of the alpine Rhine is revealed. However, this potential is not without restriction. Abstracting such large quantities from a point so high on the Rhine would have a great impact on downstream interests. Less water would be available for the dilution of wastewater and for infiltration from the river channel to the groundwater aquifers, shipping routes would be hindered, and downstream ecosystems threatened.



Change in phosphorus concentration between 1977 and 1995 in the Glatt River, a tributary of the Rhine near Zurich. Phosphate concentrations in surface waters have declined in recent years, owing to elimination of phosphorus in sewerage treatment facilities and the ban on phosphates in washing detergents that has been in effect since 1986.
In catchment areas under intensive agricultural use, however, phosphates still drain readily into river water (surface runoff, erosion).
(Data: Swiss Agency for the Environment, Forests and Landscape)

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On average, mountains in humid areas provide 30 to 60% of downstream fresh water, while this figure rises to 70 to 95% in semi-arid to arid environments.

Explanations for previous double page

The previous double page presents a global map with the locations of the case studies presented in this report. For selected rivers, graphs illustrate the importance of the mountain areas in contributing to the total river flow in the lower part of the basins. With the data available, it is difficult to separate the contribution of the mountains. In most of the cases, not all of the tributaries from the mountains are recorded. Therefore, the figures provided do not show the full extent of the mountain contribution to the lowland river flow. Furthermore, the lowland flows provided were not always measured at the mouth of the rivers. Nevertheless, the following examples illustrate the importance of mountains as water towers (in alphabetical order):

Euphrates
The mountains of the Euphrates watershed generate the water that is used in the Mesopotamian lowlands (Syria and Iraq). The consumption in the lowlands shows the great dependency of the lowlands on external water resources.

Indus
The water from snow- and icemelt in the Karakorum, Hindu Kush and Himalaya is used for extensive irrigated agriculture in the arid lowlands. The peak flow in August is the result of the monsoon rainfall (see case study 6).

Mekong
The river flow from the mountains is of vital importance in the pre-monsoon season, contributing about 40 to 50% of the total flow. The downstream wet season flow is dominated by the monsoon rains and is mainly provided by the lowland watersheds (see case study 8).

Niger
The peak runoff from the mountains and highlands of Guinea and Ivory Coast coincides with the rainy season (July to October). The Niger River transports the mountain water to the semi-arid Sahel lowlands, where this vitally important water is used during the cropping season from June to November. As a result of the great distance between the mountains and the lowlands, the river flow in the lowlands is delayed by weeks or even months.

Nile
All the mountains in the Nile watershed, including the White Nile, provide three times more water than the river flow near Cairo. During summer mountain water is stored in Lake Nasser. It is used for irrigation and energy production, and to provide a steady flow downstream (see case study 1).

Rhine
The example of the Rhine River clearly illustrates the importance of snow- and icemelt during spring and summer for the water supply of Central Europe (see case study 5).

Rio Grande
The lowlands in the Rio Grande watershed depend greatly on the water towers of the Rocky Mountains and Sierra Madre Oriental. Due to consumption and high evaporation rates, the water balance in the lowlands is negative, but it is smoothed by the contribution of mountain waters.

Rio Negro
The water balance in the lowlands of the Rio Negro is negative throughout the year. Therefore, the headwaters from the Andes (occupying about 60% of the basin) play a key role in the water supply to the arid lowlands.

Saskatchewan
The Rocky Mountains of Canada occupy only 17% of the Saskatchewan basin, but generate 43% of the annual flow in the lowlands, and 80% of the flow during the summer (compare with case study 11).

Syr Darya
In the Syr Darya basin, massive water abstraction for the irrigation of cotton has dramatically changed the hydrological regime, which is characterized by snow- and icemelt. The water flow depicted in the lowland was observed in the middle course and not at the mouth to the Aral Sea, where the impact would be much greater (see case study 4).

