Mountains and freshwater supply

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Making the link between mountains, forests and water.

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MOUNTAINS - A GLOBAL PRIORITY

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 also has religious and cultural values. Unfortunately, water is becoming scarce in many areas and regions of the planet. The latest data from the World Water Council's *Report on sustaining water* (1996) show clearly how alarming the situation is: "In 1950, only 12 countries with 20 million people - faced water shortages; by 1990 it was 26 countries with 300 million people; by 2050 it is projected to be as many as 65 countries with 7 billion people, or about 60 percent of the world's population, mainly in the developing countries". The report calls for immediate and effective action in order to maintain freshwater availability in the coming century. As documented in the recently published report on freshwater management (Liniger *et al.,* 1998), mountains play a crucial role in the supply of freshwater to humankind, in both mountains and lowlands.

Since the 1970s, mountain ecosystems have received increasing recognition in several research programmes. In 1992, at the United Nations Conference in Environment and Development (UNCED - Earth Summit) in Rio de Janeiro, Chapter 13, entitled Managing fragile ecosystems - sustainable mountain development, was included in Agenda 21, the main document of the meeting. The UN Commission on Sustainable Development subsequently appointed FAO as Task Manager for this mountain chapter. Through an unprecedented level of collaboration among UN agencies, national governments, international organizations, non-governmental organizations (NGOs) and research institutions, a comprehensive report, *Mountains of the world: a global priority* (Messerli and Ives, 1997), and a companion policy document, *Mountains of the world: challenges for the twenty-first century* (Bisaz *et al.,* 1997) were presented to the special session of the UN General Assembly, Rio+5, in 1997.

THE ROLE OF MOUNTAINS AS WATER TOWERS

All the major rivers of the world have their headwaters in highlands and more than half of humanity relies on the freshwater that accumulates in mountain areas. Although they constitute a relatively small proportion of river basins, most of the river flow downstream originates in mountains, the proportion depending on the season. These "water towers" are crucial to the welfare of humankind. As demand grows, the potential for conflict over the use of mountain water increases. Careful management of the sources of water as well as of the resources themselves 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, triggering precipitation. In semi-arid and arid regions, only highlands have sufficient precipitation to generate runoff and groundwater recharge.

Storage and distribution of water to the lowlands. Waters captured at high altitudes flow under gravity via the stream network or groundwater aquifers to the lowlands, where the demand from population centres, agriculture and industry is high. For example, the 1.4 million people of La Paz and El Alto (Bolivia) depend mostly on water supplies from surrounding glaciers lying above 4 900 m above sea level, and 75 percent of the electric power for these cities is generated by the hydropower plants on the eastern escarpment of the Andes.

In humid areas throughout the world, the proportion of water generated in the mountains can comprise as much as 60 percent of the total freshwater available in the watershed, while in semi-arid and arid areas this proportion is generally over 90 percent.

The life-sustaining role of water. Clean and reliable water supply is fundamental to human existence and health. Since 1940, global freshwater abstractions from all sources (i.e. extraction for use of surface or groundwaters) have more than quadrupled (Figure 1). Seventy percent of the water is used for irrigation. The dependency of world food production on mountain waters is evident, particularly in the arid and semi-arid climates of the tropics and subtropics where most of the developing countries and more than half of the world's population are located. Furthermore, water stored in mountain lakes and reservoirs has additional economic value as a potential source of hydroelectric power. Mountain freshwater also sustains many natural habitats, in both highlands and lowlands, thus contributing to the conservation of biodiversity.

