"WATER TOWERS"—A GLOBAL VIEW OF THE HYDROLOGICAL IMPORTANCE OF MOUNTAINS

Daniel Viviroli
Department of Geography
University of Bern, Switzerland
viviroli@giub.unibe.ch

Rolf Weingartner
Department of Geography
University of Bern, Switzerland

Abstract: Mountains and highlands are often referred to as natural "water towers" because they provide lowlands with essential freshwater for irrigation and food production, for industrial use, and for the domestic needs of rapidly growing urban populations. Therefore, better knowledge about mountain water resources in different climatic zones is essential for adequate management of these resources. In this chapter, a data-based approach is used that enables the quantification of the hydrological significance of mountains. The study reveals that the world's major water towers are found in arid and semi-arid zones and that pressure on mountain water resources in general will sharpen due to climatic change, population growth, and competing use.

Keywords: mountains, hydrology, runoff, highland, lowland, water resources, comparative assessment

1. INTRODUCTION

Most of the rivers on our planet originate in mountain regions. The discharge, which builds up in the mountains, is transported via river systems to lower lying areas where a large fraction of mountain water is used for irrigation and for food production. Although mountain regions—defined as areas more than 1,000 m above sea level—make up only 27 percent of the Earth's continental surface (Ives et al. 1997), the share of the world's population they supply with water largely surpasses this value. For this reason, mountains are often referred to as natural "water towers."

It is generally agreed that mountain regions, with their disproportionnately high discharge compared to lowlands, are of significant hydrological importance. However, as far as quantification of this significance is concerned, there is a good deal of uncertainty in the scientific world (e.g.,

E. Wiegandt (ed.), Mountains: Sources of Water, Sources of Knowledge, 15–20.

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). Within a region, mountain discharge can represent as much as 95 percent of the total discharge of a catchment (Liniger et al. 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 adequately represent the high degree of spatial and temporal heterogeneity of discharge conditions in mountain areas. Additionally, in water-scarce regions discharge data has a high strategic value that is frequently kept secret. This makes basic scientific studies more difficult and mitigation of conflicts over water resources impossible.

2. QUANTIFICATION OF THE “WATER TOWERS”

On the basis of knowledge gained from studying the hydrology of the Alps (Viviroli 2001), a data-based approach to assessing the hydrological significance of mountains was adopted using discharge data provided by the Global Runoff Data Centre (GRDC 1999). The pattern of mean monthly discharge, changes in specific discharge with increasing catchment size, and the variation in mean monthly discharge proved to be particularly suitable parameters for assessing the hydrological significance of mountainous regions. 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. 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 tropical rains clearly dominate the hydrograph and override mountain influences. The most restrictive criteria proved to be the presence of accessible, reliable, and representative data with gauging stations suitably distributed across the river course.

The interrelation between mountain and lowland discharge for each case study was examined through a gauging station located above an altitude of 1,000 m, which served as a “mountain station,” and a second one in the vicinity of the river mouth, which served as a “lowland station.” In addition, regional precipitation and temperature conditions were taken into account to incorporate the discharge regime into the climatic context of the region.

There are three particular hydrological characteristics of mountain areas. The first is a disproportionately large discharge, typically about twice the amount that could be expected from the areal proportion of the mountainous section. Mountain discharge portions ranging from 20–50 percent of total discharge are observed in humid areas, while in semi-arid and arid areas the contribution of mountains to total discharge amounts to 50–90 percent of total discharge, with extremes of over 95 percent (Figure 1). Second, discharge from mountainous areas is highly reliable and causes a significant reduction of the coefficient of variation of total discharge. Third, the source of the discharge is linked to the retarding effect of snow and glacier storage, which transforms winter precipitation into spring and summer runoff and is essential for the vegetation period in the lowlands.

