

Abstract

Mountain and Hydrology Research has a long tradition, but only the Rio Conference 1992 created a real breakthrough for a new awareness about the mountains of the world and their natural and human resources. In the years 1997 and 1998 the mountains as water towers for a thirsty planet got a special interest of the UN institutions, which led not only to the International Year of Mountains 2002 and the International Year of Freshwater 2003, but also to a better cooperation between science and policy.

The particular hydrological characteristics of mountains areas are manifested by disproportionately large discharge, compared to the surrounding lowlands. Mountains account for 20-50% of total discharge in humid temperate regions, while in semi-arid and arid areas, the contribution of mountains to total discharge are 50 – 90 % with extremes of over 90 % (e.g. Nile, Colorado, Orange, Syr Daria, Amu Daria, Rio Negro etc.). Moreover, discharge from mountainous areas is highly reliable and causes significant reduction of the coefficient of variation of total discharge. These findings were quantified and used to elaborate an overall assessment of the hydrological significance of mountain areas. The dryer the lowland, the greater the importance of more humid mountain areas.

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

Increasing demands on limited water resources ensure that mountains water resources will play an increasing important role in the 21st century. But we need more and better data,

especially for the mountains of the tropics and subtropics, and this means for the developing world, where water scarcity means immediately food shortage. The scientific community has the responsibility to analyse the consequences and complex interactions of climate, water and land-use changes, but also of growing population and its impact on watershed management and agriculture-forestry-policy, in order to develop adequate long-term strategies on water resources management in the mountains and highlands for the surrounding lowlands.

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

Bruno Messerli

Institute of Geography, University of Bern
Hallerstrasse 12, 3012 Bern
Switzerland

Phone: 0041 / 31 / 819 33 81
E-mail: bmesserli@bluewin.ch

1. DEVELOPMENT OF A GLOBAL POLICY SINCE RIO DE JANEIRO 1992

The strong orientation of the Rio Conference towards the environment and development provided the setting for an intervention in the PrepCom 1991 in Geneva and that of early 1992 in New York to ensure the inclusion of a Mountain Chapter in Agenda 21. This was enthusiastically supported by the delegates from the Himalayas, the Andes and East Africa, who had experienced international co-operation through the International Centre for Integrated Mountain Development (ICIMOD, founded 1983 in Kathmandu, Nepal), the African Mountain Association (founded 1986 in Addis Ababa, Ethiopia) and the Andean Mountain Association (founded 1991 in Santiago, Chile). The new chapter was unanimously accepted 1992 in the so-called Earth Summit. However, its importance was not properly understood by many political delegations. Rather, it was assumed that natural hazards, land use problems, agriculture and forestry and all aspects of development and conservation were part of national policies and national competences that could hardly be classified as having international or even global importance.

This perception changed for the better at the UN special General Assembly for the evaluation of Agenda 21 in New York 1997, five years after Rio. The initiatives of FAO as the officially designated task manager of the Mountain Chapter of Agenda 21, UNESCO and UNU with their mountain research and development programmes, the foundation of the Mountain Forum 1995 and a lot of local to regional non-governmental initiatives were fundamental to provide greater awareness for the mountains of the world. But most important was to rethink the global significance of mountains between 1992 and 1997. As a result the

book , “Mountains of the World - A Global Priority” (Messerli and Ives 1997), and an attractive brochure with the title “Mountains of the World – Challenges for for the 21st Century” (Mountain Agenda 1997) were presented to this special UN General Assembly in New York 1997. It was at this point that the political delegates began to understand the global significance of mountains. The expression “water towers” was used for the first time and it was also clearly said, that cultural and biological diversity, vital recreation areas of an ever more urbanised world population, sacred places in a lot of cultures and religions, privileged regions for protection and especially the water resources have not only a local or national importance, but much more an international regional to global significance.

Only one year later, 1998, water problems were the main topic on the Agenda of the UN Commission for Sustainable Development (UNCSD) in New York. For this commission meeting a new attractive brochure with the title “Mountains of the World – Water Towers for the 21st Century” was created and presented to the national representatives of the UN member countries (Fig. 1; Mountain Agenda 1998). To present a global overview of mountain water resources was still very difficult, due to missing data and missing methodical approaches. But case studies from Europe, Africa, Asia and the Americas showed very clearly that quite all the major rivers of the world have their headwaters in mountains, probably more than half of humanity relies directly or indirectly on the fresh water that accumulates in mountains. This message was well understood in the global political arena: the mountains of the world were no longer merely local and national problems, they had become globally significant in and for the 21st century. Based on this new understanding, the decision for an “International Year of Mountains 2002” was taken shortly after the UNCSD meeting. Finally, as a great surprise, the General Assembly decided in the year 2000 to declare 2003 as the “International Year of Freshwater”. These two joint international years on mountains and on freshwater offered the

