Bruno Messerli, Daniel Viviroli and Rolf Weingartner

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

Mountains as "Water Towers" play an important role for the surrounding lowlands. This is particularly true of the world's semiarid and arid zones, where the contributions of mountains to total discharge are 50–90%. Taking into account the increasing water scarcity in these regions, especially for irrigation and food production, then today's state of knowledge in mountain hydrology makes sustainable water management and an assessment of vulnerability quite difficult. Following the IPCC report, the zone of maximum temperature increase in a 2 x CO_2 state extends from low elevation in the arctic and sub-arctic to high elevation in the tropics and subtropics. The planned GCOS climate stations do not reach this elevation of high temperature change, although there are many high mountain peaks with the necessary sensitive and vulnerable ecosystems. Worldwide, more than 700 million people live in mountain areas, of these, 625 million are in developing countries. Probably more than half of these 625 million people are vulnerable to food insecurity. Consequences of this insecurity can be emigration or overuse of mountain ecosystems. Overuse of the ecosystems will, ultimately, have negative effects on the environment and especially on water resources. New research initiatives and new high mountain observatories are needed in order to understand the ongoing natural and human processes and their impacts on the adjacent lowlands.

INTRODUCTION

"Poor access to freshwater means that two billion people currently live under what experts call severe water stress. With population growth and economic expansion, this figure is expected to nearly double by 2025. Climate change would further exacerbate this situation". This quotation in Wallström et al. (1) depicts the dramatic situation today and the uncertainty regarding the future in the wake of the rapidly growing population, urbanization, industrialization and irrigation for food production, especially in the developing world. The UN General Assembly has wisely proclaimed the period 2005–2015 as the International Decade for Action, "Water for Life", beginning on World Water Day, 22 March 2005. The main aim is to further cooperation at all levels in order to achieve water-related goals of the Millenium Declaration, the Johannesburg Plan of Implementation of the World Summit for Sustainable Development and Agenda 21. The same period 2005–2015 also has been proclaimed as the "International Decade for Education for Sustainable Development". This combination of "Water for Life" and "Sustainable Development" is very important and holds promise, also for the preservation and management of water resources.

The fact that two billion people are living under severe water stress, and that most of these people are living in the tropics and subtropics, indicates that the main risk areas lie within the seasonal precipitation regime between the monsoon and Mediterranean type of climate. New demographic data show, that about 70% of the world population is living between 30°N and 30°S, if we include the densely populated plains of the Indus and the Yellow River. This means, about 4 billion compared to a total of 5.7 billion people on our planet live in this climatic and hydrologically sensitive and hazardous zone (2). It is in these regions in particular that the mountains as water towers will play an increasingly important role for the people in the highlands and in the surrounding lowlands. The dryer the lowlands, the greater the importance of the more humid mountain areas. Therefore, water quantity and quality will probably be the most critical topics in mountain research for the coming decades. Water resources in mountain areas may be subject to dramatic changes within the coming decades, due to ongoing and potentially accelerated changes in atmospheric conditions as well as terrestrial systems response. The impact of these anticipated changes is particularly critical for mountain systems, because they constitute the water towers that will be the source of competing uses of water for irrigation, drinking water, hydropower, industrial uses, and partly also for recreational purposes within the mountains and in the lowlands (3).

THE HYDROLOGICAL SIGNIFICANCE OF MOUNTAINS AND HIGHLANDS

Basic Knowledge Gained in the European Alps

The European Alps may serve as a model region for hydrological studies, since reliable and relatively detailed data are available for this area. In the case of the Rhine river, a clear discharge pattern between the mountainous upper section and the lower reaches of the river can be detected as a result of the change in the feeder supply from snow in the mountains to rain in the downstream areas. In an average year, discharge in the Swiss section of the Rhine, which is mainly mountainous, contributes 45% of total discharge, although the catchment area in Swiss territory represents only 22% of the total watershed. In the summer months, the discharge contribution of the Swiss section clearly surpasses 60% with the melting of snow and ice in the high Alps (4). In addition, Baumgartner et al. (5) estimate that precipitation volumes are about 2.2 times larger in the Alps than in Europe, whereas evaporation volumes are comparable, which results in discharge volumes for the Alps 3.3 times larger than those for Europe as a whole. These generalized patterns are further confirmed by an analysis of catchment-based data from the European Water Archives (6), which showed larger precipitation and discharge volumes as well as more reliable discharge patterns for the Alpine section of the Rhine catchment (4). Moreover, it is possible to obtain an overview of the basic hydrologic character of the whole catchment and to differentiate be-

