Mountains of the world, water towers for humanity: typology, mapping, and global significance

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Mountains of the world, water towers for humanity: Typology, mapping, and global significance

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1. Introduction

[2] During the past two decades, mountains have gained increasing attention in science and politics. Especially the mountain-specific chapter 13 in the Rio Earth Summit's Agenda 21 [*UNCED*, 1992] underscores the global role that mountains play in debates on environment and development issues [*Funnell and Price*, 2003]. What concerns water resources, the symbolic term "water towers" is widely adopted today, expressing the importance of mountains for providing freshwater for the adjacent areas downstream [e.g., *Bandyopadhyay et al.*, 1997; *Liniger et al.*, 1998]. Furthermore, population distribution is closely linked to occurrence of large river flows [*Meybeck et al.*, 2001], which often originate in mountains. With the International Year of Mountains 2002 and the following International Year of Freshwater 2003, the concerns of mountain water resources have obtained further legitimacy. In a changing environment with population growth, the role that mountains play for lowland water supply has to be identified more closely.

[3] Although there is great need for closer knowledge about mountain runoff for the sustainable management and planning of water resources, progress in view to these questions lags behind other fields of hydrological research [*Kundzewicz and Kraemer*, 1998]. Sparse and topographically biased gauging networks [*Briggs and Cogley*, 1996] as well as large errors especially in precipitation measurements [*Sevruk and Kirchhofer*, 1992] contrast with the high spatial heterogeneity of hydrological, meteorological and climatological patterns in mountains. Consequently, accurate figures for the hydrological importance of mountains on a global scale are still disputed today, although the principles of the hydrological highland-lowland linkage have been recognized long since. While regional studies in densely gauged areas may attain higher accuracy [e.g., *Viviroli and Weingartner*, 2004b; *Weingartner et al.*, 2007], uncertainties are large on the local and the global scale.

[4] A recent study including all climate zones found an estimate of 32 percent for mountain contribution to global discharge [*Meybeck et al.*, 2001], while regionally, mountain discharge may represent up to 95 percent of total flow in a catchment [*Liniger et al.*, 1998]. A comparative assessment of case studies [*Viviroli*, 2001] demonstrated that the contribution from mountains to total runoff is about twice what would be expected on basis of their share in surface area. A global assessment assembled from these case studies [*Viviroli et al.*, 2003] identified the most marked water towers as "wet islands" within dry climate zones. Examples for inferior importance of mountains on downstream hydrology were found in humid tropical climates (e.g., Mekong, Orinoco, and Amazon rivers). It was concluded that each region has its own particularities and that it is therefore necessary to consider climate zones (e.g., humid tropical versus arid subtropical versus temperate) and scales (global, continental, regional) to reveal the hydrological importance of mountains under different conditions [*Viviroli and Weingartner*, 2004a].

[5] Moving on from the single-basin perspective, we attempt a global assessment of the hydrological importance

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of mountains in order to identify regions which should receive special attention in research and water resources planning. First steps toward a spatially distributed global-scale analysis were made by *Dürr* [2003]. With the currently available global data and the possible resolution of 0.5° × 0.5° grid cells, a certain degree of generalization has to be taken into account, while on the other hand, it becomes possible to identify critical zones on the global scale by connecting information about the available freshwater resources in the highlands with human water needs in the adjacent lowlands. Since the aim is to assess actual water resources in river systems, we explicitly focus on long-term mean values of runoff and not on precipitation. We consider natural water fluxes, disregarding reduction of river flow due to water use, now frequent in dry regions [*Vörösmarty and Meybeck*, 2004; *Meybeck and Vörösmarty*, 2005]. Statements concerning groundwater flows have to be omitted because of insufficient data.

2. Definitions and Data Sources

2.1. Water Towers

[6] The term "water tower" originally refers to "a tower supporting an elevated tank, whose height creates the pressure required to distribute the water through a piped system" [*Soanes and Stevenson*, 2004]. In the context of hydrology, it is used as a symbolic term for a mountain area that supplies disproportional runoff as compared to the adjacent lowland area. The concept is therefore a relative one, the extent of disproportionality also depending on the location from which the mountains are looked at. We will focus on the disproportionality of mountain runoff as compared to average conditions in the respective lowlands. Furthermore, a "water tower" can have multiple functions, such as for ecosystems and water resources (irrigation, industrial or domestic supply) as considered in this article, but also for hydropower, sediment loads and nutrient balance.