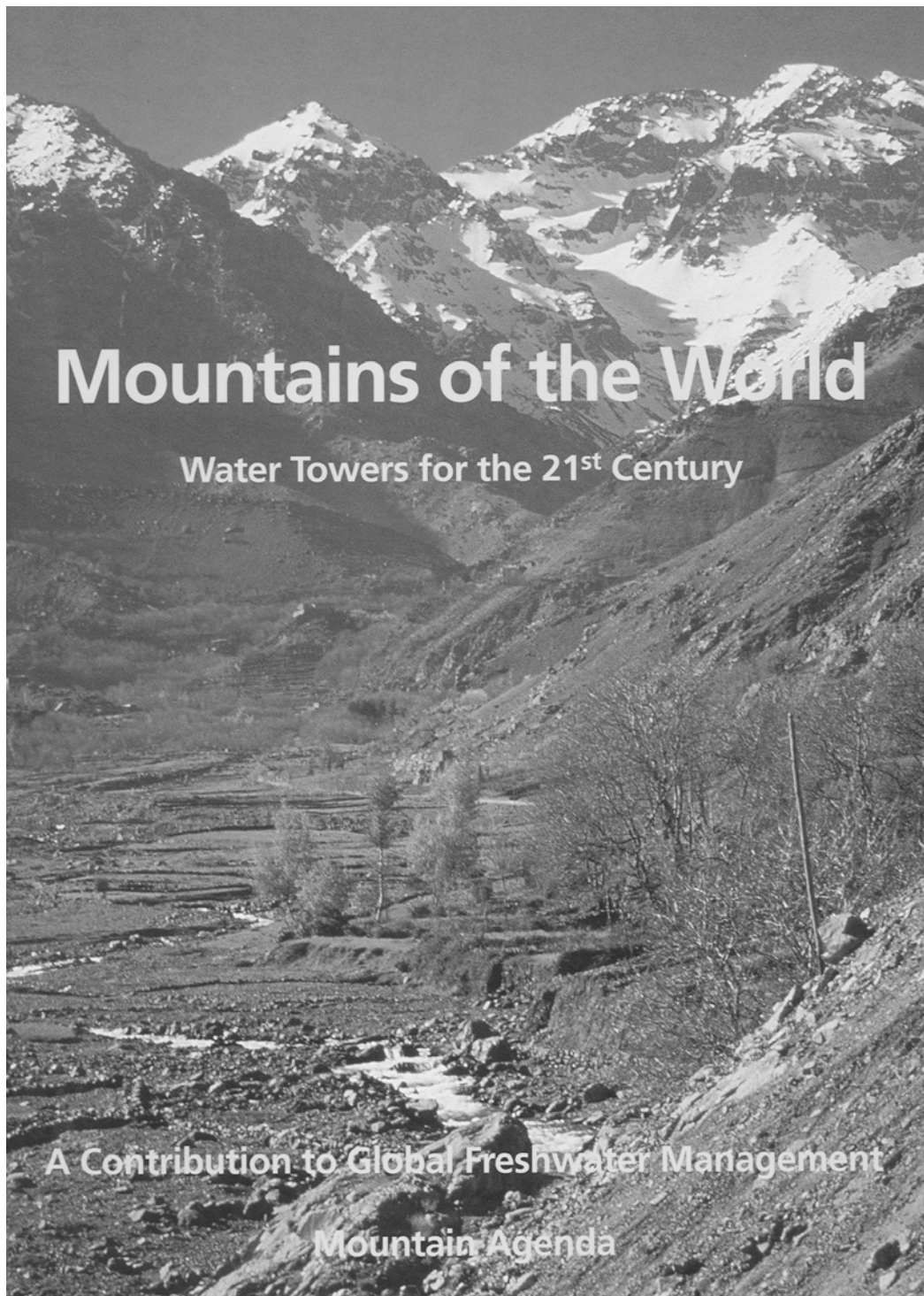


Fig. 1: First publication about the hydrological significance of the mountains of the world for the United Nations Commission on Sustainable Development (UNCSD) for the 1998 spring session on “Strategic Approaches to Freshwater Management”. Front cover: High Atlas, Morocco, Toubkal 4165 m: A water tower for the intensively irrigated land use systems in the valley bottoms and surrounding lowlands (Mountain Agenda 1998).

possibility not only to cooperate, but also to improve the information for the the political community and to encourage the scientific community to take new initiatives and new responsibilities for basic and applied research projects on mountain water resources and mountain watersheds.

Besides the official UN policy decisions there have been and there will be a lot of international institutions and initiatives with a focus on mountain water resources. For example: major international conferences on Headwater Control took place since 1989, focused on field-oriented grassroot movements. This organisation published together with UNU and the International Association of Soil and Water Conservation the so-called Nairobi “Headwater Declaration for the International Year of Freshwater 2003 (UNU 2002), but without any quantification of mountain water resources. An other example is the UN “World Water Assessment Programme”, but even in the third World Water Forum in Kyoto 2003, mountain water resources did not exist in the preliminary programme and only thanks to a last minute intervention of UNESCO (2003), it became one of many symposia in a huge conference.

In summary, the five years from Rio 1992 to New York 1997 were the time which was necessary to upgrade the significance of mountains and their resources from the national to the global level. The following years from New York 1997 to the “World Summit on Sustainable Development” (WSSD) in Johannesburg 2002, the International Year of Mountains 2002, the International Year of Freshwater 2003 and finally the International Decade for Water for Life 2005 – 2015 were the decisive years to think not only about longer term strategies and initiatives, but to think also about a better cooperation between policy and science from the local to the global level.

2. HYDROLOGICAL SIGNIFICANCE OF MOUNTAINS AND HIGHLANDS

Mountains and Highland play a fundamental role for the available freshwater in the surrounding lowlands. However, as far as quantification of this significance is concerned, there is a good deal of uncertainty in the scientific world (e.g. Rodda 1994). A recently published study estimated the proportion of mountain discharge to global total discharge at 32 percent (Meybeck et al. 2001), while other studies indicate figures between 40 and 60 percent (Bandyopadhyay et al. 1997). From a regional point of view, mountain discharge can represent as much as 90 percent or more of the total discharge of a catchment (Mountain Agenda 1998). On a global scale, few measurement series exist for discharge in mountainous regions and the periods they cover are extremely limited. This restricted data base does not measure up to the high degree of spatial and temporal heterogeneity of discharge conditions in mountain areas. This means, for assessing the hydrological importance of mountains we have to take into consideration the increasing uncertainty and generalisation from the local to the global level. Additionally, in water-scarce regions discharge data have a high strategic value and are frequently kept secret. This makes basic scientific studies more difficult and mitigation of conflicts over water resources quite impossible.

Basic knowledge gained in the European Alps

The European Alps may serve as a model region for studies in mountain hydrology because of the reliable and detailed data. In the case of the River Rhine, a clear contrast in the 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 mountainous Swiss section of the Rhine above Lake Constance, contributes 34 percent of total discharge at Lobith, close to the mouth in the Netherlands, although the mountain catchment area within Swiss territory represents only 15 percent of the total watershed. In the summer months, the discharge contribution of this alpine Swiss section clearly surpasses 50 percent when the melting of snow and glacier ice produces high and reliable discharge volumes (Viviroli and Weingartner 2004 a).

The mountainous part of the Rhine River plays a distinctive role in the hydrology of the whole basin because of higher precipitation, lower evaporation and, consequently, more effective runoff generation in the Alps as compared to that in the lowlands, especially in the summer months. This is illustrated in Figure 2, showing the resulting water balance components for two sub-catchments of the Rhine basin: the climatological water balance (precipitation minus evaporation) in the alpine sub-catchment is markedly higher because of higher precipitation and lower evaporation than that of the upper Rhine catchment (Karlsruhe) about 550 km downstream. Together with seasonal storage in winter, this mountain influence predominates between May and August when melting of snow and glacier ice produce a significant runoff. This summer runoff from the Alps arrives downstream at a time of negative water balance, thus compensating for the smaller and partly negative water balance term (Fig. 2). In the higher central Alps even precipitation of 2088 mm for the period 1969 – 1990 were measured and this means 1711 mm runoff and 382 mm evaporation, suggesting that 82 % of the precipitation is available for runoff as well as seasonal and long-term storage (Schädler and Weingartner 2002). But also the high stability and decreasing variability with increasing mean altitude are important aspects of runoff in mountain areas. The influence of snow (nival regime types above approximately 1550m mean basin altitude) and of glacial regime

types (approximately above 1900m mean basin altitude) becomes decisive, in contrast with the more irregular precipitation processes in lower altitudes (Viviroli and Weingartner 2004 b).