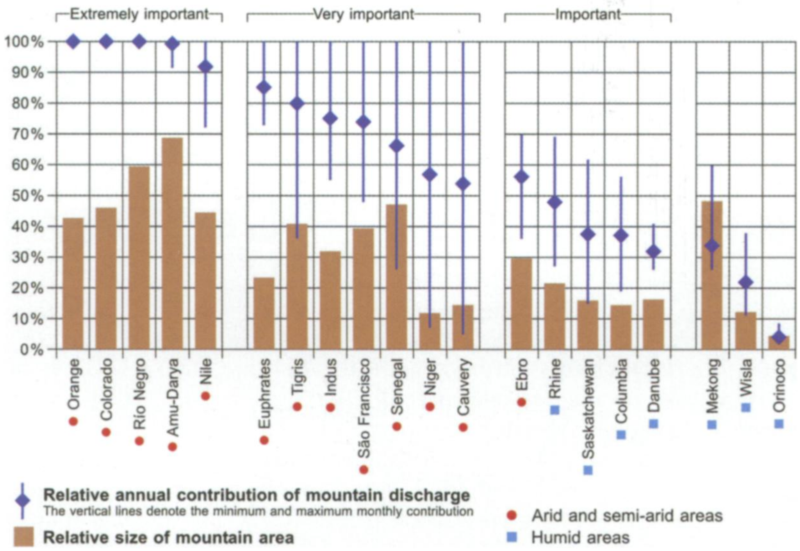

Figure 1. Mean annual mountain contribution to total discharge of freshwater and proportion of mountain area (represented by a gauging station in the vicinity of about 1000 m a.s.l.) relative to the entire catchment for the selected river basin.

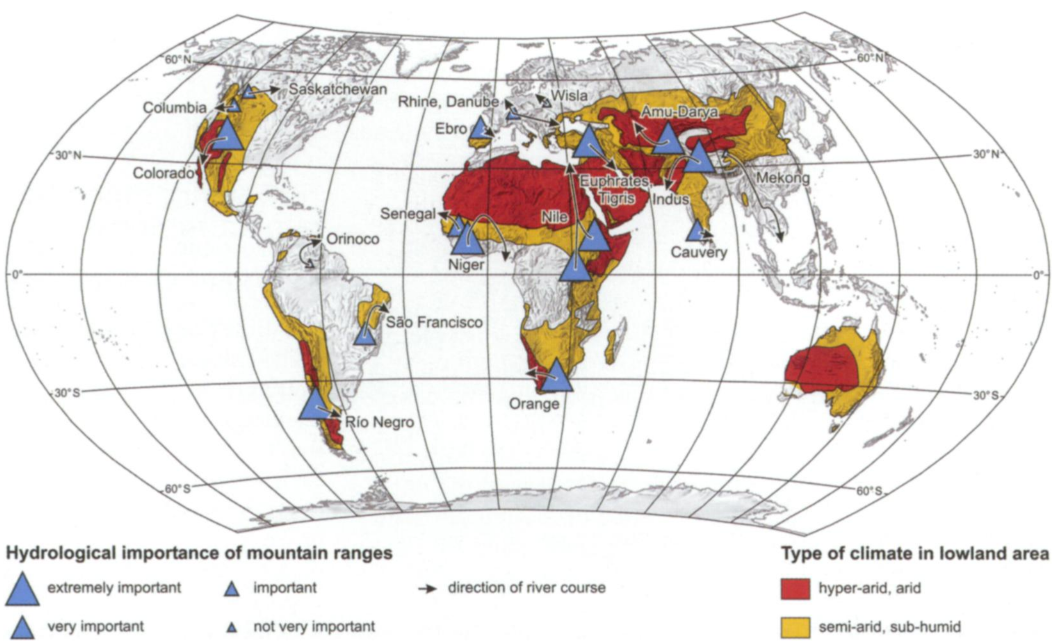

Figure 2. Hydrological significance of mountain ranges for selected river basins, based on Figure 1.