Major river basins of the world

River	Continent	Mean discharge (m^3/sec)	Drainage area (km^2)	International basins
Amazon	S. America	180,000	7,180,000	Yes
Congo	Africa	42,000	3,820,000	Yes
Mississippi	N. America	17,500	3,220,000	Yes
Ob	Asia	12,600	2,975,000	Yes
Nile	Africa	1,585	2,880,000	Yes
La Plata/Paraná	S. America	19,500	2,650,000	Yes
Yenisey	Asia	19,600	2,600,000	Yes
Niger	Africa	5,700	2,090,000	Yes
Amur	Asia	12,500	1,855,000	Yes
Zambezi	Africa	2,600	1,330,000	Yes
Indus	Asia	3,850	1,263,000	Yes
Orinoco	S. America	28,000	1,085,000	Yes
Ganges	Asia	15,000	1,075,000	Yes
St. Lawrence	N. America	10,400	1,030,000	Yes
Orange	Africa	349	1,020,000	Yes
Brahmaputra	Asia	20,000	940,000	Yes
Yukon	N. America	7,000	855,000	Yes
Euphrates-Tigris	Asia	1,459	810,000	Yes
Danube	Europe	5,450	805,000	Yes
Mekong	Asia	15,900	795,000	Yes
Rio Grande	N. America	101	670,000	Yes
Colorado	N. America	168	630,000	Yes
Chari (Lake Chad)	Africa	1,268	600,000	Yes
Huang He	Asia	1,365	445,000	Yes
Rhine	Europe	2,201	160,000	Yes
Song-Koi	Asia	3,900	120,000	Yes
Lena	Asia	16,400	2,490,000	No
Yangtze	Asia	35,000	1,970,000	No
Mackenzie	N. America	7,500	1,805,000	No
Volga	Asia	8,000	1,380,000	No

What role do mountains play in determining the quality and quantity of fresh water in the major river basins of the world? Further investigations are urgently needed!
(Data: JRO 1981, World Resources Institute 1992)

Case studies from Asia

The Indus River: mountain water for the world's largest irrigation network

Case study 6

Ninety per cent of the lowland flow of the Indus River originates in the high mountains of the Hindu Kush, Karakorum and Western Himalaya. Three-quarters of this water is used for irrigation in the world's largest irrigation network.

Freshwater contribution from the mountains

Although published figures differ significantly, it can be concluded that some 90% (between 5600 and 6700 m^3/sec) of the mean annual flow into the Indus basin originates in the front ranges and high mountains of the Hindu Kush, Karakorum and Western Himalaya. The contributions of the main rivers measured at the foot of the mountains are 13% from the Kabul, 37% from the Indus, 14% from the Jhelum, 15% from the Chenab, 4% from the Ravi, 7% from the Beas and 10% from the Sutlej. Less than 10% of the average runoff is the result of rainfall over the Indus plains.

The runoff reflects the seasonal rainfall and snowmelt regimes of the mountain watersheds. The foothills and front ranges are predominantly exposed to seasonal monsoon rains, leading to runoff peaks from June to September, which produce some 70% of the total annual runoff of the Indus. Up to 40% of the central parts of the Karakorum are covered by ice. Snowfall in the high mountains, at altitudes above 4000 m a.s.l., is on an average equivalent to more than 2000 mm of rainfall annually. This contrasts greatly with low rainfall in the plains (less than 200 mm per year) and within the deeply incised mountain valleys (less than 120 mm per year).

Mountain water for irrigation

Most of Pakistan's 130 million inhabitants depend on the largest interlinked irrigation network in the world, which is fed by the Indus and its tributaries. Only 25% of the country's surface is arable land – of which around 135,000 km^2 is under irrigation and only some 65,000 km^2 is suitable for rainfed agriculture. The complex irrigation system is based on three major reservoirs, approximately 20 barrages, 12 inter-river link canals, and nearly 60,000 km of main canals. This irrigation network plays a prime role in smoothing the difference between peak summer runoff during monsoon and winter runoff. Roughly three-quarters of the river flow remains within the irrigated area, and only some 25% of the mountain runoff finally reaches the Arabian Sea as system outflow. It should be noted, however, that occasional severe monsoon storms can cause major flood catastrophes in the lowlands.

The Indus Water Treaty (1960) between India and Pakistan (and Pakistan's provinces) is the main contractual basis for the "Indus Basin Plan". The resulting infrastructure for irrigation schemes and energy production became one of the main pillars of the countries' economies.

