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Assessing the Hydrological Significance of the World's Mountains

Mountains and highlands are often called the world's natural "water towers" because they provide essential freshwater for populations both upstream and downstream. Despite this, knowledge about the significance of mountains in the hydrological cycle is still uncertain. The present article takes a regional approach, using case studies to assess and compare the hydrological significance of mountains. Methods are developed based on the experience gained in the Rhine River catchment and then applied to 19 additional selected catchments worldwide, with the river Euphrates serving as an example. The resulting comparative assessment serves as an elaboration on the hydrological significance of the world's mountains and underscores their function as sources of large, reliable, and compensatory discharge. The mean annual mountain contribution to total discharge in the river basins included in our case studies is disproportionately high, at 63%, with a mean relative mountain area of only 32%. Furthermore, distinctions can be made according to climatic regions, clearly highlighting the vital role of mountain runoff in lowlands in arid and semiarid areas. This means taking mountains and highlands more carefully into account in terms of monitoring and scientific research and especially in terms of watershed management and conflict management.

Keywords: *Mountains; hydrology; runoff; comparative assessment.*

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Introduction

Experts at an international conference on mountains held in Lima in 1995 stated that, worldwide, possibly as much as 80% of running freshwater originates in mountain areas. This astonishing figure—which is of major political importance in view of the emerging water crisis in the 21st century—was originally scheduled for publication for the 1997 Special UN General Assembly on Agenda 21. Later, however, a decision against publication was taken, owing to uncertainty and doubt surrounding the validity of the data and enormous gaps in knowledge, particularly with reference to mountain areas in the tropics and subtropics. This served to confirm a 1988 statement by Klemes: "mountain regions represent, in practical terms, the blackest of black boxes in the hydrological cycle." This, in turn, was reconfirmed by Rodda (1994): "Mountains are the origin of much of the world's water resources. Yet less is known hydrologically about mountains on a global scale than about plains, hilly regions, and other areas." Meybeck et al (2001) seemed to contest these claims concerning the hydrological significance of mountains: on the basis of a 0.5° grid, they determined that on a global scale the surface discharge from mountains was 32%. Their study is of great interest for its definition of mountains from a hydrological point of view. Yet their figure included areas such as the cold high latitudes (polar, subpolar, or permafrost regions) and the humid equatorial low latitudes (rainforests and adjacent areas), where discharge is not determined by mountains, land use is not intensive, and population density is low.

The key questions therefore remain unchanged today:

- How much discharge can we expect in the regions most vulnerable to water scarcity, where the population will increase and irrigated areas could decrease?
- What is the most promising approach for assessing mountain water resources and determining the amount of discharge in light of the estimated 80% and the globally modeled 32%?

TABLE 1 Comparison of water balance figures for Europe and the Alps (Baumgartner et al 1983, p 195).

	Alps	Europe	Relation Alps/Europe
Precipitation (P)	145 cm	66 cm	2.2
Discharge (D)	91 cm	28 cm	3.3
Evaporation (E)	54 cm	38 cm	1.4
Relation D/P	63%	43%	1.5
Relation E/P	37%	57%	0.6

The present study is based on discharge data series from the Global Runoff Data Centre (GRDC 1999). Despite the existence of these data, we should bear in mind that on a global scale very few measurement series exist for different altitudes and that the periods covered are extremely limited. This situation is further complicated by the fact that discharge conditions in mountain areas exhibit a high degree of spatial and temporal heterogeneity. Moreover, these limitations are aggravated by political conditions: it is precisely in the critical areas where adequate water resources can mean the difference between life and death that secrecy prevails. This makes basic scientific studies more difficult and conflict resolution impossible.

Methods

Because relatively few data are available, monthly means (GRDC 1999) had to be used; from these data

Irrigation practice

The manuals supplied with the kits suggest irrigation with 2 buckets/barrels per day for highland areas. On this basis, farmers provide 1 bucket/barrel in the morning and 1 in the afternoon throughout the growing period. But there are 4 distinct stages in the life cycle of a plant: the initial stage, the mid-season stage, the late season stage, and the harvest stage. At each stage, crop water requirements are different.

A study in Kiambu, Kenya, compared water use efficiency under current practices with an alternative that uses the same amount of water (2 barrels/buckets), but for a different fixed schedule of 7, 2, 2, and 14 days during the 4 growing stages, respectively; the latter practice saved about 40% of the water consumed by the former.

Conclusions and recommendations

"Smallholder" does not necessarily mean "simple." The couplings, fittings, and control valves could make systems as simple as the IDE kits appear complex for smallholder farmers in rural areas, since these are unfamiliar. Farmers may not be able to operate and maintain the system if they do not get the necessary theoretical and practical information. The attitude that a farmer knows better than others how to irrigate his field needs to be changed. This attitude usually leads to the tendency not to provide sufficient explanation about the installation, operation, and maintenance of the system, as many of the steps involved are assumed to be simple (Figure 5).

The main objective of farmers is to improve their crop yields, which is possible with drip irrigation. However, this cannot come about unless the clogging problem is addressed. For low cost drip systems, practical solutions could include the following:

- Enlarging the area of the bucket kit filter and chlorinating, when clogging is mainly due to suspended sediments.
- Preparation of acidic chemicals from locally available materials to neutralize the salts in saline water.

Smallholder drip systems require little initial capital. Nevertheless, the low initial investment of US$10 needed for the IDE bucket and US$20 for a drum kit may still be expensive for poor farmers. This could impede the adoption of the system because most farmers will not risk their limited resources and fields. The government or international development organizations should thus support the introduction of such sustainable new technologies.

The success of smallholder drip systems also depends greatly on convincing farmers that the system will pay for itself within a maximum of 1–2 years. Hence, investigating means of further reducing costs without decreasing quality should be a research priority.

Many villages in the highlands of Eritrea are remote and difficult to access. The following strategies are thus crucial to disseminate the technology quickly and ensure that it is sustainable:

- Development of a network of traders and dealers that can deliver goods to remote areas for a reasonable profit.
- Conducting a massive public information campaign to stimulate demand for the product at a sustainable level.