tween mountainous and lowland sections using discharge measurements (4). On that score, insights into the hydrology of mountainous areas can be transferred with due care from the Alps to other major mountain ranges (7). As an example, the discharge pattern of the Euphrates is dominated by large volumes of meltwater from the Pontine and the Taurus mountains, with the result, that mountain discharge between March and May is actually greater than the rest of the total discharge. On the one hand, the low-lying areas generate virtually no discharge at all, and on the other hand, discharge is in fact "consumed" principally for irrigation purposes. Overall, the portion of total discharge generated in the mountain section of the catchment varies between 55% and 100% according to the season (7). Other examples are shown in Figure 1. That this preliminary approach to a global or at least a regional overview stands for an appeal to the strong need for more detailed and better data in order to make more precise assessments about the hydrological significance of mountains.

An Approach to Quantifying Water Towers

A preliminary approach to an assessment of the hydrological significance of mountains and highlands was taken using discharge data provided by the Global Runoff Data Center (GRDC) (8). River basins in various parts of the world were selected as case studies. On a global scale, very few measurement series exist, the periods covered are very limited and the evaluation of the spatial and temporal heterogeneity of discharge conditions in mountain areas is not yet satisfactory for most regions of the world. The relationship between mountains and lowlands was examined, primarily using gauging stations above an altitude of 1000 m and the second one in the vicinity of the river mouth. In addition, it was an important condition, that the upper gauging station was situated in a real mountain relief and topography, ideally as close as possible to the borderline between mountain and plain. In addition, the regional precipitation and temperature conditions were taken into account, in order to incorporate the discharge regime into the climatic context of the region.

In general, the particular characteristics of mountain areas are manifested by disproportionately large discharge, typically about twice the amount that could be expected from the areal proportion of the mountainous section (Fig. 1). Mountains account for 20–50% of total discharge in humid areas, while in semiarid and arid areas, the contribution of mountains to total discharge are 50–90% with extremes of over 90% (Fig. 1; e.g. Nile and Orange in Africa, Amu Darya in Central Asia, Colorado in North America and Rio Negro in South America). Moreover, discharge from mountainous areas is highly reliable and accounts for a significant reduction in the coefficient of variation of total discharge (7). These and other findings were quantified and used to elaborate an overall assessment of the hydrological significance of mountain areas. The study reveals very clearly, that the world's most significant water towers are found in arid and semiarid zones (Fig. 2).

Retarding Effect of Snow and Ice Storage

Knowledge of snow-cover dynamics is a prerequisite of all studies of hydrology, climatology and biology in mountain areas. As an example, the spatial variability of snow cover in the European Alps is very high, due to the orientation in the westwinds, the different climatic conditions on the North- and South-sides, and to the change from the more oceanic western to the more continental eastern side (9). Such differences are probably much more pronounced in the vast mountain systems like the Himalayas and the Andes. So far, only time series of point measurements of the snow-height and water equivalent have been investigated, but no special information on the highly sensitive and dynamic snow-cover are available for longer time series. However, since 1981, the Institute of Geography of the University of Bern receives and archives without any interruption the NOAA-AVHRR data, covering the whole Alps. Since 2001, an operational status is reached, the data with a resolution of 1.1 km^2 for the whole Alps are available immediately after receipt by the ground station (9). If we use the example of the Alps, we should keep in mind, that the same methods and techniques would be possible for the Himalayas, the Andes or the Central Asian mountains. The Aral basin is a very instructive example for such a snow regime (10). In the high mountains of Tien Shan and Pamir, the annual precipitation ranges from 600–2000 mm with 30% falling as snow. The lowland deserts cover most of the basin and are characterized by low rainfall – less than 100 mm yr^{-1} and high evaporation. Because of snow and glacier melt, the flows of the two rivers Amu Darya and Syr Daria are highest in summer and are characterized by a low interannual variability, which is very important for the management of water resources. If we take into consideration that the mountains provide more than 95% of the basin's freshwater, then we understand the high significance of the snow-cover in the mountains for the hydrology in the desert lowlands.