These and other basic characteristics—including the extent of human utilization of mountain runoff and regional precipitation and temperature patterns—have been analyzed and quantified (Viviroli 2001), and were used to elaborate an overall assessment of the hydrological significance of mountain areas (Figure 2). The study reveals that the world's major water towers are found in arid and semi-arid zones. The drier the lowlands, the greater the importance of the more humid mountain areas (Viviroli et al. 2003). High-resolution demographic data (CIESIN/IFPRI/WRI 2000) show that—if the densely populated plains of the Indus, Yellow and Yangtze Rivers are included—about 70 percent of the world's population

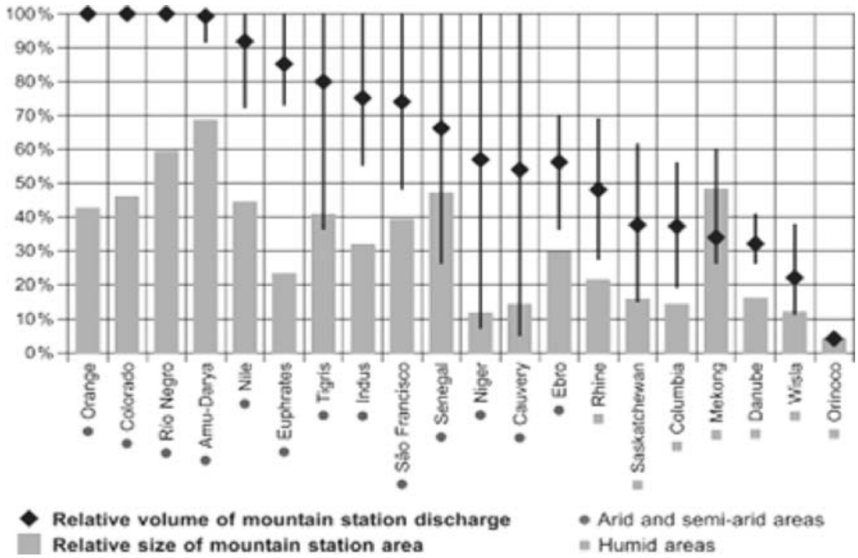

Figure 1: Mean Annual Contribution of Mountain Areas to Total Discharge and Mountain Area as Proportion of Total Catchment Area.[1]

[1] The vertical lines denote the maximum and minimum monthly contribution to total discharge.

lives between 30 degrees northern and southern latitude where drought-prone areas are frequent. This implies that mountain waters are essential and that pressure on mountain water resources will rise, especially in these zones because population growth is also more intense there.

Figure 2: Hydrological Significance of Mountain Ranges for the Selected River Basins.

3. MOUNTAIN WATER RESOURCES IN A CHANGING WORLD

The future of mountain water resources will be sharply influenced by climate change (see IPCC 2001). Changes in precipitation, snow cover patterns, and glacier storage are likely to affect discharge from mountain-dominated territories with respect to timing, volume, and variability and will influence runoff characteristics in the lowlands as well (Figure 3a). Catchments that are dominated by snow are particularly sensitive to change and will therefore probably be most strongly affected by shifts in discharge patterns. Leung et al. (2004) found in their study that, along with a regional warming of 1–2.5°C, annual snowpack was reduced by about 70 percent in the western US coastal mountains by mid-century, leading to less snow accumulation and earlier snowmelt during the cold season—and thus reduced runoff and soil moisture in summer. It must be noted, however, that the reliability of current estimates dealing with discharge as influenced by climatic change is limited because of the uncertainty of regional climatic forecasts and because of the large scales used in global circulation models (GCMs), which are difficult to transform to a local scale (Arora and Boer

2001; Nijssen et al. 2001). In addition, due to the uncertainties involved in climate change scenarios, research on mountain water resources is further hindered by the problems occurring when applying hydrological models to snow-covered areas and higher altitudes, irrespective of whether meso-scale (Zappa 2002) or global-scale approaches (Döll et al. 2003) are taken.