Identification and promotion of simple and low-cost technologies that enable access to and delivery of water is also essential for a successful adoption of drip technology. For example, treadle pumps can be used when the water source is a shallow open well. The hilly topography of the highlands also allows gravity flow to the tanks if water is tapped at upstream sites.

Last but not least, introducing a new technology means a change in the land use system; therefore, capacity building is essential.

FIGURE 5 Successful use of drip irrigation depends on support from specialists for installation and maintenance. (Photo by Brigitta Stillhardt)

FURTHER READING

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we proposed to determine the interaction between mountains and lowland areas. To devise and subsequently test a suitable approach, we chose the Rhine basin as an exemplary region for which reliable and relatively detailed data are available. Analyses showed that it is possible to differentiate and obtain an overview of the basic hydrological character of the whole catchment using discharge measurements for the main river (Viviroli 2001).

The patterns of mean monthly discharge, the changes in specific discharge with increasing catchment size, and the variation in mean monthly discharge proved to be particularly suitable parameters for the present study. In the case of the river Rhine, there is a clear contrast in the discharge pattern between the mountainous upper section and the lower reaches of the river, where the discharge pattern changes as a result of the feeder supply changing from snow to rain. In an average year, discharge in the Swiss section of the Rhine, which is mainly mountainous, contributes 45% of the total discharge, although the catchment area within Swiss territory represents only 22% of the total catchment.

The above figures are confirmed by water balance estimations by Baumgartner et al (1983). As can be seen in Table 1, precipitation volumes are about 2.2 times larger in the Alps than in Europe, whereas evaporation volumes are comparable and therefore represent a smaller percentage of precipitation (it should be noted that the evaporation value of 38 cm for Europe seems too low). This 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 Archive (FRIEND 1999), which showed larger precipitation and discharge volumes as well as more reliable discharge patterns for the alpine section of the Rhine catchment (Viviroli 2001). Long-term storage in glaciers, which in Switzerland amounted to 74 km^3 in 1980—1.85 times the annual runoff originating from Swiss territory (Schädler 1985)—is not considered in these water balance figures.

Based on the knowledge gained about the river Rhine, and taking into account the limited data available, the following parameters were chosen for the case studies: discharge character, generation of discharge, climatic factors, variation in discharge, and use of runoff.

Nineteen river basins in various parts of the world were selected for the case studies, depending on climatic and topographical criteria and availability of data, including investigation of the interrelation between mountain and lowland discharge. A measuring station above 1000 m served as a "mountain station," and another on the lower reaches of the river served as a "lowland station." The stations used are listed in Table 2. These case studies formed the basis for the concluding synthesis.

The limit of 1000 m (27% of the earth's continental surface lies above this altitude) should be understood as an approximate value only and not as an absolute limit for mountain areas, particularly because a precise and uniform definition of "mountains" on a global scale is hardly possible (Ives et al 1997). This limit should be seen in relation not only to topography but also to the increase in precipitation with altitude, which is usually greatest between 1500 and 4000 m (Rodda 1994).

It must be noted that the selected approach does not take into account changes in long-term groundwater, glacier, and reservoir storage because the data are insufficient to assess these parameters. The same applies to evaporation losses and water use, which cannot be separated in the hydrograph comparison between mountain and lowland stations. Owing to insufficient data, as mentioned above, only an overview of the basic hydrological character of highland–lowland interactions can be considered, rather than a detailed water balance analysis, which would require detailed data sets for runoff, precipitation, evaporation, storage change, and water use.

Exemplary case study: The Euphrates

The Euphrates catchment was chosen as an example because, topographically, it can be divided easily into mountain and lowland areas and because a clear hydrological interpretation of the highland–lowland relationship is possible. This example explains the method used.

- *Discharge characteristics:* Discharge from the Pontine Mountains and the Taurus is a decisive factor in the discharge pattern of the river Euphrates (Figure 1). Particularly in spring, the discharge pattern is dominated by large volumes of meltwater from the mountains, with the result that mountain discharge between March and May is actually greater than total discharge. On the one hand, the low-lying areas generate virtually no discharge at all, and on the other, discharge is in fact "consumed," principally for irrigation purposes. Overall, the portion of total discharge at Kadaheyeh (lowland station) generated in the mountainous section of the catchment up to Keban (mountain station) varies between 55% and 100% according to the season.
- *Specific runoff:* Mountain runoff represents a much higher specific discharge (discharge per square kilometer per second) than does total discharge, in particular during the period of maximum discharge in spring mentioned above (Figure 2). Consequently, the dominant role of discharge from the mountainous part of the catchment is the result of the disproportionately high level of discharge generated in the

TABLE 2 River basins with measuring stations used in this study: mountain (1) and lowland (2).

River	Station	Country	Catchment area (km²)
Amu Darya	1 Kerki 2 Chatly	Russian Federation Uzbekistan	309,000 450,000
Cauvery	1 Krishnarajasagar 2 Grand Anicut	India India	10,600 74,004
Colorado	1 Lees Ferry 2 Limite Internacional Norte	USA Mexico	289,562 631,960
Columbia	1 Birchbank 2 The Dalles, Oregon	Canada USA	88,100 613,830
Danube	1 Bratislava 2 Ceatal Izmail	Slovakia Romania	131,338 807,000
Ebro	1 Castejon 2 Tortosa	Spain Spain	25,194 84,230
Euphrates	1 Keban 2 Hindiya	Turkey Iraq	36,835 274,100
Indus	1 Attock 2 Kotri	Pakistan Pakistan	265,122 832,418
Mekong	1 Chiang Saen 2 Mukdahan	Thailand Thailand	189,000 391,000
Niger	1 Koulikoro 2 Malanville	Mali Benin	120,000 1,000,000
Nile	1 Tamaniat 2 el Ekhsase	Sudan Egypt	1,913,194 3,746,812
Orange	1 Upington 2 Vioolsdrif	South Africa South Africa	364,560 850,530
Orinoco	1 Tama-Tama 2 Puente Angostura	Venezuela Venezuela	37,870 836,000
Rhine	1 Rheinfelden 2 Lobith	Switzerland Netherlands	34,550 160,800
Rio Negro	1 Paso de los Indios (Río Neuquén)* 2 Primera Angostura (Río Negro)	Argentina Argentina	30,200 95,000
São Francisco	1 Manga 2 Juazeiro	Brazil Brazil	200,789 510,800
North Saskatchewan	1 Lea Park 2 The Pas	Canada Canada	55,200 347,000
Senegal	1 Galougo 2 Dagana	Mali Senegal	127,000 268,000
Tigris	1 Mosul 2 Baghdad	Iraq Iraq	54,900 134,000
Wisla	1 Szczucin 2 Tczew	Poland Poland	23,901 194,376