Missing Knowledge: Uncertain Assessment of Vulnerability

The runoff generation in mountain areas is characterized by an extraordinary heterogeneity of topography, vegetation and soils, by a spatially and temporally differentiated snow-cover and especially by extreme events and high seasonal and annual climate variability. Long-range data series are missing in the mountain hydrology, especially in the critical zones of the tropics and subtropics. All this means, that our knowledge is very limited about the runoff generation in different altitudes and under different natural conditions and land-use systems (11). Especially for the semiarid and arid zones it would be important to know, how far the recharge of the groundwater in the alluvial plains is directly connected to the runoff from mountain areas, as it can be seen and measured in the valley bottoms around the Alps. Taking into account the increasing water scarcity in these semiarid and arid regions, especially for irrigation and food production, the current state of knowledge about mountain hydrology is inadequate, and is making sustainable water management and an assessment of vulnerability impossible.

THE DYNAMICS OF THE NATURAL SYSTEM AS A SOURCE OF CHANGING VULNERABILITY

Climate variability and climate change are important elements for the assessment of freshwater resources in the mountains of the different climatic zones. Figure 3 shows the increase of the mean annual temperature with doubled levels of carbon dioxide, taking into consideration not only a horizontal, but also a vertical differentiation of the projected global climate change. The values are zonally averaged, across all longitudes and based on the average of 8 general circulation model simulations, comparing the control runs with the 2 x CO_2 simulations. The values are superimposed on a transect through the Americas from Alaska to Antarctica, which shows the highest points of the mountain ranges (white line). The mean annual freezing line (from radiosonde data) is shown as a black line. The black dots indicate the Global Climate Observing System (GCOS) stations and their distribution with elevation, planned for the western cordilleras of the Americas. The basic document comes from IPCC (12), all additional elements are from R. Bradley, University of Massachusetts, Amherst; (pers. comm). This most fascinating figure shows that the zone of maximum temperature change that the models simulate extends from low elevation in the arctic and sub-arctic to high elevation in the tropics and subtropics on the Northern- and Southern Hemispheres. It is interesting to see, that even the highest peaks do not extend into the zone of maximum warming, but they are still projected to reach the warming zone of 2° to 3°C. This figure is further developed by Bradley in order to avoid a zonally averaged value for all longitudes around the globe. He simply extracted the data for the mountain regions of the transect through the Americas, based on different models. As a result, the study shows almost the same pattern with the same elevation of the maximum warming in the tropics and subtropics. These high temperature increases appear to be directly related to enhanced convection in the rising limb of the Hadley circulation, with release of latent heat.