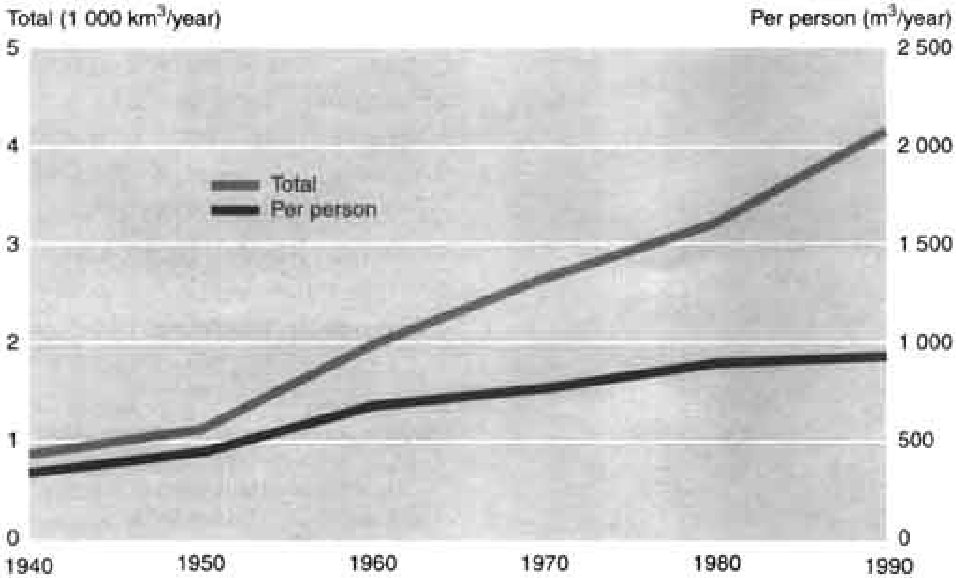

FIGURE 1 Increase of global freshwater consumption

Source: World Resources Institute.

Fragile ecosystems. Mountains are highly fragile ecosystems. High rainfall, steep slopes and erodible soils can induce severe surface runoff, soil erosion and landslides. Eroded sediments are major pollutants of surface waters. Land use, development of infrastructure, mining and tourist activities in mountain areas may significantly affect the quantity and quality of river water and groundwater.

Conflicts over water. Worldwide, 214 river basins, host to 40 percent of the world's population and covering more than 50 percent of the earth's land surface, are shared by two or more countries. The distribution of water from mountain areas was the cause of 14 international conflicts noted in 1995. For example, the Arab-Israeli conflict, although primarily a security and territorial dispute, also involves the supplies of freshwater from the Anti-Lebanon mountains, Mount Hermon, the Golan Heights and the hills of the West Bank.

Disputes over water also arise on a smaller scale, between highlands and lowlands within national borders as, for example, around Mount Kenya.

"Sacred" mountain water. Throughout the world people have always looked to mountains as the source of water, life, fertility and general well-being. They have been, and in some places still are, worshipped as the home of deities and as the source of clouds and rain that feeds springs, rivers and lakes on which societies depend for their very existence.

IMPACT OF MOUNTAIN RESOURCE MANAGEMENT ON FRESHWATER SUPPLY

The Mount Kenya experience - direct and indirect human impact

Rivers originating from the glaciers of Mount Kenya flow through the montane, high elevation moorland to the forest belt, where rainfall is highest, and rivers and groundwater aquifers are recharged. Ninety percent of the dry season flow of the Ewaso Ng'iro River collects in the alpine, moorland and montane forest belts (above 2 400 m) on Mount Kenya. On the lower mountain slopes and in the piedmont, both the population and the area of cultivation have more than tripled over the last 20 years and river water abstractions for irrigation have dramatically increased. Currently, 60 percent of the people in the Ewaso Ng'iro basin live in this area and the remainder live downstream on the semi-arid plains, where they depend for their livelihood on water generated upstream.

Decreasing dry season river flow is a serious problem; since the 1960s, the average dry season flow of the Ewaso Ng'iro River has been reduced in the lowlands to one-eighth of its previous level. Since the 1980s, the once perennial river has had prolonged periods with no flow. Consequently, the unique wildlife ecosystems of the Samburu and Buffalo Springs game reserves in the lowlands suffer during the drought period and this has had a negative impact on tourism, the primary source of foreign exchange in the region. Nomadic pastoralists and their livestock, and the wildlife in the lowlands, are drastically affected and are forced to move upstream in the search for water and grazing land. As a result, conflicts with farmers are increasing.