* The two equivalent tributaries Neuquén and Limay form the Río Negro at their confluence outside the mountain section. The mountain station values were obtained by adding the corresponding figures from both tributaries. (Source: GRDC 1999)

mountains; at the mountain measuring station an annual average of as much as 85% of the total discharge was measured, whereas this part of the catchment represents only 23% of the total area of the basin (see Figure 3). Discharge is therefore around 3.7 times greater than would be expected from the area of this section of the catchment.

- *Climate:* High summer is a dry period in both mountains and lowlands, discharge being considerably lower at this time in both areas. The dry season lasts longer in the lowlands, and winter precipitation figures are markedly lower than in the mountains. Whereas total annual precipitation can be as much as 1000 mm in mountain areas (mainly in winter and spring), the arid conditions of the Syrian Desert dominate in the middle section of the catchment, with annual precipitation of between 100 and 150 mm or less (Müller 1987; New et al 1999). The source of any significant runoff is therefore only the mountain section, with its considerable precipitation and winter accumulation, mainly in the form of snow.
- *Variability:* Overall, year-to-year variability in monthly discharge in the mountains is fairly low. It is in spring in particular that discharge from the mountains has a marked compensatory effect on total discharge, which, interestingly, can be seen also in the summer half-year. The persistence of the latter effect is most likely caused by contributions from groundwater discharge.
- *Water use:* Thanks to discharge volumes that can be relied on every year, it is possible to operate irrigation systems in the Euphrates basin on a permanent basis; it is not by chance that this area was the center of the fertile crescent (Mesopotamia) in ancient times. The area along the river Euphrates is still important for agriculture today. Despite the prevailing dry conditions, intensive farming is possible thanks to irrigation systems comprising numerous channels. In Syria, the use of discharge from the Euphrates is intensified on account of the Assad Dam; the surrounding steppe area is an important focal point for Syrian development policy because the western parts of the country, which receive large amounts of rainfall, are already heavily overfarmed. The Atatürk Dam, which was built in 1990 as part of the Southeast Anatolia project, and 22 other dams that are planned will lead to a considerable increase in the use of mountain discharge in Turkey (Çarkoðlu and Eder 1998). The discharge data for the Euphrates used here (1964–1972, GRDC 1999) date from before the launch of the Southeast Anatolia project and the construction of the Atatürk Dam and were therefore subjected to only minor human influence (for details see Kolars and Mitchell 1991).

FIGURE 1 Mean monthly discharge measured in the Euphrates basin at (1) Keban (mountain station) and (2) Hindiya (total discharge). Bars show (a) consumption and (b) discharge contribution in the lowlands.

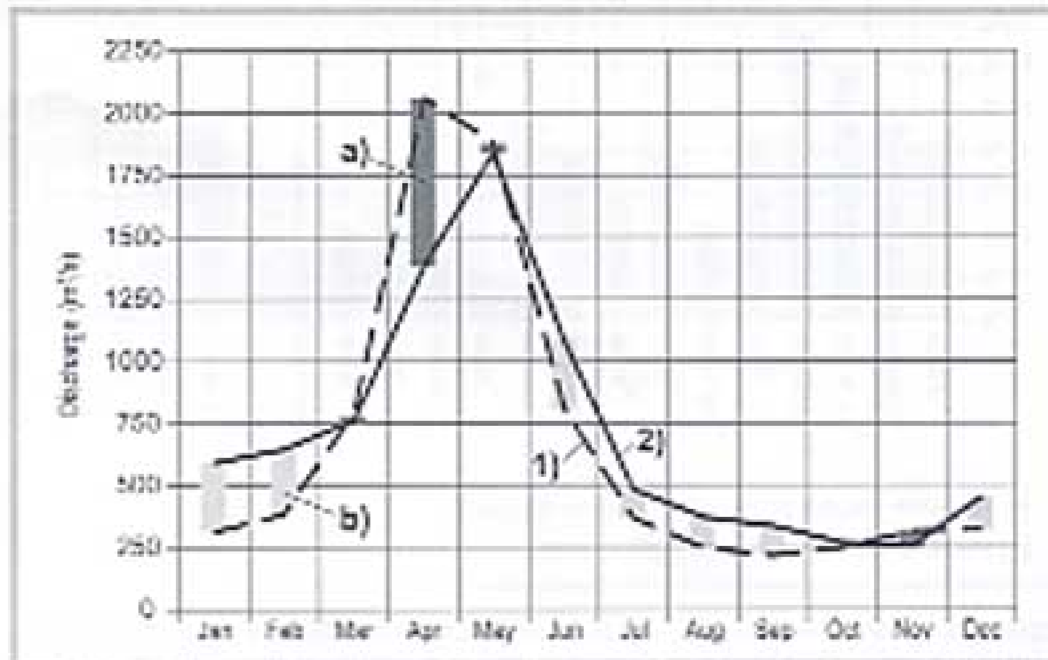


FIGURE 2 Specific runoff: (a) peak month, (b) annual mean, and (c) month with the lowest values. Data for 3 stations in the Euphrates basin: Keban, Kadaheyeh, and Hindiya.