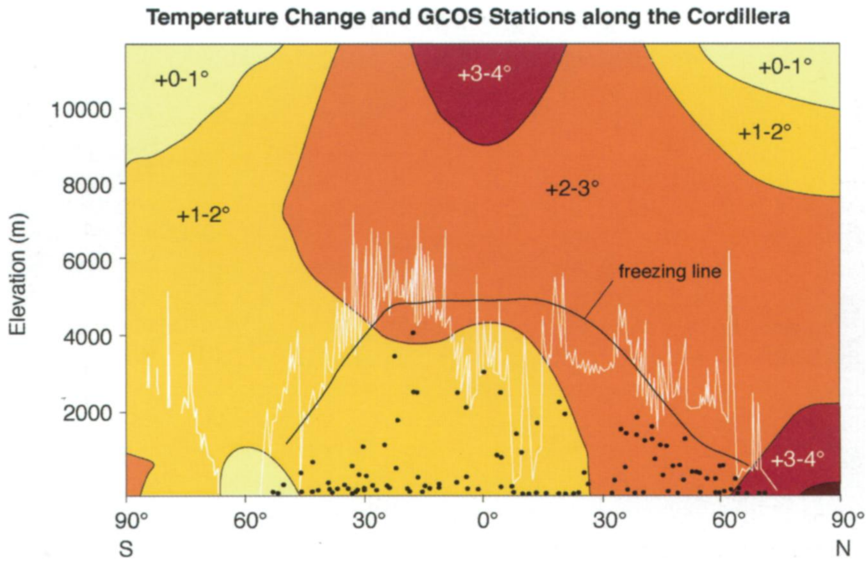

Figure 3. Projected changes in mean annual temperature with 2 x CO_2. A transect through the Americas. The white line shows the highest peaks on this transect and the black line shows the mean annual freezing line. The black dots indicate the planned GCOS stations. For further comments see text. (Pers. comm.).

The temperature data from Barnaul, the main town in front of the Altai mountains in southern Siberia are an interesting contribution to this figure. This climatological station was established in 1835 and has one of the longest ranges of data in Asia. It is interesting to see, that in the 120 years from 1838 to 1958, the mean annual temperature increased by 1.77°C. In the following 43 years from 1958 to 2001 it was 1.45°C, showing a most interesting acceleration of the warming process. In other words, on a latitude of about 50°N, in the center of the Eurasian continent, the mean annual temperature increased over the last 60 years by around 2°C (13). This order of magnitude, much higher than in the mid- and low latitudes of the Northern Hemisphere, is a certain confirmation for the simulated different warming at low elevations, as can be seen in Figure 3.

In the framework of our topic, two points are of interest:

First the planned GCOS stations do not reach—in the critical zone between 30°N and 30°S—the elevation of high temperature change. There are enough mountain peaks, but they are not beeing used to form a network of observatories, which could serve as an early warning system. The Mountain Research Initiative (MRI) has taken up this problem and initiated a planning process for a new and long-term observation and research project in the mountains of the world (14).

Second, we do not know yet, how this differentiated temperature change will affect the precipitation regime in the mountains, especially in this critical zone of the tropics and subtropics. Temperature and precipitation changes must always be regarded as coupled variables. "On a global scale, the term climate change is often equated with the term climate warming. However, the energy cycle of the climate system is intrinsically linked with the hydrological cycle. To a first approximation, it would indeed be more appropriate to equate climate change with climate moistening". This interesting statement, Schär and Frei 2004 (in press), may show the significance of the hydrological cycle, but also the difficulties related to evaluation of potential changes. Precipitation will not occur uniformly, but changes will be associated with specific geographical and topographical patterns and will vary with seasons. More specifically, the mid- and high latitudes are expected to experience a high relative increase in total precipitation, in particular during winter, while there is evidence that subtropical and semiarid regions might experience an increased risk for summer droughts (15). Moreover, heavy precipitation events, which are most important for the hydrological processes, are not directly linked to mean precipitation amounts. Without going into more details it is obvious that the consequences of global "warming" on global "moistening" is still a very complex and partly contradictory research process. As an example, we quote the IPCC report (12) with the projected changes of the mean annual runoff data for 2050, compared with the values for 1961–1990. Two different general Ocean-Atmosphere-Circulation Models of the Hadley Center with a 1% annual increase of CO_2 were used to draft these two world maps. A close comparison shows the very different results, especially for mountain regions like the southern Rocky Mountains, the Andes, parts of East Africa, Central Asia, the Himalayas and the Indian plains, etc. Clearly, we are confronted with serious uncertainties, especially for the developing countries in this highly sensitive climatic zone, where mountain water resources play a fundamental role for the adjacent lowlands. Moreover, even slight changes in the temperature regime can have strong impacts on the snow-cover and on the glaciers, which influence or even change the runoff regime. In this sense, a network of high mountain observatories should have a high priority as an indicator system for the whole water cycle and for water supply. This is one important element in the life support systems, especially in the semiarid and arid regions, which cover most probably more than 40% of the earth's land surface. Changes in natural systems will determine the changes in the vulnerability of the most sensitive mountain ecosystems.