Global climate change is not the only factor to influence mountain water resources. Population growth in critical lowland areas will strongly accentuate pressure on mountain water resources (Falkenmark and Widstrand 1992; Vörösmarty et al. 2000), especially with regard to increasing food demand and changing dietary habits (Yang and Zehnder 2002) but also because of competing use for hydropower generation and industrial use. This pressure will foster the construction of engineering works in mountainous areas, such as dams and river channels and development of large-scale irrigation schemes and energy production projects. With today's engineering skills, even large-scale river water transfers such as India's "River Link Project" (originating from the Brahmaputra and Ganges in the north to the south and west of India) or the "South-to-North Water Transfer" in China (from the Yangtze River to the Yellow River) become possible. These measures are, in turn, expected to cause changes in runoff regimes in lower lying areas with effects on water availability in the lowlands (Figure 3b) and with the potential to increase conflicts and foment political tensions. The possible constellations of power and intents of upstream and downstream users are manifold. The Southern Anatolia Project marks an example where regional development is taking place in the upstream area (Turkey) by means of a large-scale hydropower generation and irrigation project (Altinbilek 2004) and where downstream countries (Syria, Iraq) are in a weaker position. In the Nile basin, the announcements of some upstream countries (Ethiopia, Tanzania, Kenya) to make more use of the Nile flows provoke harsh retorts from the more powerful downstream country (Egypt), where the dependence on the mountain discharge is vital (Pelda 2004).

Population growth within mountain regions is also likely to result in an intensification of land-use (Figure 3b2), which in turn will lead to soil degradation and erosion. The possible consequences of this phenomenon, such as floods and poorer water quality, will affect mainly local and regional levels with only minor impacts on lower lying areas (Hofer 1998).

Although it is difficult to state specific political consequences, there are a number of issues that seem to be of importance for future policy making. With regard to climate change, an effective climate policy is imperative to prevent fundamental changes in the availability of mountain water resources. Moreover, better monitoring of vulnerable mountain areas is needed because they provide a highly sensitive warning system for environmental changes (Messerli et al. 2004). Population pressure fosters increased efforts to

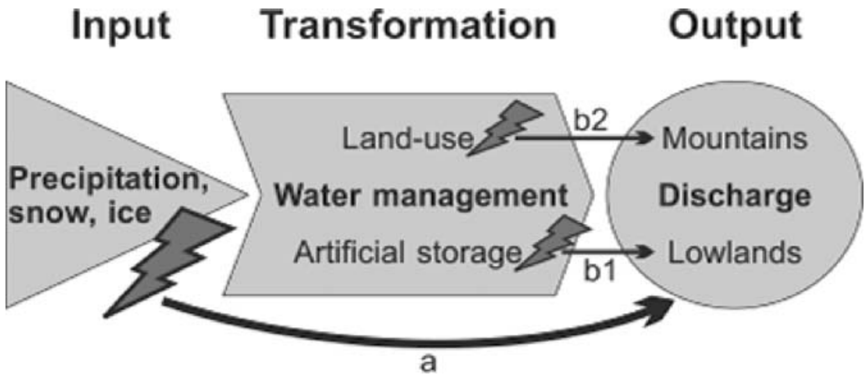

Figure 3: Future Threats to Mountain Water Resources: Climatic Change and Population Growth. (a) Climate change affects discharge in mountains as well as in lowlands; (b1) water management changes caused by population growth alter runoff in lowlands in case of extended artificial storage (b2) or in mountains in case of land-use changes. See text for further explanations.

impound mountain water resources, with dire consequences. These will have to be mitigated through more cooperative negotiation endeavors and the commitment of multilateral basin riparian organizations. Finally, it is in the interest of lowland areas to support the economic health of mountain regions so that their resources are used in a sustainable manner, which would maintain the quantity and quality of mountain runoff.

Despite the fact that global water resources are sufficient today, there exist wide spatial and inter-temporal disparities in its availability. Thus, marked increases in local and regional water scarcity can be expected in the future (OECD 2001). As the world's water towers, mountains will continue to play a paramount role in meeting the increased demands for food production, drinking water, energy supply, and industry in the twenty-first century (Viviroli and Weingartner 2002). Access to clean fresh water is a basic human right, one which is not yet available to all and will be even more difficult to guarantee in the future. Thanks to their climatic characteristics, the mountains on our planet play a special role in the water cycle, and therefore water management must start in mountain regions. There is also a complex interaction between mountains and lowlands that needs to be recognized. This interaction should be given paramount consideration in planning the development of resources (macro-scale watershed management), and the decisive role of mountains should be taken into account at future conferences on water resources and in conflict management. As a basis for deepened process knowledge and for planning, there is great need to improve the current monitoring of mountain water and climate, along with making data publicly available and for knowledge to be exchanged between neighboring countries and between highland and lowland areas.