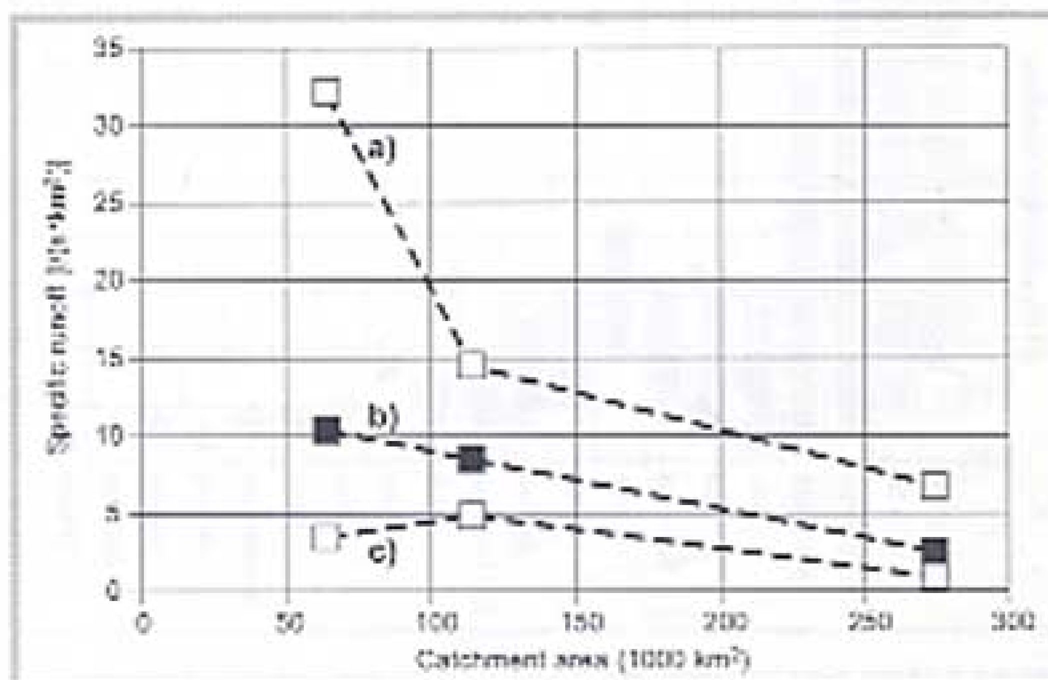
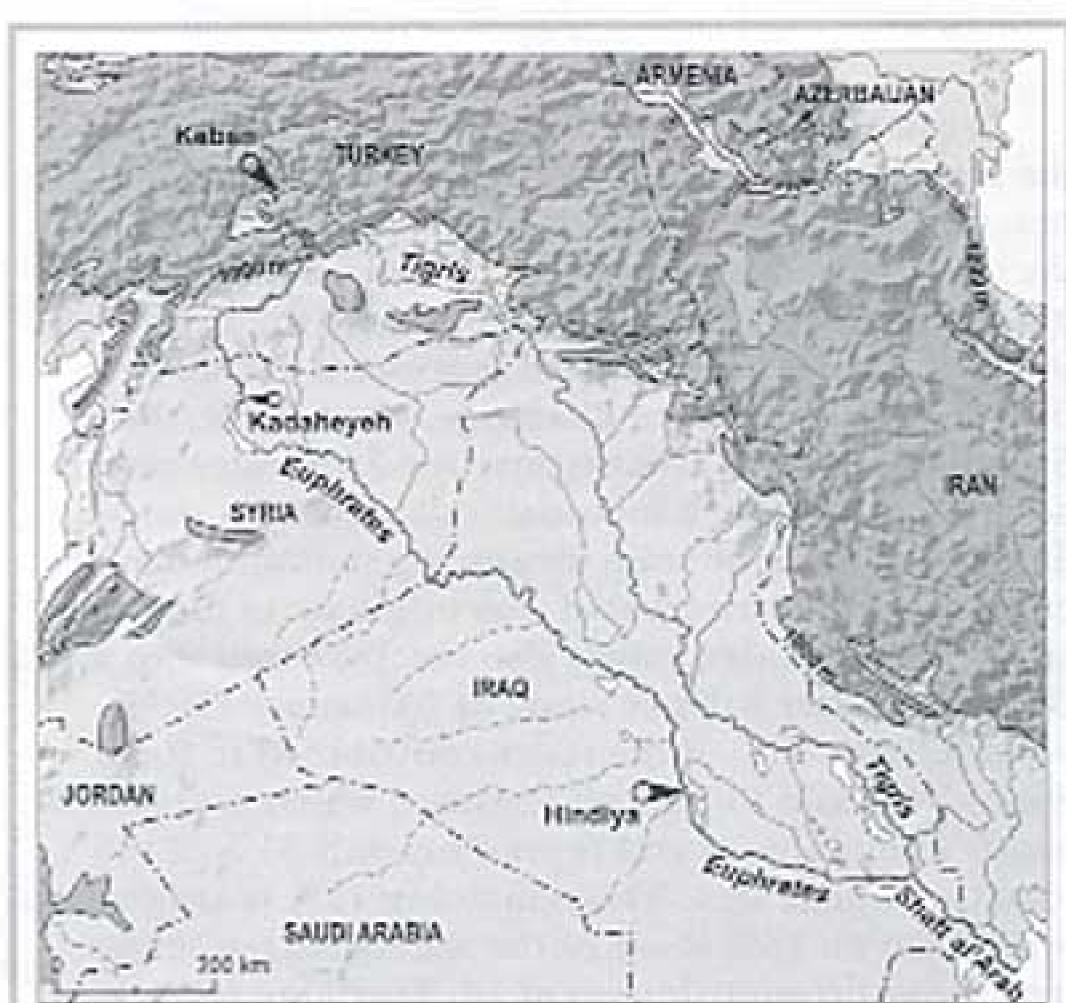


FIGURE 3 Map of the Euphrates basin showing national boundaries, the 3 measuring stations used, and the 1000-m contour line. (Map by Alex Hermann)