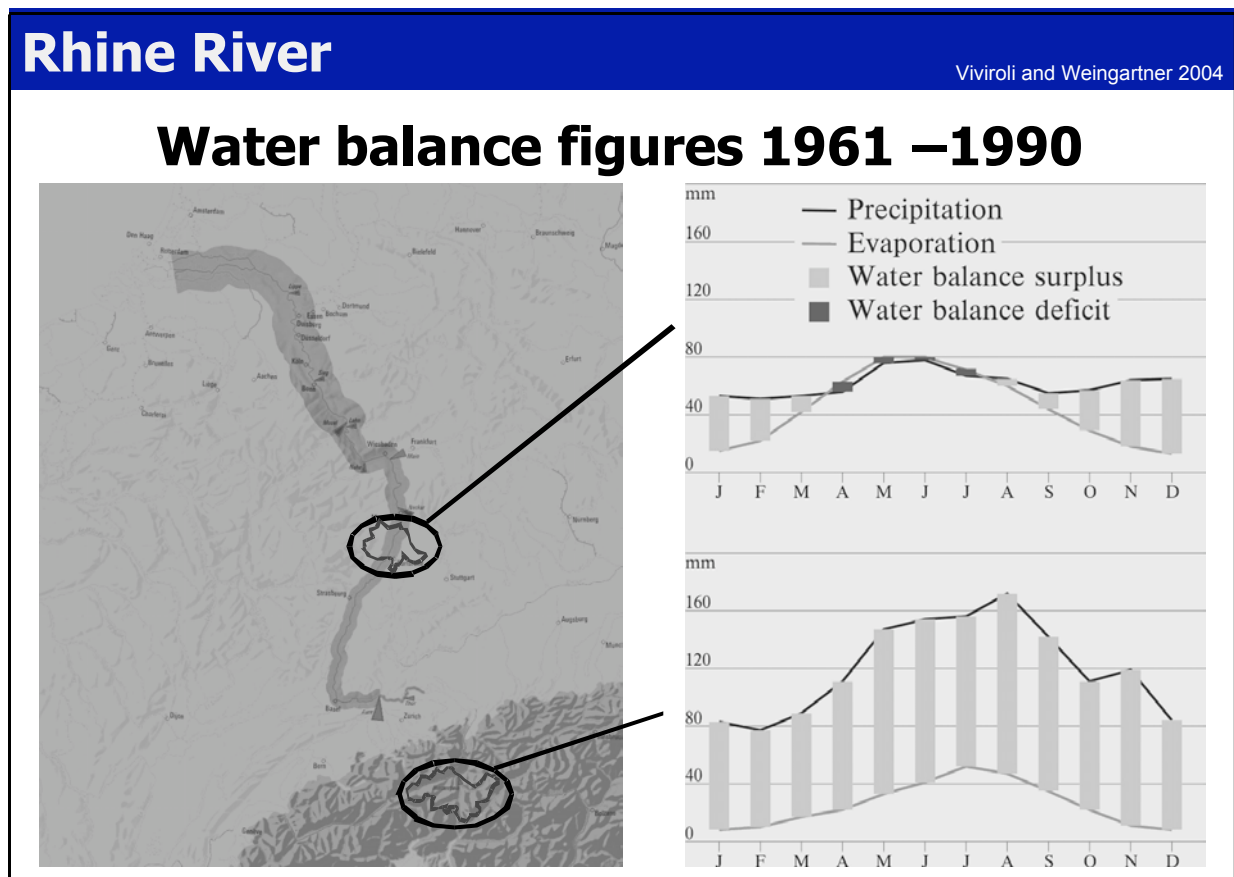


Fig. 2: Mean annual water balance 1961 – 1990 for two selected sub-catchments of the Rhine River with the stations Felsberg in the Alps (mean altitude 1989m, area 321 km²) and Karlsruhe in the upper Rhine valley (mean altitude 177m, area 1944 km²): A.climatological water balance (Viviroli and Weingartner 2004 a; GRDC 1999).

Extending the view to the European Alps in their entirety, Table 1 examines the four major streams which drain the alpine arc. As observed in the Rhine River, runoff formation is disproportionately high in relation to relative catchment areas. The Alps, situated in a humid temperate climatic zone, play a remarkably important role for western Europe with a mean contribution of 26 to 53 % of total discharge and 36 to 80 % of summer discharge. This raises

Hydrological Significance of the Alps

	Mean alpine contribution to total discharge (%)	Summer alpine contribution to total discharge (%)	Alpine share in surface area (%)	Disproportional influence of the Alps
Rhine	34	52	15	2.3
Rhone	41	69	23	1.8
Po	53	80	35	1.5
Danube	26	36	10	2.6

Tab. 1: The hydrological significance of the four main rivers of the Alps for western Europe (Viviroli and Weingartner 2004 b).

two questions: What would Europe look like without the Alps and more important, if the mountains have such an importance in the humid – temperate zone, what would be their hydrological significance in the most critical and vulnerable arid and semi-arid regions, which cover more than 40 % of the land surface and which show a rapidly growing population in the semi-arid areas of the developing world?

General knowledge gained in the World's Mountains

In sharp contrast to the large temporal and spatial variability of hydrological processes in mountain areas, the availability of long-term measurements series for higher altitudes is very limited on a global scale and especially for the mountains of the tropics and subtropics. Public access to data is further hindered in regions of frequent water-scarcity for political reasons, especially in South Asia. On the basis of knowledge gained from studying the hydrology of the Alps, a data-based approach to assess the hydrological significance of mountains was taken using discharge data provided by the Global Runoff Data Centre in Koblenz, Germany (GRDC 1999). The pattern of mean monthly discharge, changes in specific discharge with increasing catchment size and the coefficient of variation in mean monthly discharge proved to be particularly suitable parameters for assessing the hydrological significance of a mountainous region. More than twenty river basins in various parts of the world were selected for case studies on the basis of climatic and topographical criteria and availability of data (Viviroli et al. 2003). The choice of the case studies aimed at covering a wide range of climatic zones and the most important mountain ranges. The inner tropical area with the two major rivers Amazon and Congo was omitted because high tropical rains also in the lowlands clearly dominate the hydrograph and override mountain influences. But also the polar and part of the subpolar regions are not depending only on mountain water resources, because the melting snow in the big plains of the Northern continents have also a strong impact on the total amount of discharge.

The most restricting criteria proved to be the presence of accessible, reliable and representative data, with the gauging stations being suitably distributed across the river course. The interrelation between mountain and lowland discharge for each case study was examined through a gauging station above an altitude of 1000 meters which served as “mountain station” and a second one in the vicinity of the river mouth which served as “lowland station”. But it was carefully checked that the “mountain station” was in an area

with mountain relief in order to exclude plains in higher altitudes. Rivers influenced by major dam storage have also been excluded. To assess specific discharge patterns along the rivers, all available stations were used. Regions without suitably located stations were excluded from the study. In addition, regional precipitation and temperature conditions were taken into account in order to incorporate the discharge regime into the climatic context of the region.

First of all, the particular hydrological 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. Mountain discharge portions of 20–50% of total discharge are observed in humid areas as it could be shown for the Alps, while in semi-arid and arid areas, the contribution of mountains to total discharge amounts up to 50–90% with extremes of over 95% (Fig. 3). The Orange (South Africa) and Colorado Rivers, the Rio Negro (Patagonia), the Amu-Darya (Aral basin) and the Nile are by far the most dependent on mountain discharge. In the Euphrates, Tigris, Indus, Sao Francisco (Brazil) Senegal, Niger (West Africa) and Cauvery (South India) river basins, the rate of mean mountain contribution is lower, but still exceeds 50 %. In addition there are months when mountain discharge represents almost 100 % of total discharge and therefore, seasonal data are of vital importance for the lowland areas downstream. For most of the remaining catchments (Ebro, Rhine, Rhone, Saskatchewan, Columbia, and Danube), the mountain contribution remains between 30 and 60 %. Exceptions are the Mekong and Orinoco river basins where runoff contributions from the mountains are less than expected.