2.2. Mountains and Lowlands

[7] Universally valid definitions for mountains can only be vague and depend on the connotation in focus, e.g., geology, tectonics, climatology, soil science, ecology, or hydrology. *Goudie* [1985] defines mountains as "substantial elevations of the Earth's crust above sea level which result in localized disruptions to climate, drainage, soils, plants and animals". If altitude is considered solely, lower-lying areas with marked relief are not included, although roughness is a major criterion for defining mountains; the treatment of high altitudes, on the other hand, is disputed as well [*Price*, 1981; *Gerrard*, 1990; *Meybeck et al.*, 2001].

[8] For precisely delineating a mountain range, it is most promising to incorporate local features of, e.g., climate, relief, geology, vegetation, or accessibility [*Browne et al.*, 2004; *Ives et al.*, 1997] (see *Baumgartner et al.* [1983] for the European Alps). For the global definition necessary for our study, however, the use of locally variable criteria is neither objective nor efficient. Therefore the two uniform definitions by *Kapos et al.* [2000] and *Meybeck et al.* [2001] were considered. We are using here the definition by *Meybeck et al.* since it offers a better distinction, particularly in high-elevation areas. It distinguishes a total of 15 relief categories, derived from average cell altitude (eight classes) and an average roughness indicator (seven classes). The definition was established on a 0.5° × 0.5° resolution, while the necessary relief and roughness indicators were derived from the 0.5' × 0.5' resolution digital elevation model GTOPO 30 (United States Geological Survey (USGS), 1996, *GTOPO 30 – Global 30 Arc Second Elevation Data Set*, data available online at http://edcdaac.usgs.gov/gtopo30/gtopo30.asp).

[9] We extended the original definition of *Meybeck et al.* [2001] by including all areas above 1000 m above sea level (asl) plus those areas between 200 and 1000 m asl with a relief roughness of more than 20 ‰ (relief roughness is a function of cell length and minimum and maximum elevation in a cell). This is equivalent to adding hills, midaltitude plains above 1000 m asl and plateaux of medium, high and very high altitude to the four mountain classes (low, middle, high and very high altitude) already identified (see *Meybeck et al.* [2001] for a detailed global map of relief types). This extension follows our concept of a "water tower" which encompasses an elevated area that potentially delivers disproportional runoff. By including all potentially important areas, we will be able to investigate whether hills and plateaux actually should be considered mountainous from the hydrological point of view, i.e., if they produce disproportional runoff. For certain regions such as China or the river Niger basin, hills may still function as "water towers" although they do not meet the definition of "mountainous" in the original definition of *Meybeck et al.* [2001]. Because of the rather generous extent of our definition, mountains and higher-altitude areas (hills, midaltitude plains and platforms of medium to very high altitude) make up 39% of global continental surface excluding Antarctica and Greenland, as compared to 25% in the definition by *Meybeck et al.* [2001]. This ensemble will be termed "mountains" in the rest of this article, while the remaining relief classes correspond to our definition of "lowlands".

2.3. Runoff

[10] A number of global drainage maps have been presented recently, e.g., by *Yates* [1997], *Graham et al.* [1999], *Arora* [2001], *Oki et al.* [2001], and *Döll et al.* [2003]. The present analysis is based upon the Composite Runoff Fields developed by *Fekete et al.* [2002]. All of these approaches reproduce long-term average annual or monthly runoff.