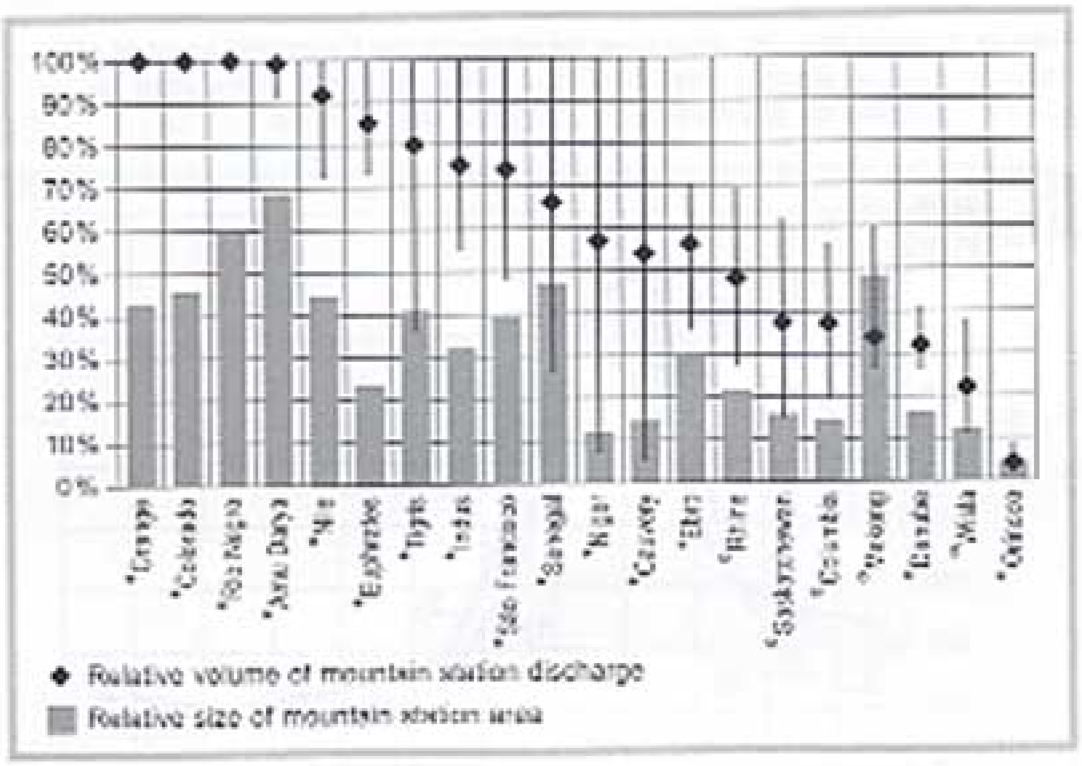


FIGURE 4 Mean annual mountain proportion of total discharge and proportion of total catchment (*, arid and semiarid areas; °, humid areas). The vertical lines denote the maximum and minimum monthly amounts (see also Figure 6).

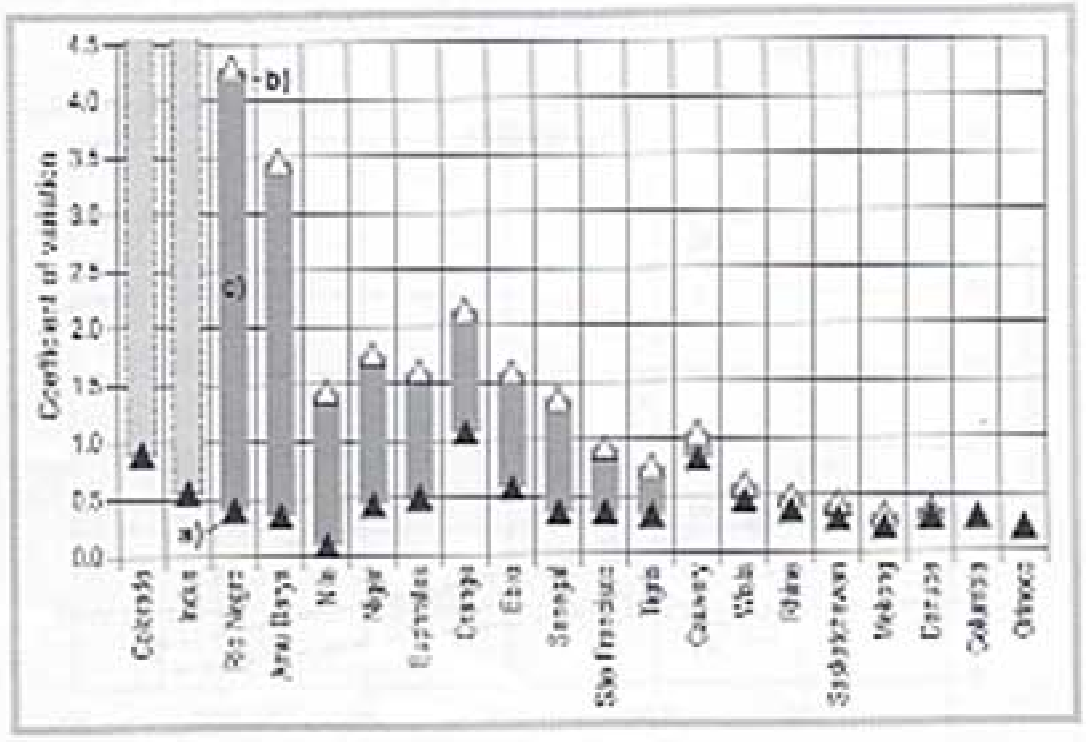


FIGURE 5 Mean monthly coefficient of variation (a) with and (b) without the influence of mountain discharge, and (c) reduction in discharge variability due to the influence of the mountains. For the Colorado and Indus rivers, the influence of the lowlands is barely recorded in the monthly mean. For this reason the coefficient of variation without the influence of the mountains cannot be determined with sufficient precision (see also Figure 6).