Meltwater from snow irrigates the lower arid slopes of the Hunza Valley. (Photo: M. Winiger)

The Himalaya: responsible for floods from local to continental scale?

It is a common assumption that the floods in Bangladesh are caused by deforestation and other human activities in the Himalaya. While the Himalayan mountains provide crucial baseflow support to the downstream lowlands during the dry season (see case study on the Indus), they do not appear to have a significant role in the generation of floods in Bangladesh.

The Himalaya plays a key role in providing the baseflow of the Ganges and the Brahmaputra, and thus in supporting the irrigation needs and shipping routes of India and Bangladesh. However, the available river flow data are not sufficient to quantify the contribution from the mountains to the lowlands. Furthermore, existing data are not always made available to regional or global data centres.

The perception

With both the Ganges and the Brahmaputra flowing through several countries, "blame" for the floods in Bangladesh has become a geopolitically sensitive matter. There was and still is a common perception that the floods in Bangladesh are caused by forest removal and other human activities in the Himalaya. The question of to what extent the flood processes are natural and to what extent they are influenced by human activities in the highlands has aroused passionate discussions among scientists and politicians.

The "reality"

Recent studies have indicated that floods in Bangladesh and India are largely independent of human activities in the Himalaya. Neither the frequency nor the volume of flooding has increased in Bangladesh over the last 120 years. Precipitation and runoff in the Himalaya do not seem to be important causes of the floods in Bangladesh.

An extraordinary rainfall event on 19/20 July 1993 over eastern and central Nepal had catastrophic effects locally, with several districts hit by floods and landslides. However, the water level of the Ganges recorded at Hardinge Bridge, located near the India-Bangladesh border, showed no dramatic influence. The flood flow of the Nepali tributaries had levelled off during passage from the hills through the plains. It is thus clear that a very extreme flood event in the Himalaya of Nepal has catastrophic effects in the mountains and adjacent plains, but almost no impact on the extent of the flood peaks far downstream in Bangladesh. The high rainfall in India's Meghalaya Hills, and in Bangladesh itself, has been identified as a dominant factor leading to the floods.

An improvement in monitoring, followed by further studies to clarify the processes active in the highland-lowland system and thus the generation of floods, together with cooperation among the states sharing the mountain water resources of the Himalaya, is needed for sustainable management of this great basin.

M

M: Meghalaya Hills

Case study 7j

Land degradation in the Jhikhu Khola watershed in the Middle Mountains of Nepal causes floods and sediment transport in rivers.

Cherrapunji, situated in the Meghalaya Hills, has an average rainfall of 9500 mm between May and September (monsoon season).

Life in Bangladesh revolves around water. (Photos: R. Weingartner)

The Mekong Basin: managing the pressures of rapid economic development

Currently, an estimated 60 million people rely on the water of the Mekong as a basis for their livelihood. The Mekong Basin is characterized by rapid economic growth. Large-scale dam construction and water abstractions are planned to meet the growing demand for water. This, together with increased pressure on mountain watersheds, is resulting in changes in the river flow pattern and consequently in the threat of increased saltwater intrusion into the delta area, which in turn jeopardizes rice production and fishing productivity in the lowlands.

C: Cambodia
L: Laos
M: Myanmar
T: Thailand
V: Vietnam

Case study 8

Flowing through six countries, the Mekong is one of the world's great international rivers. From its source at over 5000 m on the Tibetan Plateau, the Mekong flows through China's Yunnan Province, touches Myanmar, forms the boundary between Laos and Thailand, crosses Cambodia, and flows into the South China Sea in Vietnam. The total length of the river is 4800 km. The downstream wet season flow is dominated by the monsoon rains and is mainly provided by the lowland watersheds. The mountain areas, which cover about 30% of the basin, are critical for maintaining the dry season flow, to which they contribute between 40 and 50%. A large portion of the lowlands of the basin is densely populated and characterized by high rates of population increase (e.g. 2.8% per annum in Cambodia).