[11] To achieve their data set, *Fekete et al.* [2002] combined observed river discharge information with a climate-driven water balance model. Snowmelt is incorporated in the model as a simple function of temperature and elevation. Runoff from glaciers is mainly locally important, but downstream contribution is mostly low [see, e.g., *Viviroli and Weingartner*, 2004b]. However, the accuracy of single cells or the seasonal importance of snowmelt delayed runoff is less important here than the runoff over larger areas. The latter is assured by a correction to measured runoff values applied by *Fekete et al.* [2002]: The authors have selected 663 gauging stations from the Global Runoff Data Center (GRDC) database, and annual interstation runoff was then calculated for the regions between the gauging stations. These interstation values were used to adjust the outputs from the UNH Water Balance Model (UNH-WBM) [*Vörösmarty et al.*, 1998] which is forced by long-term mean monthly climate (precipitation and air temperature) and uses land cover and soil informa-

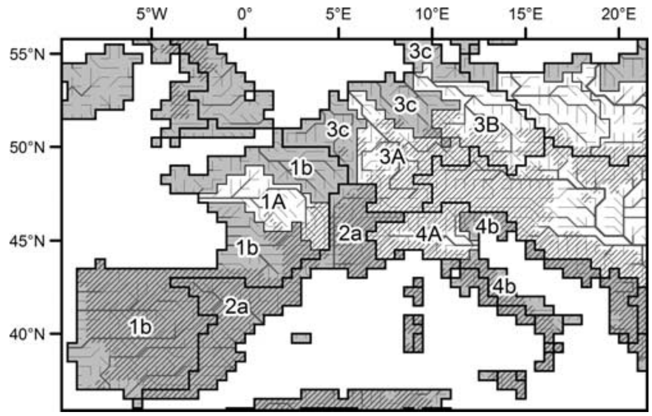

Figure 1. Hydrological division of continental surface into "analysis basins" using the simulated topological network STN–30p boundaries [*Vörösmarty et al.*, 2000a, 2000b] for river basins with a surface area larger than 100,000 km^2 (white) and the coastal catchments typology [*Meybeck et al.*, 2006] for the remaining areas (dark gray). Mountain areas are shown in hatch marks. Samples: 1A = Loire River basin (118,282 km^2), 1b = remaining Iberian-Biscay coastal catchment; 2a = Balearic coastal catchment (no large river basins contained); 3A = Rhine River basin (165,059 km^2), 3B = Elbe River basin (148,530 km^2), 3c = remaining North Sea coastal catchment; 4A = Po River basin (102,183 km^2), 4b = remaining Adriatic coastal catchment. For the Po River basin the area is clearly too high since the STN–30p grid is not able to separate it from the adjoining Adige River basin [see *Syvitski et al.*, 2005].

tion (see *Vörösmarty et al.* [1998] for details). The result is a spatially and temporally distributed runoff simulation which reproduces at-site discharge measurements. The quality of mountain area runoff is discussed in section 5.3.

2.4. Analysis Basins

[12] Since the significance of mountains in water resources is assessed in relation to the adjacent lowland areas, a hydrological reference between mountain and lowland areas has to be established. Following the resolution and referencing of the runoff data (see section 2.3), the river basins from the simulated topological network STN–30p [*Vörösmarty et al.*, 2000a, 2000b] were used. STN–30p represents potential flow pathways at 0.5° × 0.5° spatial resolution across the entire nonglaciated surface of the globe. It was derived from provisional flow directions for each land-based grid cell in a digital elevation model [*Edwards*, 1989] which were then adjusted with help of digital overlays of rivers and independent map sources.

[13] A major problem was how to handle small catchments since the resolution of a global-scale analysis is not sufficient to represent them accurately. Therefore the basins from the STN–30p were combined with the coastal catchments presented by *Meybeck et al.* [2006]. This typology is based upon a coastal segmentation with respective upstream basin areas and was originally developed to facilitate the budgeting of global riverine transfers from land to oceans; care was also taken to produce climatologically homogeneous coastal zones. For our combination, river basins with a surface area of more than 100,000 km^2 (165 basins with a total area of 92.0 M km^2) were taken from the STN–30p, while the remaining small catchments (total area 41.6 M km^2) were merged using the coastal catchment typology, resulting in another 231 basins. Figure 1 illustrates this procedure for western Europe; for example, the Loire River basin (1a, 118,282 km^2) is a large river basin, while the remaining small basins in the Iberian-Biscay coastal segment are aggregated to a single unit (1b, 1,109,150 km^2). All basin-relative computations are based upon the resulting "analysis basins" and carried out for the continental surface excluding Antarctica and the glaciated parts of Greenland.