Two main factors are affecting river flow in the lowlands:

Increasing water abstractions. A growing population and immigration into the area surrounding Mount Kenya increase the water needs for drinking, for industrial and urban use and, most important, for irrigation. In addition, the control and management of abstractions is inadequate. Currently, ten times more water is taken out than regulations, if properly supervised, should allow. Monitoring of abstractions, improved procedures for allocation and better management and control are urgently needed.

Land use change and intensification.

Changes in land use also have had an impact on river flow and water quality. Removal of vegetation cover and intensified land use on the northern slopes of Mount Kenya (Figure 2) have led to increased surface runoff during heavy storms, causing erosion and pollution of the surface water. Flash floods, previously unknown, have been recorded in recent years flooding old farm houses and tourist lodges. Investigations are still being undertaken to quantify the impact of human activities and land-use change on runoff and floods, and on river flow during the dry season.

Soil moisture measurements under different land uses show the amount of water lost through evapotranspiration. A comparison of natural forests with plantations and cropland on Mount Kenya showed that soil under cypress plantation was the driest, as the water was used up much faster than under natural forest. Rainfall was not sufficient to recharge the groundwater. Under natural forest, the soils were more moist and there were periods of groundwater recharge. It is only natural that a fast-growing tree will use more water than a slow-growing one in absolute terms (but not necessarily so in terms of consumption per cubic metre of wood produced). Under crops such as potatoes the soils had a higher water content and groundwater recharge was the highest. Although surface runoff occurred during heavy storms, cropland still provided the greatest contribution to groundwater and river flow.

FIGURE 2 Land-use change from forest (right) to large-scale farming (left) to small-scale farming (centre). What are the consequences for me river flows?

The experience of the Himalaya - the effect of scale

It is a common assumption that the floods in Bangladesh are caused by deforestation and other human activities in the Himalaya (Figure 3). However, while the mountains provide crucial water flow to lowlands downstream during the dry season, they do not appear to have a significant role in the generation of floods in Bangladesh.

Both the Ganges and the Brahmaputra rivers flow through several countries, and therefore "blame" for the floods in Bangladesh has become a geopolitically sensitive issue. To what extent the flood processes are natural and how much they are influenced by human activities in the highlands has aroused passionate discussions among scientists and politicians.

Recent studies (Hofer, 1998) indicate 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. For example, an extraordinary rainfall event on 19/20 July 1993 over eastern and central Nepal had catastrophic effects locally, with floods and landslides in several districts. However, the water level of the Ganges near the India-Bangladesh border was not affected. The flood crest of the Nepali tributaries had levelled off during its passage from the hills to the plains. Very heavy rainfall in the mountains and adjacent plains had almost no impact far downstream in Bangladesh. Thus, at the local level, land use may have an impact on runoff, erosion and floods whereas at the regional level, flooding is a natural hazard and largely beyond human control. Furthermore, the replacement of forests by carefully managed and terraced agriculture has no negative effect on erosion, sediment transport and flooding (Hamilton, 1987; Hofer and Messerli, 1997).

FIGURE 3 Land degradation in the Jhikhu Khola watershed In the Middle Mountains of Nepal, causing local floods and sediment transport in the rivers

The experience of the Swiss Alps - the hydrological role of forests

The contribution of the Swiss mountains to the flow of the River Rhine in the Netherlands is disproportionally large, varying seasonally from 30 percent in winter to 70 percent during the summer when stream flow is minimal in the lowland rivers but high in the Alps as a result of snowmelt and icemelt. Similarly large proportions of mountain water in the annual flow are observed in the River Rhone (32 percent of the mountain area contributes 47 percent of the lowland flow) and the River Po (32 percent of the mountain area contributes 56 percent of the lowland flow).

The importance of the Alpine region is primarily based on enhanced precipitation owing to the orographic effect. Much of this falls as snow at higher altitudes and may form snowpack and glaciers, leading to delayed runoff during the summer, the growing season. Alpine catchments are characterized by much higher mean annual discharge per unit area (more than 30 litres/second per km^2) than catchments in the Central European lowlands (about 10 litres/second per km^2).