Conflicting demands

China has completed a dam in the main stream channel and intends to construct several others to support industrial development and irrigation. Thailand, already an important user of Mekong water, has plans for interbasin diversions from the Mekong Basin to the neighbouring Chao Phraya Basin to relieve Bangkok of its shortage of fresh water. Total planned abstractions for this project are reported to amount to 9 to 30% of the Mekong's dry season flow. Laos has set up an ambitious programme for hydropower generation mainly in the mountain areas, with a view to exporting most of it for foreign exchange. In southern Laos alone, over 30 dam sites have already been identified.

Nam Ngum reservoir, Laos: The Mekong and its tributaries – of which many important ones originate in mountain areas – have come under increased pressure in recent years from commercial logging and dam construction for hydroelectricity. (Photo: T. Kohler)

Tibetan Plateau and mountains: the origin of the headwaters of some of the major rivers of the world, among them the Mekong and the Yangtze. (Photo: M. Ryser)

Mountain areas in the basin are under increasing land use pressure. The intensity of commercial logging and shifting cultivation have increased in recent years due to inappropriate land use policies, migration and resettlement, and population growth. This intensified land use leads to reduced vegetation cover and thus is likely to influence the hydrological regime.

The likely impact

The compound effect of human activities within the Mekong Basin, and especially its upper reaches, on the river flow is difficult to assess. The three major factors to consider in this respect are:

(1) Land use change, e.g. deforestation, may lead to more extreme river flow with increased flood peaks and reduced dry season flows.

(2) Dam construction for hydropower generation has the opposite effect, storing peak flows and releasing water during low flow periods.

(3) Water abstractions for irrigation and for domestic and industrial use reduce river water availability, mainly during low flow.

The overall result of these impacts could be a reduced dry season flow. This would exacerbate the level of saltwater intrusion from the sea, which already adversely affects approximately 60% of the Mekong Delta area. The potential for disruption of livelihoods in the lowlands is thus clear. The Mekong's aquatic ecosystems are unique, and its diversity of fish species is among the greatest in the world. Fish is the most important source of protein for local populations, and fishing is an important source of income. With 50% of Vietnam's total rice crop grown in the Mekong Delta, irrigation is also a vital activity which could be affected by upstream changes.

The challenges ahead

Sustainable use of the Mekong water resources will have to be based on a basin-wide approach, the participation of all stakeholders including local populations, and joint responsibility among the countries which share the basin. A fair and equitable distribution of Mekong water should be based on water resource monitoring, agreed rules of water use, and the preservation of the unique aquatic ecosystem. Proper management of mountain watersheds will be particularly important for securing sustained dry season flow. Achieving these aims will require extensive political negotiation for which the Mekong River Commission could be a vehicle. Without such an approach, the potential for future conflicts is clear.

Case studies from the Americas and Oceania

Case study 9j

Glaciers in the tropical Andes: a life-line during the dry season

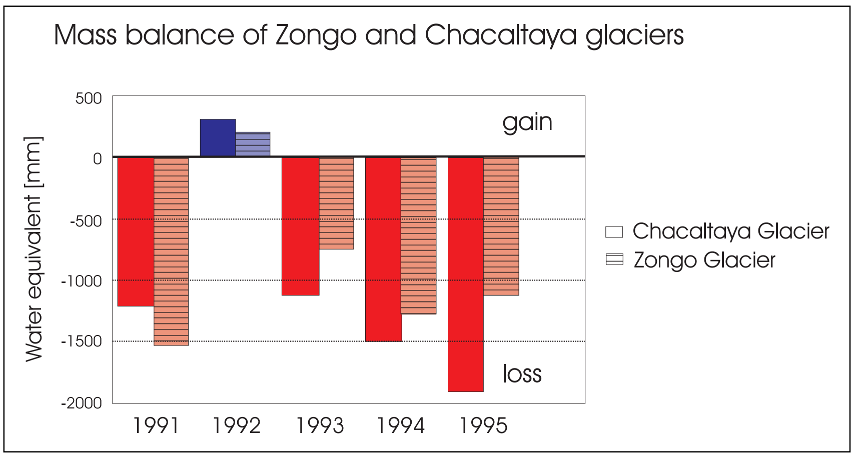
In Bolivia, Peru and Ecuador, glaciers are the principal natural reservoirs regulating freshwater flow during the year. Glacial meltwater, which has traditionally been used for irrigation, is now a life-line for major Andean cities such as La Paz, the capital of Bolivia.