The compensatory effect of mountain discharge on total discharge was estimated through comparison of year-to-year variability of monthly flows at the selected mountain and lowland stations. The difference signifies the reduction in total discharge variability through the

Proportion of mountain discharge

Viviroli et al. 2003

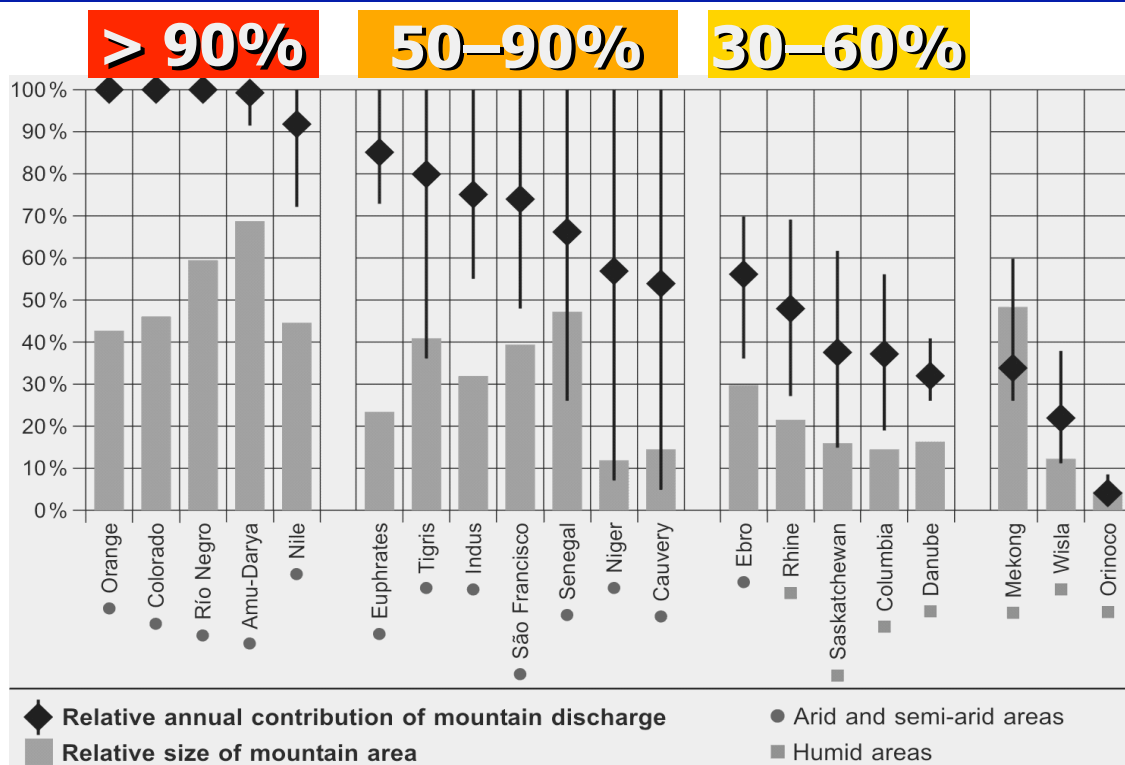


Fig. 3: Mean annual mountain contribution to total discharge of freshwater and proportion of mountain areas (represented by a gauging station in the vicinity of about 1000 m altitude or higher) relative to the entire catchment for the selected river basin. The vertical lines denote the maximum and minimum monthly amount of discharge (Viviroli et al. 2003).

influence of the more reliable mountain runoff. This effect generally corresponds with disproportionate mountain runoff contributions; its magnitude is vast for the Colorado and Indus rivers and is clearly discernible in basins under significant mountain influence. Even for the Orinoco and Mekong rivers which do not benefit so much from disproportionate volumes of mountain runoff, a clear reduction in runoff variability can be observed thanks to mountain influence (Viviroli and Weingartner 2004 a).

The retarding effect of snow and ice storage

The knowledge of snow cover dynamics is a prerequisite for 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 west-winds, the different climatic situation on the North- and South-side and the change from the more oceanic western to the more continental eastern side. Such differences are probably much more pronounced in the huge mountain systems like the Himalayas and the Andes, but there only point measurements of the snow-height and water equivalent were investigated, no longer time series on the highly sensitive and dynamic snow-cover. But since 1981, archives without any interruption have the daily NOAA-AVHRR data, covering the whole Alps. Since 2001, an operational status is reached, the data with a resolution of 1,1 km² for the whole Alps are available immediately after receipt by the ground station (Wunderle et al. 2002). This example shows that the same methods and techniques could be used for the Himalayas, Andes or Central Asian mountains. The Aral basin is a very instructive example for such a snow regime (Spreafico 1997). 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 less than 100 mm/ yr rainfall 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 in a densely irrigated land use system. If we take into consideration that the mountains provide more than 90% of the basin's freshwater, then we understand the high significance of the snow cover in the mountains for the calculation of the water resources 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 mountains of the developing world and especially – as we said - 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 (Gurtz et al. 2003). Especially for the semi-arid 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 regions, especially for irrigation and food production, the todays state of knowledge about mountain hydrology is insufficient and makes a sustainable water management and an assessment of its vulnerability quite impossible.

3. CLIMATE CHANGE AND ITS IMPACT ON MOUNTAIN WATER RESOURCES

The complex relationship between global warming, precipitation and runoff

It is a very difficult question how the differentiated temperature change will affect the local to regional precipitation regime in the mountains of the world. Temperature and precipitation changes must be always 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. The total moisture content of the atmosphere will increase by about 6% per degree warming”

(Schär and Frei 2005: 258-259). This interesting statement may show the significance of the hydrological cycle, but also the difficulty to evaluate 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 higher relative increase in total precipitation, in particular during winter, while there is evidence that sub-tropical and semi-arid regions might experience an increase risk of summer droughts (Weatherald and Manabe 1995). 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 of this interesting discussion, we must state that the consequences of the global “warming” and the global “moistening” are still a very complex and partly contradictory research process. As an example, we quote the IPCC (2001) report with the projected changes of the mean annual runoff data for 2050, compared with the values 1961 – 1990. Two different general Ocean-Atmosphere-Circulation Models of the Hadley Center with a 1% annual increase of CO₂ were used to draft these two instructive world maps (Fig. 4). A comparison shows the very different results, especially also for mountain regions like the southern Rocky Mountains, the Andes, parts of East Africa, Central Asia, the Himalayas and the Indian plains, etc. This means very clearly that we are confronted with serious uncertainties, especially for the developing world in this highly sensitive climatic zone, where the mountain water resources play a fundamental role for the adjacent lowlands. Moreover, we should not forget that even slight changes in the temperature regime can have strong impacts on the snow cover and on the glaciers, which again influence or even change the runoff regime. In this sense, a network of high mountain observatories would have a high priority as indicators or as early warning system also for the water cycle and the water supply in regions with an uncertain precipitation regime. As a whole, climate change and climate variability have an impact on the human system and also on the most sensitive mountain ecosystems, which again have an effect on the human system.