Alpine rivers were once important trade and transportation arteries. During the first half of the nineteenth century, large quantities of clear-cut timber were shipped from the Alps to France and the Netherlands. During this period, Switzerland repeatedly experienced major flood events that cost dozens of lives and caused extensive damage (Figure 4). Both foresters and politicians warned at the time of the connection between clear-cutting of timber and increased runoff. This factor influenced the passing of the first national forestry law in 1876, which contained strict provisions for forest protection. More recent studies, however, indicate that some natural events in the last century were so extreme that flooding would have occurred even if no timber had been cut. The linkage between deforestation and increased high flows is far more complex than was assumed at that time, or even today, in some quarters.

"Classic" experiments conducted in the Emmental show that after storm events with non-extreme rainfall, peak flows are lower in rivers with forested catchments than in those whose catchments do not have good vegetative cover (Burger, 1954). In other words, peak flows in rivers are flattened out owing to the more gradual release of water from the forest soils than would be the case in an area with soils of lower infiltration rate and storage capacity. In the latter, the surface runoff would be higher and the storm flow of the river higher and more abrupt. Total annual discharge is lower in forested areas than in non-forested areas, owing to evapotranspiration. Similar studies in other countries have reached the same basic conclusions, although they make clear that, in addition to forest cover, other factors such as geological and soil conditions, morphology and climate can have a considerable influence on runoff (Bosch and Hewlett, 1982).

It is clear that the infiltration rate and storage capacity of the soil on the forest floor are of paramount importance (Keller, 1992). Forests with soils of good structure and which are rich in organic matter have relatively high water-retention capacity. However, the influence of the forest ceases as soon as the soil is saturated (Figure 5). When this happens, as during the extreme rainfall events as those which occurred in Switzerland in the last century, flooding is more apt to occur.

IMPACT OF MOUNTAIN LAND USE ON FRESHWATER RESOURCES AND THE ROLE OF FORESTS

Case studies indicate that there are both direct and indirect impacts of mountain resource use. The *direct* impacts are:

- water use from rivers and aquifers, such as surface abstractions and the pumping of ground water, affects the quantity of water;
- point source pollution, such as waste water discharge into rivers, affects water quality.

FIGURE 4 Clear-cutting of forests and overgrazing were thought to be the main causes of severe floods resulting in extensive damage, primarily in the nineteenth century, as shown in the catchment area of the Lambach near Brienz, Switzerland in 1893

FIGURE 5 The influence of the forest in reducing peak runoff ceases as soon as the soil becomes saturated. Any additional rainfall will run off immediately and quickly reach river channels, thus causing floods

Since these impacts can be identified, if there is a need and political will regulations can be introduced to control both water use and waste discharge (including water treatments and the use of certain chemicals).

The *indirect* impacts are:

- land use that changes the water cycle and the quantity of water (e.g. river flow);
- non-point source pollution (also called land-based pollution), which influences the water quality. In many parts of the world this is the major source of river and groundwater pollution.

The indirect impacts are much more difficult to identify and quantify than the direct impacts because of the complicated interactions of land, soil and vegetation, and thus they are more difficult to control.

What is the effect of land use on the availability of freshwater?

The key to assessing the impact of land use in the mountains on water resources is an understanding of how land-use changes, and particularly intensification, affect the water cycle. Rodda (1994) clearly expresses the challenge: "From the hydrological point of view, mountain regions present a paradox. Although they provide the bulk of the world's water resources, knowledge of these resources is generally much less extensive, reliable and precise than for other physiographic regions." As Klemes (1988) says, mountain regions represent, in practical terms, "the blackest of black boxes in the hydrological cycle".

If rainfall at any one time is greater than the infiltration rate of the soil (its capacity to absorb the water), surface runoff occurs. Accelerated runoff increases the risk of soil erosion, which reduces soil fertility and the capacity of the soil to store water. This may lead to reduced vegetation cover and productivity, forcing people to intensify land use. As a result, the vegetation is further degraded and productivity curtailed. The water cycle is changed and a vicious cycle of degradation is initiated (Liniger, 1995). As simple as this principle is, it is difficult to determine under which type of land use, under which soil type and under what climatic conditions the cycle of degradation is initiated, and at what point the capacity to recover is lost for future generations.