[14] For 30 basins without lowland cells (mostly upper altitude endorheic areas), the lowest-lying cell according to the topological network STN–30p was changed to lowland manually in order to establish a plausible reference for calculation of mountain-lowland-relative figures. No changes were necessary for basins with only lowland cells since they are not relevant for our analysis.

2.5. Climate

[15] In order to understand the potential of mountains as "water towers", it is essential to examine their hydrological significance in different climate zones. To achieve this, the life zones scheme according to *Holdridge* [1967] was employed, offering appropriate resolution regarding critical climate transitions (see also discussion in section 5.2). The typology uses temperature, growing season length, mean annual precipitation and a potential evapotranspiration ratio to discern between five and eight humidity provinces for six latitudinal regions. The originally 39 classes were aggregated to 15 classes by *Leemans* [1992] which we further condensed into seven climate types that suit our hydrological point of view (Table 1).

Table 1. Climate Classification Condensed From *Leemans'* [1992] Aggregated *Holdridge* [1967] Life Zones Scheme[a]

Class	Contains Aggregated Holdridge Life Zones	A, %	POP, %	Q, %	q, mm a^{-1}
Polar and cold	tundra and polar; cold parklands	14.8	3.2	11.9	245
Cool	forest tundra; boreal forest	11.3	4.0	11.6	313
Temperate	temperate forest; warm temperate forest	9.9	23.3	15.2	465
Steppe	steppe; chapparal	9.7	13.6	1.9	59
Arid	cool desert; hot desert	18.5	7.9	0.3	5
Subtropical	tropical semiarid; tropical dry forest	18.3	24.8	8.8	147
Humid tropical	tropical seasonal forest; tropical rain forest	17.5	23.2	50.3	872

[a]A: Share in continental surface area (total: 133.6 M km^2); POP: Share in global population (total: 6.06 billion people); Q: share in global total discharge (total: 40,606 km^3 a^{-1}); q: Average total runoff; Antarctica and glaciated parts of Greenland are excluded.

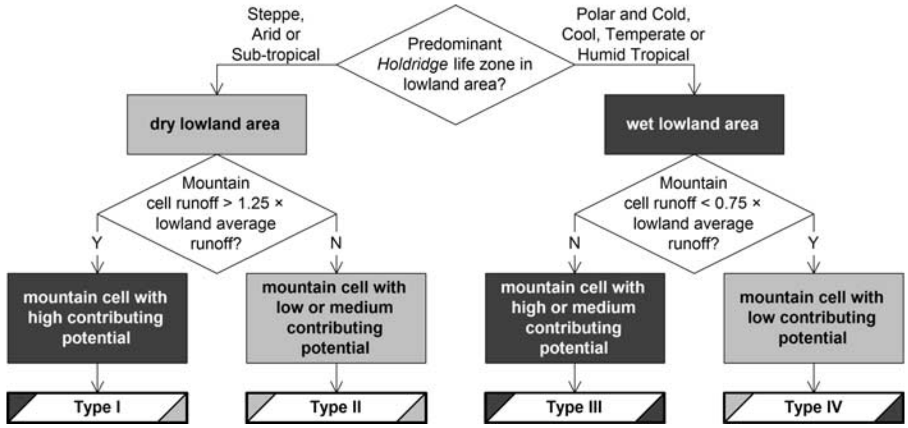

Figure 2. Flow chart for distinction of different Earth system mountain types for individual mountain cells.

2.6. Population

[16] For reasons of compatibility with the runoff and mountain typology data sets in use, population data prepared by *Vörösmarty et al.* [2000c] was employed. They used current country level population statistics, distributing them with the help of spatial extents of urban areas, populated places and with city lights from remote sensing. With a resolution of 0.5° × 0.5° and the reference year 2000, these data are sufficiently accurate and up-to-date for our global analysis. The incorporation of more recent and higher-resolution data (e.g., Oak Ridge National Laboratory (ORNL), 2004, *LandScan 2004 Global Population*, data available online at http://www.ornl.gov/sci/landscan/) proved difficult because they are not fully congruent with the hydrological data sets in use.

3. Methods

[17] To map and assess the hydrological significance of mountain areas, two indicators are introduced. They are later applied to all mountain cells and can either be mapped globally or tabulated according to relevant regions (e. g. by climate zone). Departing from the mere relation of highland to lowland runoff (indicator 1, relative water yield), four types of mountain cells are defined by incorporating lowland climate, representing the natural Earth system state. This is followed by adding human water needs (indicator 2, water resources contribution) which represents the demand perspective of man.