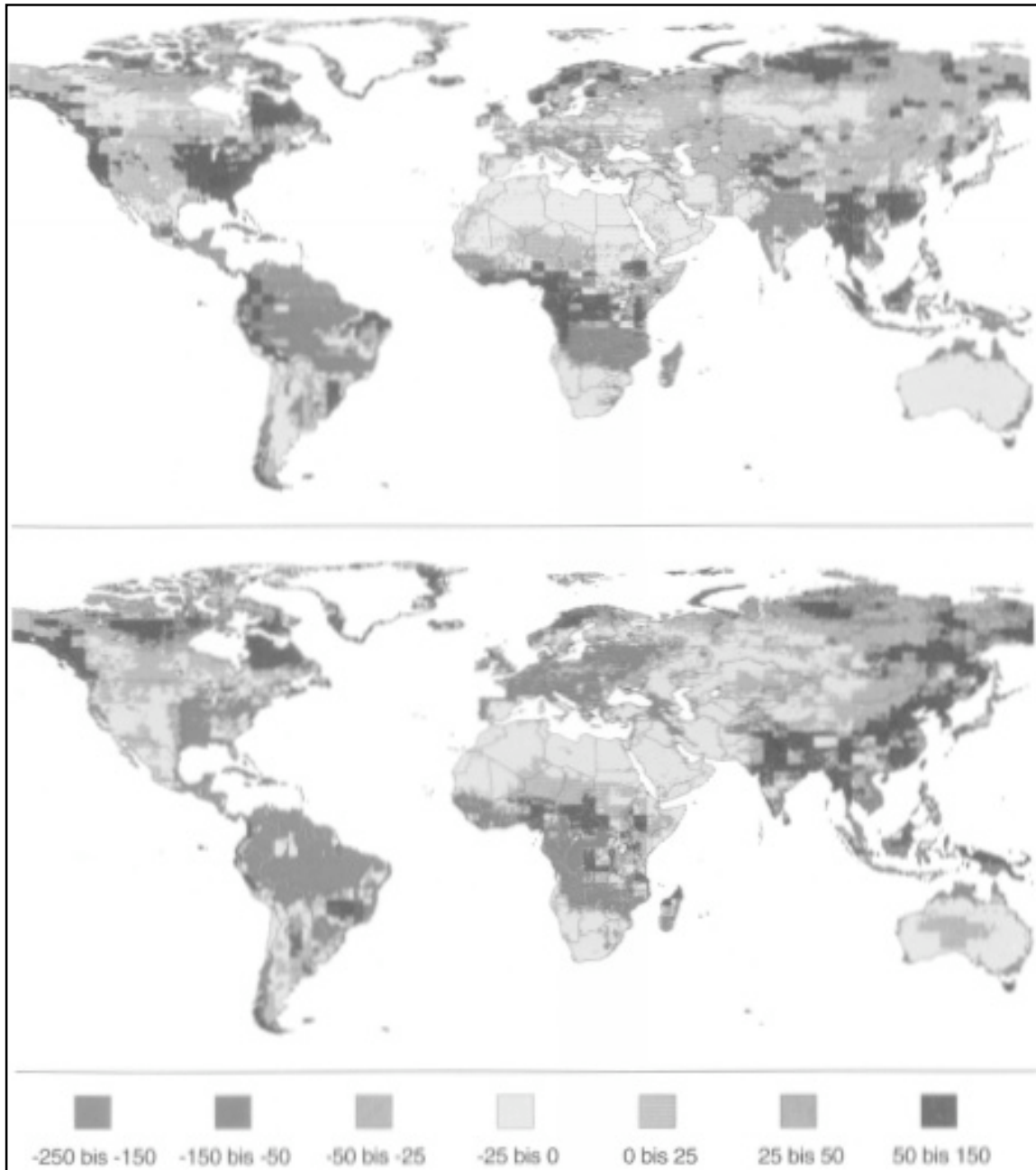


Fig. 4: Projected change of the annual discharge for the year 2050 in mm/yr, based on two versions of a General Circulation Model and on an increase of one percent CO_2 per year (IPCC 2001).

Global warming and water resources in snow dominated regions

In a warmer world, less winter precipitation falls as snow and the melting of winter snow occurs earlier in spring. Even without any changes in precipitation intensity, both of these effects lead to a shift in peak river runoff to winter and early spring, away from summer and autumn when demand is highest. Where storage capacities are not sufficient, much of the winter runoff will immediately be lost to the oceans. With more than one-sixth of the Earth's population relying on glaciers and seasonal snow packs for their water supply, the consequences of these hydrological changes for future water availability – predicted with high confidence and already diagnosed in some regions – are likely to be severe (Barnett et al. 2005). On a global scale, the largest changes in the hydrological cycle due to warming are predicted for the snow-dominated basins of mid- to high latitudes, but also to mountain areas in quite all the climatic zones. As an example, if it is true that approximately 80 % of the water used for agricultural, industrial and domestic purposes in the western USA originates from the high elevation winter-spring snowpacks (Price and Barry 1997), then the consequences of any climate change can be very serious. Some authors project for the western USA a warming to be 0.8 – 1.7°C greater than present values. This warming is projected to be accompanied by little or no change in precipitation and this could lead to a large reduction in mountain snow pack and a substantial shift in stream-flow seasonality, so that by 2050 the spring stream-flow maximum will come about one month earlier in the year. There is not enough reservoir storage capacity to handle this shift in maximum runoff and so most of the early water will be passed on to the oceans. These hydrological changes will have considerable impacts on water availability (Barnett et al. 2005). But also in Canada's western prairie provinces, Schindler and Donahue (2006) can show that climate warming and human modifications to catchments have already significantly reduced the flows of major rivers during the summer months, when human demand and in-stream flow needs are greatest. All

the major rivers crossing the western prairies originate in the Rocky Mountains, where deep snowpacks and melting glaciers maintain river and groundwater supplies. There are signs, that these mountain water supplies are diminishing. The authors predict that in the near future climate warming, via its effects on glaciers, snowpacks and evaporation, will combine with cyclic drought and rapidly increasing human activity in the western prairies could cause a crisis in water quantity and quality with far-reaching implications. For the Australian Alps, snow cover duration is highly sensitive to temperature changes. 1° C warming could reduce snow cover duration by 50 percent or more at low to moderate elevations, while a 3° C increase would eliminate the snow cover at sites around 1800 – 2000m which have a modern (simulated) duration of 100 days (Whetton et al. 1996).

All together, mountains with their high elevation snow and ice cover and highly sensitive ecosystems above and below the upper timberline will play a fundamental role in a changing climate in order to maintain the function of water towers for the more intensively used surrounding lowlands.