The 3044 glaciers of Peru store 56.15 km^3 of ice. During the dry season, most runoff is glacial meltwater. Some of it is diverted into irrigation channels, many of which are of pre-Columbian origin. All the measured glaciers in Peru have lost substantial masses of ice in recent years: the length of the Broggi Glacier, which measured 1.6 km in 1948, decreased by 654 m between 1948 and 1991. 53 m of this loss occurred in 1991 alone.

The Zongo Glacier of Bolivia is a water tower which supplies water for La Paz. (Photo: M. Grosjean)

About 1.5% of the global ice volume is stored in mid- and low-latitude glaciers. However, due to their proximity to centres of human population and consumption, these water reservoirs are exceedingly important. In semi-arid tropical mountains, such as the Central Andes, glaciers provide fresh meltwater throughout the year, even during the dry season. Whereas Mexican glaciers (11.4 km^2), African glaciers (10.9 km^2), and Indonesian glaciers (6.9 km^2) are limited in their extent, the glaciers in the tropical and subtropical Andes cover 2676 km^2, almost equalling the extent of the glaciers in the Alps (2910 km^2). The 1.4 million people of La Paz and El Alto depend mostly on water supplies from surrounding glaciers lying above 4500 m. 75% of the electric power for these cities is generated by a row of eight hydropower plants in the Zongo Valley of the eastern escarpment of the Andes from 4750 m down to 1200 m altitude. Conflicts over traditional irrigation, domestic supplies, and hydroelectric power generation have already arisen in the Andean valleys close to the large centres.

The Zongo Glacier provides an important buffer against seasonal variability in precipitation, thus ensuring a continuous freshwater supply for La Paz. During the dry season between April and November (monthly precipitation ranging from 10 to 40 mm), the Zongo Glacier alone provides La Paz with 50 to 120 l/s of water. It is even able to respond immediately in extreme dry years (e.g. El Niño years), when meltwater discharge increases due to the higher temperatures. However, such short-term positive effects result in substantial ice losses from these glaciers and, ultimately, in the disappearance of this freshwater reservoir. This is likely to be a critical process in light of global warming.



The Zongo and Chacaltaya glaciers of Bolivia have shown highly negative net balances during recent years and have lost substantial masses of ice. (Data: B. Pouyaud, B. Francou)

Tropical glaciers are highly sensitive to climatic changes. Worldwide, most glaciers are rapidly retreating, e.g. the Mount Kenya and Kilimanjaro glaciers of Africa and many Himalayan glaciers.

Andean water: supply for the world's largest copper mines in Chile

The entire economic development of the Atacama Desert depends on small streams that come from the Andes. These mountain water resources are of vital importance. Further economic growth in one of the richest mining areas of the world is limited by these resources.

The Atacama Desert in the Andes of northern Chile, one of the driest places on earth, yields exceptional metal ore deposits. The extremely scarce water resources, which sustained the indigenous Atacameña culture for thousands of years, are currently under extreme pressure from the mining industry and growing urban areas. The water resources generated in the high mountains of the Andes are transported by pipeline over hundreds of kilometres to areas of demand, i.e. the large copper mines and expanding urban centres.

The water resources

Due to their orographic effect, the high mountains of the central Andes form a rainfall zone in the Atacama Desert, while areas below 3000 m altitude receive virtually no rainfall. However, annual precipitation in the highest mountains rarely exceeds 200 mm, and most of the groundwater resources in the basins were recharged during wetter climatic phases thousands of years ago. Thus they are non-renewable water resources. Total available water resources in the area (126,000 km^2) are 10 m^3/s.