Natural vegetation is generally characterized by high rates of infiltration compared with other types of land cover with a similar soil base. Because under natural conditions there are usually several storeys of vegetation, the top layers of the soils are well protected and well structured; any change from the natural growth to forest use, plantations, grazing land and crop production may reduce infiltration and the storage capacity of the soil.

The change from natural forest cover to other types of land cover and land use has often been associated with degradation of natural resources. Observations and research findings show that in the first years following land-use change, when the vegetation cover is removed and the topsoil disturbed, high rates of runoff and soil erosion occur. However, depending on what the new land use is, after the early years of transition, the negative impacts may be reduced as improved management practices are established and good vegetative cover is restored (Hamilton, 1987). Adequate soil cover, efficient management and conservation practices are important for sustainable use of resources. In mountains all over the world agricultural systems have been developed that do not destroy natural resources and that have locally well- adapted sustainable systems of water and land use.

Changes in land use and vegetation affect not only runoff but also evapotranspiration. When cropland, grazing land and forests are compared, cropland is found to have the lowest rate of evapotranspiration and forests the highest. Increased evapotranspiration reduces the groundwater recharge and the contribution to river flow. However, great differences occur according to the plant species and the rate of production.

Another difficulty in assessing the impact of land use on freshwater resources is the problem of scale (Hamilton, 1987). Whereas impacts at the local scale can be identified, the human impact in large basins is difficult to identify and appears to become insignificant.

What is the effect of land use on the quality of freshwater?

Any intensification of land use from natural forests to plantation or agriculture increases the probability of reduced water quality. Even if the water cycle is unchanged, use of fertilizers, insecticides, herbicides or other substances may pollute water resources downstream. Siltation is also a problem where erosion rates increase as a result of removal of vegetative cover. As runoff increases, non-point source pollution is likely to become a serious threat to water quality. Whereas in many cases, point source pollution has been reduced in recent years, non-point source pollution has increased and is a much greater threat.

Further clarification of the role of mountain forests is needed

The role of providing and protecting water resources has been attributed to forests for generations. Folk tales and myths throughout the world illustrate that natural forests provide clear and pure water (Küchli, 1997). However, in only a few cases has this been properly documented and compared with other land uses (such as plantation forestry, grazing or crop cultivation) in relation to river flows, groundwater recharge and water quality. Whereas the impact of intensified land use on water quality is likely to be negative, there is not sufficient evidence to quantify this. Furthermore, the effects on the water cycle of water availability, erosion and soil productivity still remain unclear in many cases. Mountain forests generally provide favourable conditions for storage of excessive rainfall whereas runoff may be higher in other types of land cover and land use, such as agriculture where soils may be compacted through cultivation or through overgrazing, which also reduces vegetative cover.

Although forest soils store water, evapotranspiration is also higher in forests than under other types of vegetation (Hamilton, 1987). Therefore, forests may use more water and leave less for river and groundwater recharge than other land-use types. Unfortunately, there are few investigations of forest productivity and the different rates of water use. Furthermore, the role of natural mountain forests in capturing additional precipitation from mist (cloud forests) is not well established.

Forests have been protected by the "myth", supported by some proven facts, of being "good" to humankind. It is timely now to clarify the multiple roles of mountain forests. These include supplying clean and sufficient water (Figure 6) and forest products, maintaining biodiversity and protecting against natural hazards such as avalanches, landslides and rock fall, as well as influencing climate.

FIGURE 6 The Weisshorn glaciers and natural forests are both sources of abundant good-quality fresh mountain water

CONCLUSIONS

Mountains are of paramount importance for the supply of water for drinking and for food, energy and industry. Freshwater from mountain areas also supports unique ecosystems and biodiversity in both highlands and lowlands. Mountain regions are under pressure from deforestation, agriculture and tourism, and from increasing demands on their resources in the densely populated lowlands (Figure 7). In many regions, they are marginal areas for human habitation, as they are limited by steep slopes, poor soils, cool temperatures and inaccessibility. The surrounding lowlands are usually more favourable for settlement, agriculture and industry, but remain dependent on the mountains for water resources.