Climate Change and Mountain Observatories

Climate variability and climate change are important elements for the assessment of freshwater resources in the mountains of the different climatic zones (Messerli et al. 2004). Figure 5 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 CO₂ simulations. The values are superimposed on a transect through the Americas from Alaska to Antarctica, which shows the highest points of the mountain ranges by a white line. The mean annual freezing line (from radiosonde data) is shown as a black line. The black dots indicate the GCOS stations (Global Climate Observing System) and their

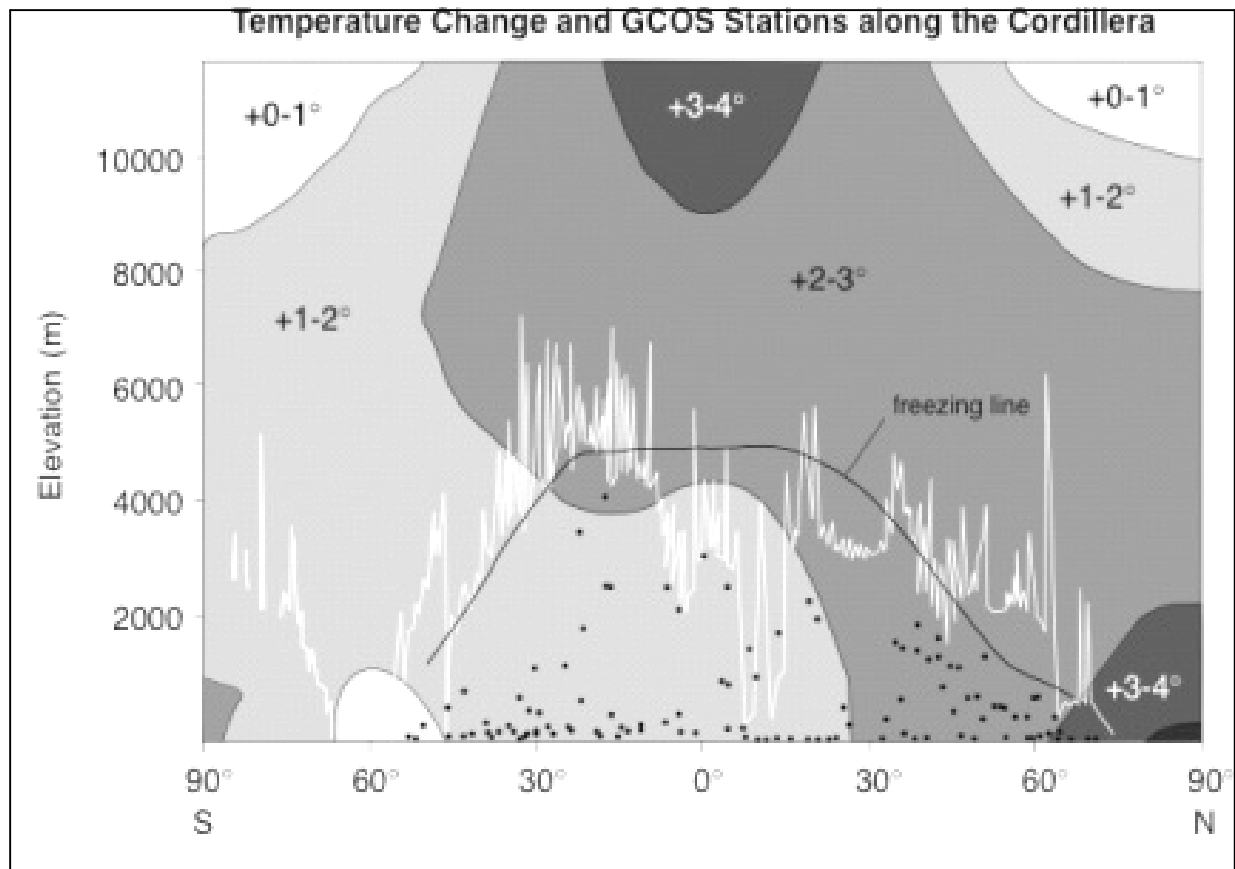


Fig. 5: A transect through the Americas: Projected changes in mean annual temperature with 2 x CO₂. The white line shows the highest peaks on this transect and the black line shows the mean annual freezing line. The black dots indicate the planned GCOS stations. For further comments see text. (Pers. Comm. R. Bradley, Univ. Massachusetts, Amherst, USA).

distribution with elevation, planned for the western cordilleras of the Americas. The basic document comes from IPCC (2001), all the other additional and most instructive elements are from Raymond Bradley (University of Massachusetts, Amherst; personal communication). This most fascinating figure shows the following: 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 sub-tropics on the northern and also on the southern hemisphere. It is interesting to see, that even the highest peaks don't 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 Raymond Bradley in order to avoid a zonally averaged value for all longitudes around the globe. He just extracted the data for the mountain regions of the transect through the Americas, based on different models. As a result, the study shows about 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. These findings provoked an enduring scientific discussion, but it seems that the discrepancies between surface and lower troposphere temperature trends or between ground measurements in high elevations and radiosonde data can be explained (Seidel and Fee 2003; ProClim-News 2005).

Figure 5 shows very clearly that the existing or planned GCOS stations do not reach – in the critical zone between 30° North and 30° South – the elevation of high temperature change. There would be enough mountain peaks, but they are not being used to form a network of observatories, which could serve not only for a competent monitoring, but also as an early warning system. The Mountain Research Initiative (MRI) has taken up this problem and initiated a planning process for a new and longer term observation and research programme in the mountains of the world in general and in particular for the CONCORD (Climate Change: Organizing the Science in the American Cordillera), a transect of selected mountains with well defined research projects or observatories from Alaska to Tierra del Fuego as a contribution to the ongoing Global Change Programmes.

4. HUMAN DRIVING FORCES AND THEIR IMPACT ON MOUNTAIN WATER RESOURCES

FAO has used the UNEP – WCMC (World Conservation Monitoring Centre) definition of mountains (FAO 2002, FAO 2003)) with six altitudinal classes, covering together 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 Lofotes Islands in northern Norway may serve as an example. Very steep walls of rocks, more than 1000 m high, beginning just at sea level, the tops covered by snow even in the summer months, all together an exciting high mountain impression. No doubt, real mountains exist also below 1000m altitude.

Vulnerability of mountain population and mountain watersheds

FAO used its own unique databank about population, livelihoods and land use, constraints and vulnerability of mountain people. In a special GIS-based analysis these data are classified and integrated in the above mentioned mountain definition with a special focus on the developing world (FAO 2003). As a result, FAO estimates the total number of mountain people at 718 million in 2000. Of these, 625 million live in developing countries and the CIS (Commonwealth of Independent States, former Soviet Union). About 60% of the total mountain area in these countries 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 three-quarters of mountain people in developing countries and the CIS are still rural (FAO 2002).