Resource use and conflicts

The "sacred" water resources from the mountains have traditionally been used for irrigation of agricultural fields in small oases in the foot zones of the mountains. In recent years, however, the copper, gold and lithium deposits have been exploited and currently account for the greater part of the Chilean national budget. In 1994, the Atacama Desert generated 17% of the world's copper production. More than 7 billion US dollars are currently invested in new mining operations. Mining in the Atacama accounts for 95% of regional exports, and for 30% of total Chilean exports. With these mining activities, the demand for water has increased rapidly. In 1996, claims submitted for water rights amounted to 16 m^3/s, greatly exceeding the 10 m^3/s currently available.

◆ **New investments in mining activities**

Case study 10

Water captured from the Putana River of the Atacama Desert is carried over hundreds of kilometres to centres of demand, i.e. the growing cities and the large copper mines, such as the Chuquicamata mine (until 1992 the world's largest open cast copper mine).

The worship of mountains for their water was a feature of Inca culture. The weather god Illapa lives in the mountains, and controls rain, storms, lightning, hail and snow. In the Atacama Desert of northern Chile, children were reportedly sacrificed annually to the mountain god for rain to ensure a secure water supply.
(Photos: M. Grosjean)

The Fraser River of the Rocky Mountains: a highly productive ecosystem for salmonids

The Fraser River of Canada is one of the few major basins in the Rocky Mountains with no mainstream hydropower or dam construction. This, combined with the ability of the mountain fresh water to dilute the current level of wastewater discharges in the lower part of the basin, has helped to preserve one of the most productive ecosystems for salmonids in the world.

Case study 11

Fragile mountain ecosystems: salmon habitats are severely threatened by suspended sediment loads originating at logging sites (such as those in the Columbia River watershed, Washington State USA), and by infrastructure development on steep mountain slopes. (Photo: M. Grosjean)

Agricultural and industrial development in the Lower Fraser Valley. (Photo: H. Schreier)

The Fraser River, draining 234,000 km^2, is 1375 km long with a mean annual flow of 3972 m^3/s. Its headwaters originate in the Rockies, which are dominated by glaciers and snowmelt. More than 85% of the basin consists of mountains that are highly diverse, with an extreme climatic variability ranging from 300 mm annual precipitation in the Central Plateau to more than 3500 mm in the Coastal Mountains. The latter, which occupy only 20% of the total catchment, provide 60% of the annual flow.

The salmonid habitat

The Fraser River is one of the leading salmonid-bearing systems in the world. It is estimated that more than 7 million migrating salmon enter the river each year, which is commercially and recreationally important. The hydrological conditions are vital for the survival of the salmon, particularly in the late autumn when the salmon make their long journey up the river to spawn. In contrast to many other major salmonid rivers (e.g. the Columbia basin, USA), the passage of the salmon up the Fraser River is not impeded by hydropower development.

The importance of the Fraser River ecosystem is accentuated by the general trend of rapidly decreasing catches of Pacific salmon, currently the subject of much debate. Overfishing, habitat loss due to urbanization, pollution of the streams, siltation of spawning areas due to soil erosion and clear-cut deforestation on the steep slopes of the mountains, and fluctuations in flow due to unusual climatic variability over the past 5 years are viewed as the main causes of the decline.

The dilution power of mountain fresh water

85% of the 1.8 million people resident in the Fraser basin live in the Lower Fraser Valley. Although it constitutes less than 10% of the catchment area, this area is responsible for 70% of total wastewater discharges from urban, industrial and agricultural sources. A further significant source of pollution originates from the pulp mills located along the middle section of the river. The hydrological regime of the Fraser River, which is dominated by inflow from the headwaters in the Rocky Mountains, is able to dilute current wastewater discharges, ensuring water quality that does not impede the passage of salmonids. However, careful wastewater management is required to maintain the unique ecosystem of the Fraser basin for the future.

The Southern Alps of New Zealand: water for electricity generation

Excessive rainfall and the storage of water in snow, glaciers and lakes in the mountains of South Island are essential for generation of New Zealand's electricity.

The Southern Alps of New Zealand are a chain of mountains 2000 to 3000 m high and over 500 km long which form a barrier to moist, mid-latitude, westerly, maritime air streams. The resultant orographic rainfall on the windward slopes is more than 12,000 mm a year in some areas, while annual rainfall over the low elevation areas in the rain shadow is less than 500 mm. Extensive seasonal snow accumulation occurs at altitudes exceeding 1000 m, with perennial snow and ice found above 2200 m.