3.1. Runoff Contribution From Mountains (Relative Water Yield)

[18] First, the disproportionality of mountain runoff to lowland runoff is assessed in order to present an overview of the hydrological significance of mountains. This is done through the dimensionless coefficient *RWY* (relative water yield) which applies to all mountain cells *i*, each situated in a respective analysis basin *j*:

$$RWY_{i,j} = \frac{rm_{i,j}}{RL_j} \tag{1}$$

where $rm_{i,j}$ is runoff in each mountain cell *i* which belongs to analysis basin *j* (mm a^{-1}) and RL_j is average lowland runoff in analysis basin *j* (mm a^{-1}). RL_j is thus an aggregate value for the whole lowland area, while $rm_{i,j}$ as well as the resulting $RWY_{i,j}$ are specific for each mountain cell.

3.2. Mountain Typology in Earth System Context

[19] To emphasize the importance of the lowland-relative view, lowland climate is incorporated explicitly in the analysis. We distinguish mountain areas cell-wise into four classes using the following scheme:

[20] First, as a climatological distinction, it is determined whether climate conditions in the lowland part of an analysis basin are dry. Lowland dryness is identified here by the predominant aggregated *Holdridge* life zone, with steppe, arid, and subtropical considered as dry, the remaining classes considered as wet (see Table 1).

[21] Then, as a hydrological distinction, the contributing potential of a mountain cell to the respective analysis basin's lowland runoff is assessed. This is achieved by comparing mountain cell runoff to average lowland runoff using the following definition: With a dry lowland, a mountain cell's contributing potential is assumed high if its annual runoff exceeds 125% of mean annual lowland runoff; otherwise, its contributing potential is medium or low. With a wet lowland, a mountain cell's contributing potential is assumed low if its annual runoff is less than 75% of mean annual lowland runoff; otherwise, its contributing potential is high or medium.

[22] This procedure assigns to each individual mountain cell one of the four following classes (cf. Figure 2):

[23] 1. Earth system mountain type I: High contributing potential to a dry lowland area. This matches the original ''water towers'' concept of mountains being elevated humid islands within a dry region.

[24] 2. Earth system mountain type II: Medium or low contributing potential to a dry lowland area. These mountain cells are not significantly wetter than the lowland area but occasionally or seasonally still may be of essential importance, even with low discharges.

[25] 3. Earth system mountain type III: Medium or high contributing potential to a wet lowland area. Although located in a region where water supply in the lowlands is sufficient on average, these mountain cells have an important supporting function and make important seasonal contributions to lowland runoff.

Table 2. Interpretation of Water Resources Contribution Index *WRC* for Individual Mountain Cells

WRC	Interpretation
≤ -1	lowland deficit which cannot be satisfied through the mountain contribution; with this absolute deficit, water can only be supplied from other sources such as fossil groundwater pumping, river diversions or desalination.
$-1 - 0$	lowland deficit which can be transformed into a surplus thanks to the mountain contribution: the supply situation is still comfortable, but mountains are essentially important for satisfying lowland water need; appropriation of the mountain supply may require water storage in reservoirs.
$0 - 1$	lowland surplus, with an additional contribution from mountains which is larger than this surplus; mountains are not needed on the average, but may still contribute important seasonal supply or may be important for other uses such as hydroelectricity.
≥ 1	lowland surplus, which is even larger than the mountain contribution; mountains are not significant for lowland water need.

[26] 4. Earth system mountain type IV: Low contributing potential to a wet lowland area. This represents rain shadow areas or high altitudes.

[27] An interpretation of these mountain types in terms of hydrological significance will be done on basis of the results in section 5.1.