FAO estimates 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 obtaining an adequate livelihood from agriculture. FAO has used estimates of

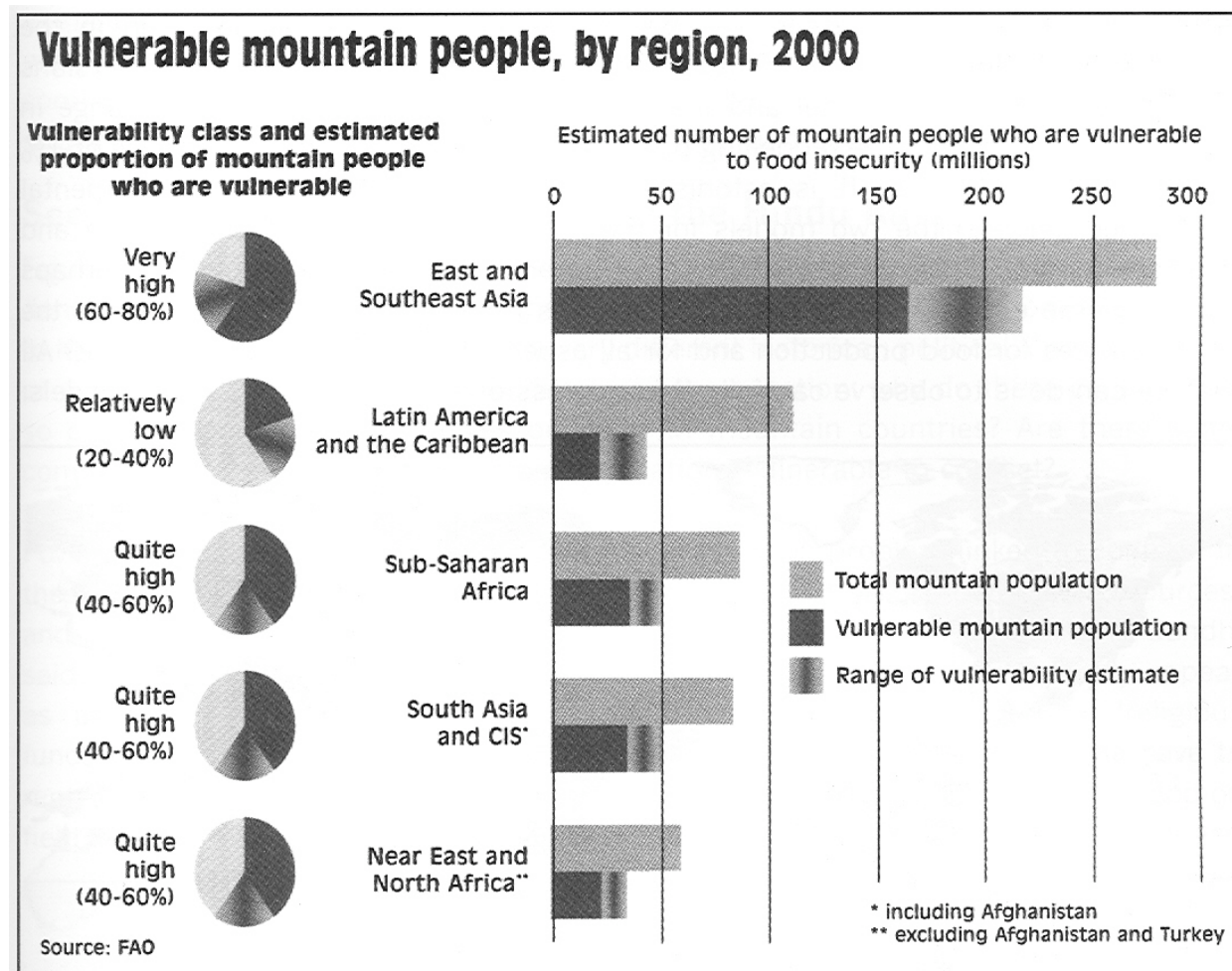


Fig. 6: FAO estimates that 625 million people are living in the mountains of the developing countries and CIS, and probably more than half are living in a situation of food insecurity (FAO 2002).

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 (Figure 6). 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 (FAO 2002). Without discussing 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, difficult accessibility and isolation, missing education and health service, non existing 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 means to use marginal land and cross some ecological thresholds like going too high, endangered by frost, or going too steep, endangered by erosion. Excessive intensification can lead to the impoverishment of the soils, to erosion or with too much fertilizer to pollution of the water sources. All together, food insecurity can be the beginning of destructive impacts on land use and land cover, on mountain ecosystems and especially also on the most sensitive headwater system.

Mountain watersheds and human interventions from the past to the future

In all our future research projects it is always instructive to pay attention to paleoenvironmental experiences. The Greek philosopher 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...”(Bury 1961). Looking at the Greek history 2400 years ago, we are always fascinated by the cultural highlights, but we don’t want to see the real life conditions which must have existed in the mountainous rural areas of the country in this time period. The following generations had to survive in destroyed ecological and

hydrological systems, the price for these damages was then and still is very high . What is happening today in some parts of the African mountains, happened 2400 years ago in some parts of the Mediterranean mountains.

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 instructive example is the recent report about the “River Link Mega Project” in India (Imhasly 2003). Why should 97% of the Brahmaputra water flow unused in the gulf of Bengal, when India is suffering from water scarcity? Therefore, 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 to link even southern India to the Himalayas with the water from Brahmaputra and Ganges.

An other most impressive example is China’s 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 (Li Guoying 2003)). Other examples are Lesotho, which is selling its mountain water to the agglomeration of Johannesburg, or Spain, which is discussing a water transfer from the Pyrenees to Andalucia in southern Spain. 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 environmental changes and human economic and demographic changes with far reaching political decisions and conflicts.

5. OUTLOOK AND CONCLUSIONS

New initiatives have been taken to improve the knowledge about mountain water resources and to create the necessary awareness for the hydrological significance of the world's mountains. In a more practical and development oriented sense, FAO has organised in all the continents special conferences about "Watershed Management and Sustainable Mountain Development" in order to prepare a next generation of watershed management programmes and projects under the general headline: Water Resources for the Future (FAO 2006). In a more scientific sense a hydrological team from the Universities of Paris and Bern is working on a global map of mountain discharge, but starting with considerations about their disproportional discharge, then moving on to an earth systems perspective with incorporation of lowland climates and finally incorporating human demand for freshwater. First and not yet published results show that mountain discharge is clearly disproportionately high in all climate zones except for the strictly humid tropics. This is correct for an Amazon and Congo river, but not for a Mount Kenya, situated exactly on the equator: Its mountain rivers play a fundamental role for a vast area with an irregular precipitation regime. This type of climate is common in densely populated sub-tropical and even humid tropical regions, where vulnerability for seasonal water shortages is high. and where the hydrological significance of mountains is of special importance (Viviroli et al. in prep.).

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 climate change or climate variability, and will therefore be most strongly affected by shifts in discharge patterns. Taking into consideration these natural and human driving forces, it becomes a priority for mountain watersheds to initiate a high mountain monitoring and

research network in the framework of and as a contribution to the Global Change Research Programmes (Huber et al. 2005).