It can thus be concluded that the greater part of the Euphrates discharge originates in the mountain section of the catchment and is of major importance for the arid lowlands downstream. The mountain measuring station covers 23% of the catchment area, whereas the discharge generated here represents a disproportionate 85% of the total discharge. If anything, these figures are conservative because the Euphrates continues to flow through a mountainous area for a short time below the mountain measuring station. Furthermore, it is fed by rivers that also originate in mountain areas. The indicated values also compare well with a GIS-based water balance study by Akmansoy (1996), which assigns 89% of the water contributed to the Euphrates basin to Turkish territory, which is predominantly mountainous and represents only 31% of the total catchment area. The remaining 11% is assigned to Syria (with an 18% share of the watershed), whereas Iraq shows no contribution at all. The large quantities of water from the mountains are especially important because they arrive during the growing season and thus play a decisive role in agriculture. In the Euphrates basin the agricultural sector is by far the largest consumer of freshwater—in Syria it accounts for 94% and in Iraq for 92% of annual freshwater withdrawals (World Bank 2001).

Comparative assessment of selected river basins

Eighteen other river basins were analyzed using the same standard criteria used for the Euphrates. The hydrological significance of their mountainous sections was subsequently compared and assessed.

Generation of discharge: One key aspect of the hydrological significance of a mountain range is the disproportionate discharge it generates. Specific runoff is a suitable dimension: a typical specific runoff pattern shows a clear decrease as the lowland catchment area increases. The relative importance of discharge generation in the mountains can be deduced from the rate of this decrease. In arid areas in particular, the upper reaches of a river with considerably higher specific runoff are predominant, whereas in humid areas the contrast is somewhat less marked. A noticeably different pattern of specific runoff can be seen in the case of the Mekong (monsoon climate) and the Orinoco (tropics): here, specific runoff increases in the lower reaches of the river, which means that discharge generation in the lowlands is clearly more important than in the mountains. This illustrates the completely different significance of lowland areas in the humid tropics as opposed to those in arid regions.

Proportion of total discharge generated by mountain areas: Apart from increased generation of discharge in mountainous areas, the particular role played by the predominantly higher level of specific runoff from mountains in relation to total discharge is also of interest. For this purpose the proportion of total discharge generated by mountain areas was compared for the selected river basins (Figure 4). The contribution from mountains represented by the selected measuring stations was ranked by magnitude, the size of the respective mountain station catchment area in relation to the total catchment area being indicated for purposes of estimating proportionality. Figure 4 shows clearly that the proportion of total discharge generated by mountains is decisive, particularly in arid zones. With values of over 90%, the Orange and Colorado rivers, the Rio Negro, the Amu Darya, and the Nile are by far the most dependent on mountain discharge. Even when the mean contribution rate is lower, there are months in the Euphrates, Tigris, Indus, São Francisco, Senegal, Niger, and Cauvery basins when mountain discharge represents almost

100% of the total discharge and is therefore also of vital importance for lowland areas downstream (see Figure 4). Even in humid zones, mountain discharge exceeds by a factor of around 2 the contribution that could be expected on the basis of the relative area. Figures for the Mekong and Orinoco basins are exceptions, however, with the contribution of discharge from the mountains being lower than expected.

Compensatory effect of mountain discharge: The ranking for compensatory effect of mountain discharge is very similar to that of the 2 aspects dealt with above (Figure 5). The grouping of the various rivers, however, is somewhat more marked, that is, a larger number of the mountain zones studied have a strong compensatory effect on the lowlands downstream. It is noticeable, for example, that the river Ebro is highly dependent on the reliability of mountain discharge, more so than could be expected from the 2 aspects dealt with above; the same applies to the Senegal, the Mekong, and the Wisla. In these river basins the compensatory effect of mountain discharge is clearly a particularly important factor, the mountains' role as natural "water towers" being characterized principally by the reliability of discharge rather than by the large discharge volumes.

Influence of climatic conditions: For the river basins included in this study, an important factor in the interaction of upper mountain reaches and lowland areas is the clear difference between the climatic conditions prevailing in the upper reaches and those in the middle and lower reaches. On the whole, the climatic conditions in mountain areas—precipitation and temperature pattern—result in an important contribution to discharge. Apart from the larger discharge volume, the temporary storage of precipitation in the form of snow and ice during the winter half-year is especially important because it leads to increased discharge during the melting period. From this point of view, mountain ranges often form a humid and cooler island within a comparatively dry area. Even in the arid zones included here, mountain climates prevail, depending on altitude, creating particular discharge conditions as a result of the accumulation of snow and the precipitation rate.

Significance for lowland areas: It can be clearly seen in the 20 river basins examined in this study that discharge from water towers is indeed very important for lowlands and the people living there and that this discharge is made use of in regions outside mountain zones. The principal user is the agricultural sector, which, with the current state of technological development, accounts for around 70% of global freshwater consumption on average (World Bank 2001). Especially in dry climate zones, water use for irrigation is of paramount importance for lowland inhabitants.