FIGURE 7 Mountain water towers for humanity

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 management. Whereas the effects of land-use change on surface runoff and erosion can be clearly quantified in test plots and small catchments, the effects on regional hydrology need further investigation (Liniger and Gichuki, 1994). This will lead to better understanding and determination of crucial limits or thresholds for land use and land-use intensification.

Integrated resource management encompassing both the mountains and the lowlands is needed at the local, national and international levels, together with better cooperation between researchers, planners, decision-makers and users at all levels. The impacts of future human activities upstream on the availability of resources downstream need to be assessed so that mutually beneficial policies can be introduced. Only integrated basin management can ensure efficient use, equitable distribution, and effective management and regulation of mountain water for the benefit of all humankind.

Bibliography

Bisaz, A., Escher, F., Grosjean, M., Ives, J.D., Messerli, B. & Price, M.F. 1997. *Mountains of the world: challenges for the twenty-first century. A contribution to Chapter 13, Agenda 21.* Mountain Agenda. Bern, Paul Haupt.

Bosch, J.M. & Hewlett, J.D. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *J. Hydrology,* 55: 3-23.

Burger, H. 1954. Einfluss des Waldes auf den Stand der Gewässer - der Wasserhaushalt im Sperbel- und Rappengraben von 1944/45 bis 1953/54. *Mitt. EAFV* [Birmensdorf], 31, 2: 493-555.

Hamilton, L.S. 1987. What are the impacts of Himalayan deforestation on the Ganges-Brahmaputra lowlands and the delta? Assumptions and facts. *Mountain Research and Development,* 7: 3.

Hofer, T. 1998. Floods in Bangladesh: a highland-lowland interaction? *Geographica Bernensia* [Bern], G48.

Hofer, T. & Messerli, B. 1997. Floods in Bangladesh. Process understanding and development strategies. A synthesis prepared for SDC, Institute of Geography, University of Bern, Switzerland.

Keller, H. 1992. Hydrologie und Waldwirkung -Forest Diseases and Hydrological Processes. *Dtsch. Gewässerkd. Mitt.* [Koblenz], 5/6: 169-171.

Klemes, V. 1988. Foreword. *In* L. Molnar, ed. *Hydrology of mountainous areas.* IAHS Publication No. 90.

Küchli, Ch. 1997. *Forests of hope, stories of regeneration.* London, Earthscan.

Liniger, H.P. 1995. *Endangered water - a global overview of degradation, conflicts and strategies for improvement.* Development and Environmental Reports No. 12. Centre for Development and Environment. Bern, Lang Druck AG.

Liniger, H.P. & Gichuki, F.N. 1994. Simulation models as management tools for sustainable use of natural resources from the top of Mount Kenya to the semi-arid lowlands. Laikipia Mount Kenya Papers D-19, Nanyuki, Nairobi.

Liniger, H.P., Weingartner, R., Grosjean, M., Kull, C., MacMillan, L., Messerli, B., Bisaz, A. & Lutz, U. 1998. *Mountains of the world: water towers for the twenty-first century. A contribution to global freshwater management.* Mountain Agenda. Bern, Paul Haupt.

Messerli, B. & Ives, J.D., eds. 1997. *Mountains of the world: a global priority.* Carnforth, UK and New York, USA, Parthenon Publishing Group and Tokyo, United Nations University.

Njeru, L. & Liniger, H.P. 1994. The influence of vegetation on the water resources of the Naro Moru catchment - a water balance approach. Discussion Paper No. D-17. Nairobi, Laikipia Research Programme.

Rodda, J.C. 1994. Mountains - a hydrological paradox or paradise? *Beiträge zur Hydrologie der Schweiz* [Bern and Birmensdorf], 35: 41-51.