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 above mentioned large scale projects in India and China. According to the World Development Indicators of the World Bank (2001), 65 countries use over 75% of their available freshwater for agriculture, that is for food production. Included in this list of 65 countries are also 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 still available for a rapidly growing 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 from scarce water resources for the whole of the development process is alarming and a feedback effect on mountain resources and ecosystems is inevitable. Perhaps we should keep in mind the following quotation from Lonergan (2005): “If there is a political will for peace, water will not be a hindrance. If you want reasons for fight, water will give you ample opportunities”.

LIST OF REFERENCES

- Bandyopadhyay J., Rodda J.C., Kattelmann R., Kundzewicz Z.W. and Kraemer D. 1997: Highland waters – a resource of global significance. In: Messerli B. and Ives J.D. (eds). Mountains of the World - A Global Priority. Parthenon, New York and London: 131 – 155
- Barnett T.P., Adam J.C. and Lettenmaier D.P. 2005: Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438: 303-309
- Bury R.G. (Ed) 1961: Plato, the complete works. Vol. VII, Plato, Critias, III a-c. Loeb Classical Library , Harvard University: 273 p.
- FAO 2002: Environment, Poverty and Food Insecurity. The vulnerability of mountain environments and people. FAO special feature: 19 p.
- FAO 2003: Towards GIS – based analysis of mountain environments and populations. Environment and Natural Resources Service, Rome: 26 p.
- FAO 2006: Water Resources for the Future. Preparing the next generation of watershed management programmes and projects. Watershed Management and Sustainable Mountain Development. Working Paper 9. Eds: Tennyson L. and Zingari C. (Conference proceedings, Sassari, 2003), Rome: 210 p.
- GRDC 1999: Global Runoff Data Centre. D-56068 Koblenz, Germany
<http://bafg.de/grdc.htm>

Gurtz J., Zappa M., Jasper K., Lang H., Verbunt M., Badoux A. and Vitvar T. 2003: A comparative study in modeling runoff and its components in two mountainous catchments. Hydrological Processes 17: 297 - 311

Huber U.M., Bugmann H..K.M. and Reaonser M. (eds)2005: Global Change and Mountain Regions. An Overview of Current Knowledge. Advances in Global Change Research, Vol 23, Springer, Dordrecht, Netherlands: 651 p.

IPCC 2001: Climate Change. Third Assessment Report of the Intergovernmental Panel on Climate Change. WMO/UNEP, Cambridge Univ.Press. Synthesis Report, Bonn 2002: 133 p.

Imhasly B. 2003: Ganges – Wasser nach Südindien, NZZ, Zürich (in German): p.25

Li Guoying 2003: Ponderation and Practice of the Yellow River Control. Yellow River Conservancy Press: 271 p.

Lonergan S. 2005: Water and War. UNEP: Our Planet, Vol. 15, No. 4, Nairobi: 27-29

Messerli B. and Ives J.D. (eds) 1997: Mountains of the World. A Global Priority . Parthenon, New York and London: 495 p.

Messerli B, Viviroli D. and Weingartner R. 2004: Mountains of the World: Vulnerable Water Towers for the 21st Century. AMBIO. spec. report No. 13, Royal Swedish Academy of Sciences, Stockholm: 29 –34

Meybeck M., Green P., Vörösmarty C.J. 2001: A new typology for mountains and other relief classes: an application to global continental water resources and population distribution.

Mountain Research and Development Vol. 21 (1): 34 – 45

Mountain Agenda 1997: Mountains of the World. Challenges for the 21st Century.

Contribution to chapter 21, Agenda 21. Inst. of Geography, Univ. of Bern: 36 p.

Mountain Agenda 1998: Mountains of the World. Water Towers for the 21st Century.

A Contribution to Global Freshwater Management. Inst. of Geography, Univ. of Bern: 32 p.

Price M.F. and Barry R.G. 1997: Climate Change. In: Messerli B. and Ives J.D.(eds):

Mountains of the World. A Global Priority. Parthenon, New York and London: 409 - 445

ProClim-News 2005: Discrepancies between surface and lower troposphere temperature trends resolved. Forum for Climate and Global Change. Swiss Academy of Sciences, Bern: 2p.

Rodda J..C. 1994: Mountains – a hydrological paradox or paradise? In: Hydrologie kleiner Einzugsgebiete. Beiträge zur Hydrologie der Schweiz, Nr. 35, Bern. Swiss Hydrology and Limnology Society: 41 – 51

Schädler B. und Weingartner R. 2002: Components of the natural water balance 1961 – 1990.

In: Hydrological Atlas of Switzerland. Weingartner R. and Spreafico M. (eds). Plate 6.3.

Federal Office for Water and Geology., Bern, Switzerland.

Schär C. and Frei C. 2005: Orographic precipitation and climate change. In: Huber U.M., Bugmann H.K.M. and Reasoner M.A.: Global Change and Mountain Regions. Advances in Global Change Research Vo. 23, Springer, Dordrecht, Netherlands: 255 – 266

Schindler D.W. and Donahue N.F. 2006: An impending water crisis in Canada's western prairie provinces. National Academy of Sciences (PNAS), Canada: 7 p.

Spreafico M. 1997: Without mountains there is no life in the Aral Basin. In: Messerli B. and Ives J.D. (eds). Mountains of the World. Parthenon, New York and London: p. 145

UNESCO 2003: Water for People, Water for Life. World Water Programme. The United Nations World Water Development Report. UNESCO and Berghahn Books. Paris and Barcelona: 576 p.

UNU 2002: United Nations University. Sustainable Management of Headwater Resources. Brochure, Tokyo: 6 p.

Viviroli D., Weingartner R. and Messerli B. : Assessing the hydrological significance of the world's mountains. Mountain Research and Development Vol. 23: 32 – 40

Viviroli D. and Weingartner R. 2004 a: The hydrological significance of mountains: from regional to global scale. Hydrology and Earth Sciences 8 (6): 1016 - 1029

Viviroli D. and Weingartner R. 2004 b: The hydrological significance of the European Alps. In: Hydrological Atlas of Switzerland. Weingartner R. and Spreafico M. (eds), Plate 6.4. Federal Office for Water and Geology, Bern, Switzerland.

Viviroli D., Dürst H.W., Meybeck M., Weingartner R. and Messerli B.: Mountains of the World – Water Towers for Humanity. Mapping the global significance (in prep)

Weatherald R. T. and Manabe S. 1995: The mechanism of summer dryness induced by greenhouse warming. *J. Climate* 8: 3096 –3108

Whetton P.H., Haylock M.R. and Galloway R. 1996: Climate change and snow cover duration in the Australian Alps. *Climate Change* 32: 447 – 479

World Bank 2001: World Development Indicators. Table 3.5 – Freshwater. Available at: www.worldbank.org. Accessed 12.2. 2002.

Wunderle S., Droz M., Kleindienst M. 2002: Spatial and temporal analysis of the snow line in the Alps, based on NOAA-AVHRR data. *Geographica Helvetica* Jg. 57, H.3: 170 - 183