THE DYNAMICS OF THE HUMAN SYSTEM AS A SOURCE OF CHANGING VULNERABILITY

FAO has used the UNEP – WCMC (World Conservation Monitoring Centre) definition of mountains (16, 17) with 6 altitudinal classes, covering about 22% of the earth's surface. Areas with an altitude of 2500 m or higher are always classified as mountains. Between 300 and 2500 m, areas are considered mountainous if they exhibit steep slopes or have a wide range of elevation in a small area or both. The Lofoten Islands in northern Norway may serve as an example. Very steep walls of rock, more than 1000 m high, beginning just at sea level, the tops covered by snow even in the summer months.

FAO used its own unique databank about population, livelihoods and land use, constraints and vulnerability of mountain people, in a special GIS-based analysis (17) to classify these data and to integrate them in the abovementioned mountain definition with a special focus on the developing world. As a result, FAO estimate the total number of mountain people at 718 million in 2000. Of these, 625 million live in developing countries and the Commonwealth of Independent States, former Soviet Union (CIS). Of the total mountain area in these countries 60% is located at altitudes below 1500 m, and 70% of the mountain population lives there. By contrast, only 15% of the mountain area is situated above 3500 m, and only 2.5% of the population inhabits these regions. Although urbanization and the growth of mountain cities is important in some regions like the Andes, more than 75% of mountain people in developing countries and the CIS are still rural (16).

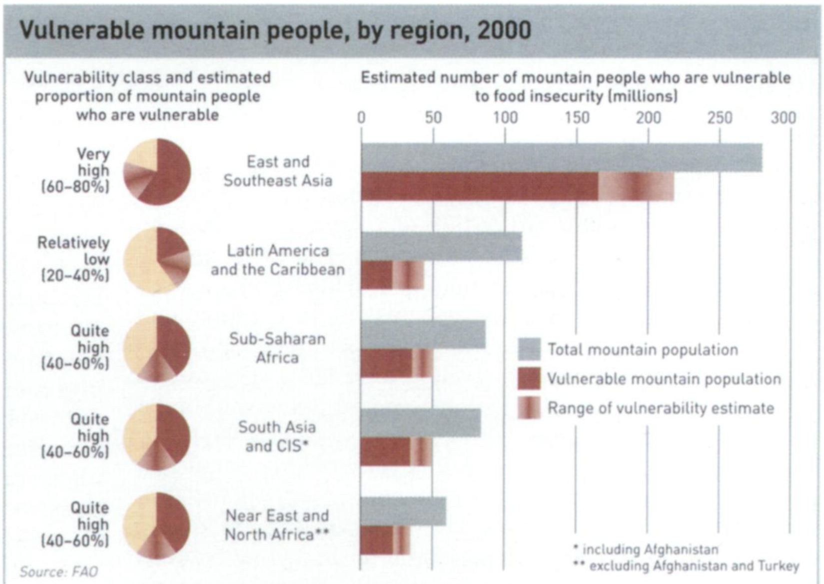

Figure 4. FAO estimates that 625 million people are living in the mountains of the developing countries and the CIS. Probably more than half are living in a situation of food insecurity (16).

Most interesting in relation to our topic is FAO's estimate that about 40% of the mountain area in developing countries and the CIS produces less than 100 kg of cereals per person per year. Rural people living in such locations have difficulty in obtaining an adequate livelihood from agriculture. FAO has used estimates of their number together with other qualitative information to arrive at a preliminary estimate of the number of mountain people who are vulnerable to food insecurity. Based on information currently available, more than half of the mountain population in developing and CIS countries, in the range of 250 – 370 million people, are vulnerable to food insecurity (Fig. 4). This estimate of vulnerability should not be confused with FAO's estimates of the undernourished population. Typically, about half of those identified as vulnerable are actually undernourished (16).