Synthesis

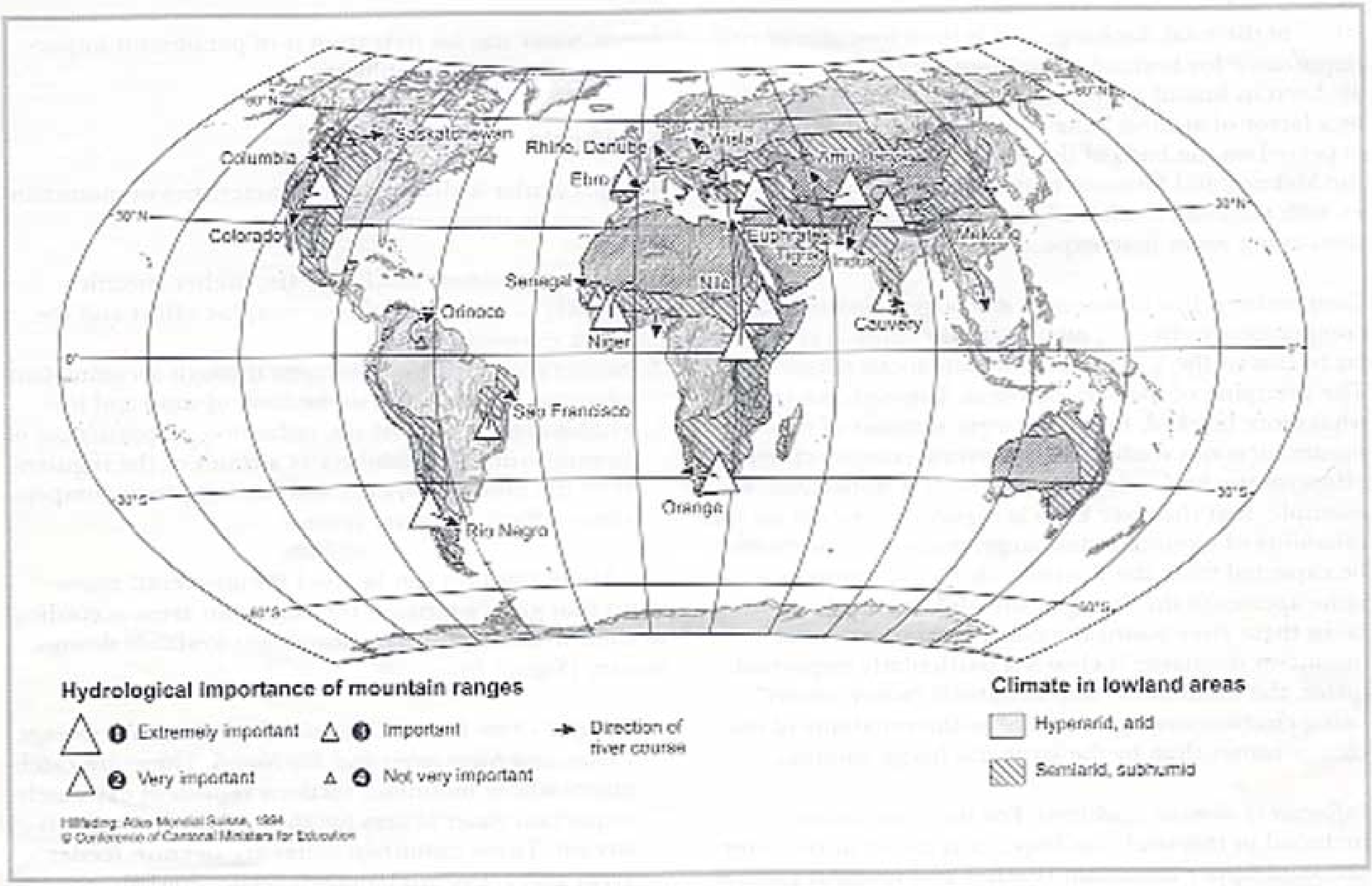
The particular hydrological characteristics of mountain areas can be summarized as follows:

1. Disproportionate discharge (ie, higher specific runoff) as a result of the orographic effect and the lower evaporation rate.
2. Seasonal retarding of discharge through accumulation of winter precipitation in the form of snow and ice.
3. Highly reliable runoff (ie, reduction, in particular, of summer runoff variability) as a result of the regularity of the melting process and the long-term compensatory effect of glacier storage.

These findings can be used for an overall assessment that gives a ranking for mountain areas according to their hydrological significance for lowlands downstream (Figure 6).

- *Group 1 (Amu Darya, Colorado, Euphrates, Nile, Orange, Indus, and Niger rivers and Río Negro):* These are catchments whose mountain sections represent extremely important water towers for the arid lowlands downstream. These mountain zones are decisive feeder areas and are of vital importance for lowland populations throughout the year. The proportion of discharge generated in the mountain areas exceeds 90% of total discharge in the majority of cases.
- *Group 2 (São Francisco, Senegal, Tigris, Cauvery, and Ebro rivers):* In these catchments the proportion of discharge from mountain areas is also important, although it varies from month to month. In this group, however, mountains are not the only important source of water. Nevertheless, they always provide a significant part of the total discharge: with 1 exception, the proportion of total discharge generated by the mountain sections of the catchments amounts to 100% for at least 1 month.
- *Group 3 (North Saskatchewan, Rhine, Columbia, and Danube rivers):* These are catchments where the upper mountainous reaches are important to some extent for discharge in the lower reaches and play a complementary role. Mountain discharge comprises between 30% and 50% of total discharge and is thus not so important as in the first 2 groups, although it contributes to and has a compensatory effect on total discharge.
- *Group 4 (Mekong, Wisla, and Orinoco rivers):* These are catchments where the upper mountainous reaches are of only minor importance. The lowlands enjoy sufficient to abundant precipitation and discharge,

FIGURE 6 Hydrological significance of mountain ranges for the lowland river basins included in the present study. (Map by Alex Hermann, based on the *Atlas Mondial Suisse*, 1994, © Conference of Cantonal Ministers for Education)



which rise as the lowland catchment area increases. Here, the mountain sections of the catchments do not make a significant contribution to the total discharge.

The map showing the results obtained (Figure 6) reveals that the world's major natural water towers are to be found in arid or semiarid zones. The drier the lowlands, the greater the importance of the wet mountain areas: the latter provide disproportionately high and reliable discharge, which has a compensatory effect and attenuates water shortages in the lowlands. This compensatory effect is mainly due to seasonal and long-term storage in snow cover and glaciers. In temperate zones, mountains are not of such great importance, although they still have a certain complementary as well as compensatory value. It is only in areas with a marked humid climate that mountains are of little significance for discharge in the lower reaches of rivers. Occasionally, however, mountain discharge can be very important even in humid zones; for example, for the river Rhine in July 1976—which was an exceptionally dry month—discharge from the Swiss Alps measured at Rheinfelden (catchment area: 34,550 km^2) represented nearly 93% of the total discharge at Lobith (catchment area: 160,800 km^2, GRDC 1999). It is interesting to note that, despite its importance as a feeder, the river Rhine is included in Group 3 above, which only serves to underline the importance of mountain discharge in Groups 1 and 2.