3.3. Mountains in Water Resources Context (Water Resources Contribution)

[28] For this first spatially explicit, global assessment, the water resources aspect is introduced by considering potential minimum anthropogenic water demand in lowlands as well as in mountains. While global maps of human water use such as irrigation now become available [e.g., *Siebert et al.*, 2005], total anthropogenic river water depletion can be determined with high resolution only at the regional scale. Therefore a per capita need of 500 $m^3\ a^{-1}$ is assumed here, being the threshold value for severe water scarcity according to *Falkenmark and Widstrand* [1992]. It should be noted that this represents an absolute minimum need which we consider here to be permanently withdrawn. Actual needs may vary locally and regionally, depending on a variety of factors such as the extent of irrigation and the state of economic development [see, e.g., *Sullivan*, 2002]. We introduce an index for water resources contribution *WRC* which is the ratio of lowland water availability (surplus or deficit) to water supply (only surplus is considered, see below) from mountains, again applicable to all mountain cells:

$$WRC_{i,j} = \frac{\left(RL_j - NL_j\right)}{\left(rm_{i,j} - NM_j\right)} \qquad (2)$$

where RL_j is average runoff in lowland area of analysis basin j (mm a^{-1}), NL_j is minimum water need of population in lowland area of analysis basin j (mm a^{-1}), $rm_{i,j}$ is runoff from mountain cell i which is situated in analysis basin j (mm a^{-1}), and NM_j is minimum water need of population in mountain area of analysis basin j (mm a^{-1}).

[29] *WRC* identifies the importance of each mountain cell i for water resources supply in the related lowland of analysis basin j. Mountain water need NM_j is calculated as a basin average (as opposed to the cell-wise treatment of mountain runoff $rm_{i,}$) to smooth out high local water demands which can be satisfied with runoff from adjacent cells. The interpretation of *WRC* values is given in Table 2.

[30] The following example adopted from the Rhine River catchment illustrates the calculation and interpretation of *WRC*: Minimum water need for the lowland population of 22 million is 11 $km^3\ a^{-1}$ or, relative to an area of 77,200 km^2, 142.5 mm a^{-1} (*NL*). Average lowland runoff is 239 mm a^{-1} (*RL*), resulting in a small, but positive lowland surplus of 96.5 mm a^{-1} (*RL-NL*). For the total mountain population of 18.6 million, minimum water need is 9.3 $km^3\ a^{-1}$ or, relative to an area of 87,900 km^2, 105.9 mm a^{-1} (*NM*). Runoff from a selected mountain cell in Central Switzerland is 1350 mm a^{-1} (*rm*), the balance for this specific cell thus being a large surplus of 1244.1 mm a^{-1} (*rm–NM*). According to equation (2), the cell's *WRC* is 0.08, indicating that lowland water resources are only just sufficient, while mountain discharge has an important supportive role and shows a considerable surplus which, for instance, is available for hydropower use. Note that the extent of the mountainous area for the Rhine River catchment is rather high here as compared to other studies [e.g., *Viviroli and Weingartner*, 2004b] because an extensive mountain definition was employed in order to identify all potentially important elevated areas (see section 2.2).

[31] The mountain water balance term ($rm_{i,j} - NM_j$) may be negative because of one or both of the following reasons: Either, mountain population is very high so its demand exceeds the available supply, or, mountain discharge is very low so that the demand of the population cannot be met. In these cases, *WRC* is not calculated. Instead, the causing conditions (high population and/or low runoff) are identified. We assume high population for densities above 21 p km^{-2} (half of the average population density in coastal catchments according to *Meybeck et al.* [2006]) and low runoff for values below 30 mm a^{-1} (just under one tenth of average runoff depth in exorheic regions, generally used as threshold for nonpermanent river flow [*Vörösmarty and Meybeck*, 2004]).

4. Results

4.1. Runoff Contribution From Mountains (Relative Water Yield)

[32] The shares of mountains in global area, discharge and runoff are shown in Table 3 for different life zones, with lowland runoff values given for comparison. Compared to their share in total area (29.8%), mountains in the arid zone clearly deliver most disproportional discharge (share: 66.5%

Table 3. Discharge and Runoff From Mountains for Condensed *Holdridge* [1967] Life Zones[a]

Life Zone	Q_M, %	A_M, %	q_M, mm a^{-1}	q_L, mm a^{-1}
Polar and cold	72.5	62.2	285	175
Cool	49.6	37.1	418	250
Temperate	60.8	43.4	650	321
Steppe	59.4	47.9	73	46
Arid	66.5	29.8	11	2
Subtropical	35.0	29.9	172	136
Humid tropical	32.0	30.6	912	854
Outside humid tropical	56.4	40.4	256	133
Steppe, arid, and subtropical	40.0	33.6	86	65
Overall	44.1	38.7	349	276