Without taking into consideration all the other factors and constraints, which could contribute directly or indirectly to vulnerable food insecurity like climatic conditions and extreme events, water availability, soil quality, demographic pressure or emigration, social and cultural aspects, political constraints, poor accessibility and isolation, missing education and health service, nonexistent integration in a local market or a national economy, etc., we must accept that food insecurity is not only an important, but also an integrating factor for the vulnerability of a society. The consequences of such a situation are serious. Either we have an emigration or we have an extension and intensification of the land-use system. Extension entails the use of marginal land and crossing some ecological thresholds, e.g. going too high, and becoming endangered by frost, or going too steep, and becoming endangered by erosion. Excessive intensification of agricultural practices can lead to the impoverishment of the soils, to erosion or with the use of too much fertilizer to pollution of the water sources. Food insecurity can be the beginning of destructive impacts on land use and land cover, on mountain ecosystems and especially on the most sensitive headwater systems.

In all our future research projects it is always instructive to pay attention to paleoenvironmental experiences. Plato wrote about 400 years BC : "...and it had much forest-land in its mountains...what now remains compared with what then existed is like the skeleton of a sick man..."(18). The following generations had to survive in destroyed ecosystems and damaged hydrological systems, the price was then and is still very high. What is happening today in some parts of the African mountains, happened 2400 years ago in some parts of the Mediterranean mountains.

In all future research projects we need to look back, but we also need to look forward. We must integrate human activities, they are important driving forces in the framework of global change research. For the Mountain Research Institute an ideal situation would be cooperation with UNESCO's Mountain Biosphere Reserves (MBR) and situating, wherever possible, high mountain observatories in a Mountain Biosphere Reserve (19). Today, about 440 Biosphere Reserves exist, about 200 in the mountains of the world. Each Biosphere Reserve is intended to fulfil three basic functions, which are complementary and mutually reinforcing: *i)* conservation (biodiversity, ecosystems); *ii)* development (environment and development); and *iii)* logistics (international network for research and monitoring). Moreover, the concept of a Biosphere Reserve contains several zones: a core zone (in mountains mostly the unused higher altitudes); a buffer zone (restricted use of ecosystems); and a development zone (in mountains mostly the lower parts or the valley bottoms with all the human activities (21). But we should not forget, in a time of climate variability and climate change, that the hydrological cycle reproduces changing conditions in the sensitive ecosystems of higher altitudes (snow, glacier, permafrost, highest vegetation limits), and transfers this message down to the human system, to land use, settlements, infrastructure, etc. before any other component of the environment in lower altitudes shows a first signal of change.

Looking into the future, mountains as water towers are threatened by other types of intervention. Until recently, dams and reservoirs were constructed in the mountains to store the water used for irrigation in the dry season. But the order of magnitude has begun to change, with new technological and engineering possibilities, the water is no longer stored in the mountain areas, it is diverted and transported over long distances. An example is the recent report on the "River Link Mega Project" in India (21). Why should 97% of the Brahmaputra water flow unused into the Gulf of Bengal, when India is suffering from water scarcity? The project should, ideally, link 37 big river systems. This will need 32 dams, 9600 km of canals, pumps and power stations, with the overall goal being to link even southern India to the Himalayas with the water from Brahmaputra and Ganges.

China has begun construction of a huge project, called the "South–to–North Water Transfer", from the Yangtze River to the Yellow River on three levels, from west to east with an upper, a middle, and a lower canal system. The longest of these canals extends more than 1000 km (22). Lesotho is selling its mountain water to an agglomeration in Johannesburg, and a transfer of water from the Pyrenées to southern Spain is under discussion. More projects and more conflicts will come, especially, where water crosses international borders. This is yet another aspect of vulnerability, but also strongly related to ongoing natural and human environmental changes.