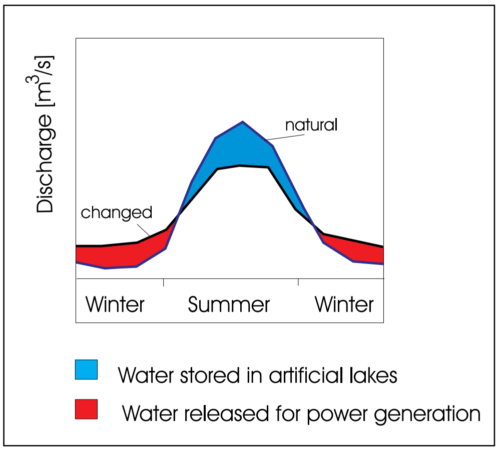
The hydrological conditions

Typically, precipitation over the windward catchments is evenly distributed throughout the year. Streamflow, however, exhibits a strong seasonal pattern, with low flows occurring in winter when water is stored as snow and glaciers, and high flows occurring with snow- and icemelt in spring and summer. Snowmelt from the mountains can contribute as much as 70% to the summer flows, illustrating the importance of the New Zealand Alps as water towers for the lowlands.

Extreme rainfall in the Southern Alps of New Zealand: maximum annual rainfall is 14,400 mm, maximum three-day rainfall 1810 mm, and maximum one-day rainfall 1330 mm.
Typical annual water balance for a catchment on the windward slopes: precipitation 9500 mm, evaporation 800 mm, and runoff 8700 mm.

The hydropower potential

Three major rivers, the Waitaki (catchment area 9800 km^2), Clutha (12,000 km^2), and Waiau (5800 km^2), drain the central and southern section of the Alps and flow to the dry lowlands in the east and south. These rivers have glacial lakes in their mountainous headwaters and provide excellent opportunities for hydropower development. The three rivers on South Island produce 43% of New Zealand's total electric energy. The water storage in artificial lakes in the mountains is critical to meet the seasonal deficit in winter when power demands are at a maximum and water availability is at a minimum. The importance of water storage is further accentuated by New Zealand's need for self-sufficiency in power, as it is an isolated island state.



Case study 12

Effect of hydropower production on monthly flows of ice- and snow-fed mountain rivers.

In the Southern Alps of New Zealand, water is stored as snow or ice and in lakes, creating the potential for hydropower development. There is a marked contrast between the mountains in the West, with high rainfall, and the adjacent arid lowlands in the rain shadow areas to the east. (Photo: Charles Pearson)

Mountain waters: challenges for the 21st century

Access to clean fresh water is a basic human right which has not yet been achieved for all. As the "water towers" of the world, mountains are of paramount importance for safe drinking water, and for food, energy, and industrial production. They also support unique ecosystems and biodiversity in both the highlands and the lowlands. Increasing demands on limited water resources, which result in a growing potential for conflicts, ensure that mountain water resources will play a prominent role in sustainable development in the 21st century. Preserving mountains as water towers is a major challenge that humankind must face.

Mountain regions are under pressure from internal factors such as deforestation, agriculture, and tourism, and from increasing demands on their resources in the densely populated lowlands. Rapid and increasing changes in mountain landscapes, and increasing demands on mountain resources, will have many impacts on freshwater availability. The case studies presented here show that without comprehensive assessment of these impacts, and without an integrated basin management approach, the results can be disastrous. Maintaining the role of mountains as water towers will require that the following challenges are met:

Managing increasing demands for fresh water

Fresh water has already become a scarce resource in many parts of the world. Even with improved water use efficiency and demand reduction strategies, the need for fresh water for domestic use, irrigated agriculture, energy generation and industrial production will continue to grow. Mountains will be expected to satisfy the greater part of this increasing demand. *Thus, freshwater resources must be carefully managed, starting at the source – in the mountain regions themselves.*