[a]Q_M: mountain share in total discharge; A_M: overall surface area; q_M: average runoff in mountains; q_L: average runoff in lowlands.

of total). This disproportionality is second highest for the temperate zone (share in total area: 43.4%, share in total discharge: 60.8%). Note that calculation of *RWY* from mountain and lowland runoff is not allowed here because runoff values refer to averages over different life zones; for *RWY,* a hydrological linkage in the sense of mountains-lowlands is necessary since it is calculated always relative to an analysis basin.

[33] To assess relative water yield correctly, Figure 3 shows the area-weighted distribution of *RWY,* distinguished by the predominant life zone in the lowlands. The essential importance of mountains for lowland areas with dry climates is highlighted: Although area-relative median values (50% of summed up area) are very low for the steppe, arid, and subtropical life zones, between 18% and 31% of mountain cells have very high *RWY* values of more than 5. Regionally, these contributions are essential.

[34] Figure 4 maps the cell-by-cell values of relative water yield in mountains (*RWY*), thus identifying disproportionality of runoff formation in mountains. Details for runoff from mountain ranges with superior water yield are found in Table 4. Extended areas with disproportionally high mountain runoff can be identified especially in semi-arid and arid regions (e.g., Ethiopian Highlands, Drakens Mountains, Great Dividing Range), but also in more humid regions (e.g., European Alps). Low relative water yield from mountains, in contrast, is found inside of large mountain massifs such as the Himalayas (e.g., Tarim Basin) and the Rocky Mountains (e.g., parts of Colorado Plateau) as well as in river basins which on the average show strongly humid conditions (e.g., Amazon and Mississippi rivers).

4.2. Mountain Typology in Earth System Context

[35] The relation to lowland climate conditions is given explicitly in the map of Earth system mountain types (Figure 5, top), where the global mountain area is distinguished cell-wise according to contributing potential and lowland climate (cf. Figure 2). The resulting map particularly reveals the location of mountain areas contributing disproportionally to lowland discharge, with distinction of associated lowland climate being dry (I, blue) or wet (III, green). This distinction can even concern one single mountain range which is orientated toward different lowland climates, as is the Highland of Bihé: north to the wet lowlands of the Zaire (Congo) River basin, south to the drier Zambezi River basin. It is further revealed where disproportionally low discharge from mountain areas occurs, again distinguished by associated lowland climate being dry (II, yellow) or wet (IV, brown). Theoretically, type IV should not be directly adjacent to lowland areas since it represents rain shadow area or high altitudes. Occurrences are found, however, as an actual precipitation increase at the rise of a mountain massif may not be captured by the typology when other parts of the basin are excessively wet (e.g., Mississippi and Amazon River basins). Regional examples for all four mountain types are listed in section 5.1 where the interpretation of this typology for water resources will be discussed.

[36] As Table 5 reveals, mountain type I clearly shows the highest relative water yield (average *RWY* = 6.0) with a runoff of 389 mm a^{-1}; with an extent of 12 M km^2, it covers 23% of global mountain area. The highest absolute discharge (11,512 km^3 a^{-1}) and runoff (734 mm a^{-1}) is found in mountain type III, which is explained by the high precipitation amounts that mountains can extract in humid climates; this type covers 30% of global mountain area. The respective average *RWY* of 1.5 admits a supportive role and points at a large surplus. The average *RWY* for type II is relatively low (0.5), but may still have high relevance in terms of seasonal and local contributions (cf. Figure 3); it has a share of 28% in global mountain area.

[37] The changing importance of the Earth system mountain types is examined in Figure 6, which shows their contribution to the lowlands for different predominant lowland life zones:

[38] 1. With all climate zones in focus, type III clearly makes highest contributions, providing 63% of mountain discharge with a share in mountain area of only 30% (*RWY* = 2.6). Type I is also of importance for runoff formation (discharge: 26%, area: 23%), although less markedly disproportional (*RWY* = 1.4), while types II and IV participate to a lesser degree in runoff formation.