NATURAL AND HUMAN DRIVING FORCES: VULNERABLE WATER TOWERS

Locally and regionally differentiated changes in temperature, precipitation, snow-cover and glacier storage are likely to alter discharge from mountain-dominated areas with respect to timing, volume, and variability, and will ultimately influence runoff characteristics in lowlands. Catchments which are dominated by snow are particularly sensitive to change, and will therefore be most strongly affected by shifts in discharge patterns.

Snowpack makes up 75% of all water in streams throughout the west of the United States, but now the snowpack levels have dropped considerably throughout the American West in response to a 0.8°C warming since the 1950s. Some areas in the Cascade Mountains of Oregon and Washington saw a decline of 60% in total snow accumulation. The biggest decreases occurred at the lowest elevation, suggesting a rise in the freezing level (23). The was observed in the Alps with decreasing snow-cover at lower elevations and even increases at higher elevations.

Not only is the global climate changing, in addition population growth in critical lowland areas will accentuate the pressure on mountain water resources. This may be shown more clearly by the abovementioned large-scale projects. According to the World Development Indicators of the World Bank (24), 65 countries use over 75% of their available freshwater for agriculture, that is for food production. Included in this list of 65 countries are Egypt, India, China, all countries which rely on mountain discharge. Even if these data are not very reliable, as the World Bank confirms, the order of magnitude is impressive. If a country has to use more than 75% of its freshwater for agriculture alone, how much is then available for rapidly increasing urbanization and industrialization? Of course, there are possibilities to improve agricultural production systems, but all the same, conflicts between water users are unavoidable. The dependence on scarce water resources for the whole of the development process is alarming and a feedback effect on mountain resources and ecosystems is inevitable.

Taking into consideration these driving forces from the natural and the human points of view, it becomes a high priority for mountain research projects to initiate a high mountain network of observatories in the framework of the "Global

Change Research Programs". The highest and the most sensitive mountain ecosystems throughout all of the climatic zones, in a transect, pole – equator – pole, are necessary as important indicator systems. Input from the natural sciences must be coupled through the Biosphere Reserves, to the human and social sciences and to local populations. This is imperative in order to develop, immediately, the necessary strategies for mitigation and adaptation to global environmental change processes. Strong cooperation is needed between the different mountain research projects Mountain Research Initiative MRI, Global Mountain Biodiversity Assessment (GMBA) (25) and Global Observation Research Initiative in Alpine Environments (GLORIA) (26). Moreover a very close collaboration with UNESCO's Mountain Biosphere Reserves Program, with FAO as the leading agency for the mountain chapter (Chapter 13 in Agenda 21) and for the Mountain Partnership Program and with other UN-organisations is a prerequisite to better management of mountain areas. The main goal must be to preserve the functional integrity of the mountain landscapes and ecosystems and to guarantee sustainable use of mountain water resources.

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Bruno Messerli studied geography and geology at the University of Bern. He became a full professor in 1968. He was Director of the Geographical Institute 1979–1984 and Rector of the University of Bern 1986/87. Professor Messerli has conducted field work on problems of glaciation, climate history, environmental change and natural resources in the Alps, in the mountains of Africa, in the Himalayas and the Andes. He was Chair of the UNESCO MAB – Mountain Program and Coordinator UNO Mountain Program.
bmesserli@bluewin.ch

Rolf Weingartner studied geography and geology at the University of Bern. He became a professor 2003. Since 1989 he has been Head of the Group of Hydrology and Editor-in-Chief of the Hydrological Atlas of Switzerland. He has conducted research projects in the Swiss Alps, in the Southern Alps of New Zealand and in the Himalayas. His research interests include: regional and mountain hydrology, floods, processes of runoff generation.
wein@giub.unibe.ch

Daniel Viviroli studied geography and geology at the University of Bern, where he received a MSc Diploma in 2002. He is currently doctoral student at Bern University and the Swiss Federal Institute of Technology in Zürich. Research Associate in the Hydrology Group in Bern. Research interests: Mountain hydrology, water resources, hydrological modelling, floods.
viviroli@giub.unibe.ch

Their address: Institute of Geography, University of Bern, Hallerstrasse 12, CH-3012 Bern, Switzerland