Safeguarding biodiversity and natural habitats created by mountain fresh water

Mountain areas are often "hot spots" of biodiversity, especially in the tropics and subtropics. Mountain water resources sustain many natural habitats, both in the mountains and the lowlands. Forests and other types of vegetation in mountain ecosystems play a key role in the water-related functions of mountains. *Maintaining protected areas and natural ecosystems in the mountains is necessary not only for ethical reasons but also to preserve natural resources for coming generations.*

Recognizing interactions between the mountains and the lowlands

In many regions, mountains are marginal areas for human habitation, as they are limited by steep slopes, poor soils, cool temperatures, and inaccessibility. The surrounding lowlands are more favourable to the location of settlement, agriculture, and industry, but remain dependent on the mountains for water resources. In some regions (e.g. in many parts of the tropics), however, mountains are preferred areas of human habitation because they have better climate and soils. Case studies illustrate that mountains in humid areas provide 30 to 60% of downstream fresh water, while this figure rises to 70 to 95% in semi-arid to arid environments. Increased human activities upstream may reduce the quality and quantity of the flows downstream on which lowland users depend. Conversely, over-development downstream may impose an unsustainable demand on the water towers upstream. There is thus a complex interaction between mountains and downstream lowlands which needs to be recognized. This interaction should be given paramount consideration in planning resource development. *There is a great need to increase awareness of the value of mountains as water resource towers and the impact they have on the lowlands.*

Watersheds in the highlands of Nepal.

Assessing mountain water resources and the impact of human activities

The increasing pressure for development in the mountains brings with it the danger of altering river flows and changing water quality. A global assessment of mountain water resources, their quantity and quality, and their limits for use is now required. Additionally, the effects of land use change in the mountains and on river flow and water quality in the lowlands must be properly assessed at different scales. In many mountain areas of the world, there is inadequate monitoring of natural resources (water, soil and vegetation), and the impact of human activities on the availability and quality of these resources in mountain areas and downstream lowlands. This, coupled with poor dissemination of information where such data are recorded, makes assessment of water resources a considerable challenge. The lack of monitoring is partly due to the harsh conditions in mountain regions, together with a lack of investment. *There is a great need to improve the current monitoring of mountain water and land resources, and to assess the impact of human activities in the mountains on natural resources. Above all, there is an urgent need to make data publicly available and to exchange knowledge between neighbouring countries, from the mountains to the lowlands.*

Investing in mountains

More emphasis must be given to sustainable mountain development, to maintenance of mountains as water towers, and to water quality. This requires investment in the mountains in terms of long-term monitoring, water resource assessment, and empowerment of mountain people as stewards of these water towers. In cases where the lowlands are economically better off than the highlands, the lowland communities must invest in the mountains or compensate for the service which mountains provide to downstream areas. In the reverse situation, highland communities need to take into account their lowland neighbours and ensure the discharge of enough clean water to sustain lowland inhabitants and natural habitats. If both mountain and lowland communities are economically disadvantaged, then the compensation to mountain communities for their stewardship should come from the national or international community. *The challenge is to identify investment mechanisms for the sustainable development of both the mountains and the lowlands.*

Rivers as lifelines: irrigation schemes in the Ganges plain. (Photos: B. Messerli)

Avoiding conflicts

The case studies presented here very clearly show the high potential for conflict over water resources between highland and lowland users within a basin. As most basins stretch across administrative or national boundaries, improved methods of equitable water allocation and improved regulation of water abstractions are important pre-requisites to minimize conflict. *Transboundary water management supported by political commitment is needed, especially for basins in semi-arid and arid regions where water resources are scarce.*

Conclusion: implementing integrated basin management

Integrated basin management encompassing both the mountains and the lowlands is the key to meeting the above challenges. Planning and management tools at the local, national and international levels should be further developed, together with better cooperation between decision makers, researchers, planners and users at all levels. A major effort must be made to identify win-win solutions for people living in both highland and lowland areas. *Only an integrated basin management approach can ensure the continued role of mountains as water towers for humankind in the 21st century and meet the expectations identified in Chapters 13 and 18 of Agenda 21.*

Mountain water from the Weisshorn, Switzerland. (Photo: H.P. Liniger)

Mountains: water towers for humanity.
(Photo: H.P. Liniger)