In a comparison similar to the one above, the importance of mountains also can be differentiated in terms of time. In the catchments included in Group 1, mountain reaches play a major role with regard to discharge in the lower reaches throughout the year; in Group 2, their influence is seasonal (eg, outside the rainy season); and in Group 3, mountains are important only occasionally, as seen in the example of the Rhine in 1976. For those rivers included in Group 4, the influence of the mountain reaches is almost negligible from this point of view.

Conclusions

Because of the generation of discharge due to climatic conditions, mountains play a special hydrological role, even though in many areas data are lacking and there is not sufficient understanding of the process to face the problems that will arise in the future. To assess the hydrological importance of a mountain area, it is not sufficient simply to analyze discharge data. Climatic conditions and intensity of land use in the lowlands are also important. In this respect, an elementary difference with highly variable transitions is evident.

In arid and semiarid areas, mountains form wet islands, and their significance increases in proportion to the size of their glaciers and the durability and volume of snow cover, which acts as a reservoir for the dry season. This zone, where serious water shortages could arise in the near future as populations increase, extends toward the poles in densely populated areas with a Mediterranean climate, whereas toward the equator it sometimes includes even extremely humid areas, with a high rate of variation in monsoon climate areas. Hence, almost all developing countries are faced with these risky climatic conditions. Therefore, it comes as no surprise that according to World Development Indicators (World Bank 2001), 65 countries use over 75% of the freshwater available today for agriculture, that is, food production. They include Egypt, India, and China, which rely heavily on mountain discharge. These figures alone show that these highly vulnerable areas cover well over 40% of the earth's surface and that over 50% of the world's population—especially from the large majority of developing countries—live and work there. It is precisely for this reason that mountain areas in these countries, with their particular hydrological character and their compensatory role with regard to runoff, are important enough to be considered to a greater extent in future conferences on water resources and conflict management, particularly in the International Year of Freshwater 2003. Water management must begin in mountains and highlands, and it is the task of the scientific community to examine the consequences for corresponding watershed management, for agriculture and forestry, and for mountain communities, and to prepare the way for sustainable development of mountain ecosystems in these critical regions of our planet.

In the humid tropical zone, mountains cannot play the same hydrological role. Precipitation of more than 1.5–2 m in the surrounding lowlands, evenly distributed throughout the year, produces such a volume of discharge that the contribution of mountains is insignificant. Moreover, population density and intensity of land use are very limited in these regions. It is not water but soil that is the most vulnerable element in the ecosystems in these regions. We should therefore bear in mind that the mountains again play a crucial role, not for the amount of water they contribute but with respect to sediments transported down to the lowlands.

In the literature the proportion of discharge contributed by mountains varies from 40% to 90% according to the region, with extreme figures of up to 95% (Bandyopadhyay et al 1997; Liniger et al 1998); these figures are corroborated by the results indicated above. The mean proportion of mountain discharge in the river basins examined in our case studies is 63% of the total discharge, with a mean mountain areal proportion of 32%. This shows that the influence of mountains is approximately double that of their relative area. If one disregards areas where discharge from mountains is insignificant (Group 4) and considers only Groups 1, 2, and 3, the mean proportion of discharge is 70%, whereas the mean proportion of total mountain area is 33%. Meybeck et al (2001) arrived at a figure of 32% for mountain discharge in relation to total discharge, representing a global annual mean for all climatic zones; this does not reflect the real importance of mountain discharge in individual spatio-temporal cases, in particular in arid areas with their high rate of climatic variation. The present article is based on an approach by which regional patterns could be deduced from individual studies.

The future of mountain water resources will be influenced by climate change, as described by IPCC (2001). Changes in local precipitation and snow cover patterns are likely to affect discharge in mountain-dominated territories in terms of timing, volume, and variability. As glaciers are expected to retreat further, their discharge contribution will increase for some time, whereas it must be assumed that their compensatory effect will diminish. However, even more important than these changes may be population growth in critical lowland areas, which will produce sharply accentuated pressure on mountain water resources (see also OECD 2001).

Outlook

Access to clean freshwater is a basic human right that is not yet available to all and will be even more difficult to guarantee in the future. As the world's water towers, mountains are of paramount importance for food production and drinking water supply, as well as for energy provision and industrial manufacturing. Increasing demands on limited water resources, which also result in a growing potential for conflicts, ensure that mountain water resources play a predominant role in sustainable development in the 21st century (Viviroli and Weingartner 2002).

In many regions, mountains are marginal areas for human habitation because they are characterized by steep slopes, poor soils, low temperatures, and inaccessibility. The surrounding lowlands are more favorable for settlement, agriculture, and industry but remain dependent on the mountains for water, as shown by this study. In many parts of the tropics, however, mountains are preferred areas for human habitation because they have a better climate and more fertile soils. Increased human activities upstream may reduce the quality and quantity of the flow downstream, on which lowland users depend. Conversely, overdevelopment downstream may impose unsustainable demands on water towers upstream. There is thus a complex interaction between mountains and lowlands, which needs to be recognized. This interaction should be given paramount consideration in planning the development of resources (macro-scale watershed management).

Our study is based on monthly mean discharge because there are too few data with a higher time resolution available for a global assessment. In many mountain areas, natural resources are still inadequately monitored, despite their importance (cf. Rodda [1994]: "The hydrological paradox of mountains"). This, coupled with poor dissemination of information where such data are recorded, makes assessing water resources extremely difficult. This lack of monitoring is partly due to the harsh conditions in mountain regions, plus a lack of investment. There is therefore a great need to improve the current monitoring of mountain water. Above all, there is an urgent need to make data publicly available and for knowledge to be exchanged between neighboring countries and between highland and lowland areas.

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