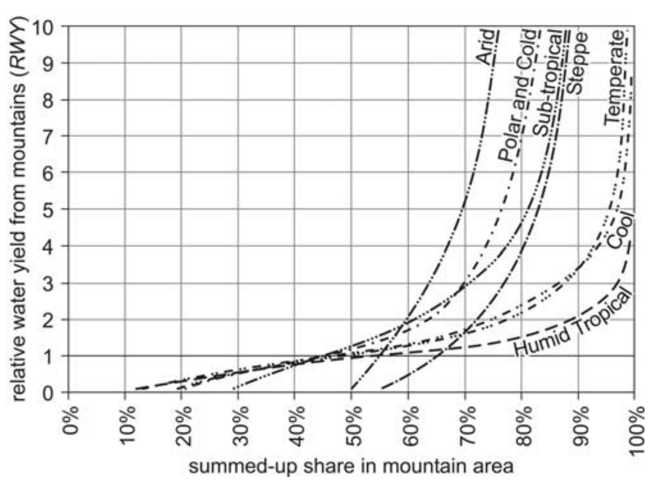

Figure 3. Relative water yield *RWY* in relation to the summed up share in mountain area, distinguished for seven condensed *Holdridge* [1967] life zones. The summed-up share refers to area-weighted cumulative distribution of *RWY* values; life zone distinction was made on the basis of the predominant zone occurring in the lowland area to which the mountain cell is related.

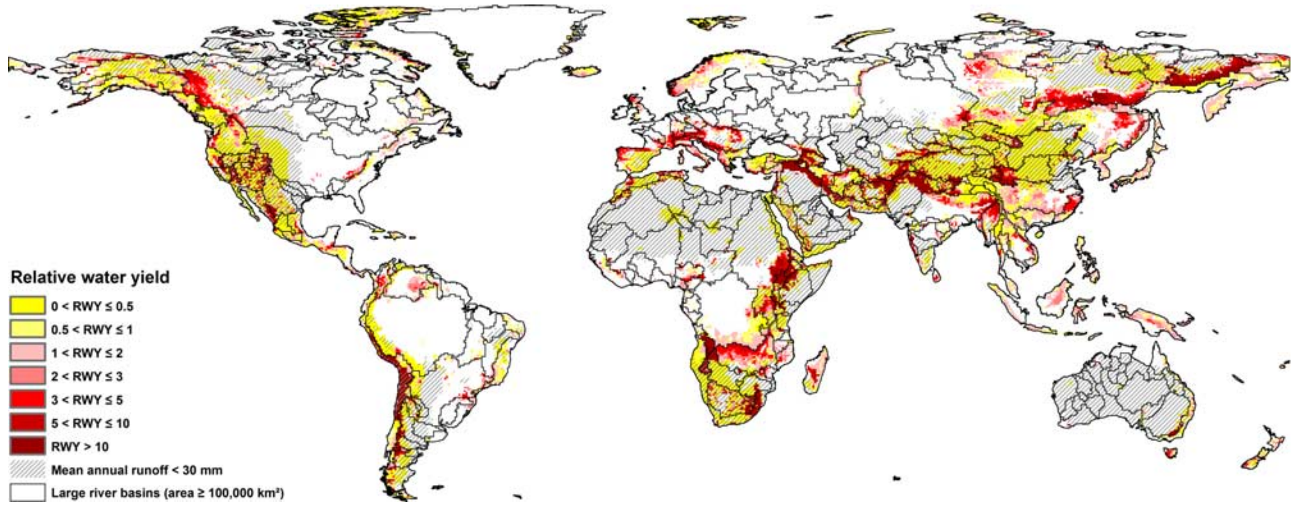

Figure 4. Disproportionality of mountain runoff formation relative to average lowland runoff (*RWY*), mapped cell by cell for mountainous areas. Disproportionality in favor of runoff is given when *RWY* is greater than 1, its importance being marked for *RWY* > 2 and essential for *RWY* > 5.

[39] 2. If the humid tropics are disregarded, *RWY* values are clearly higher. While type I gains importance (discharge: 39%, area: 27%, *RWY* = 2.8), type III has somewhat lower shares, although with an increased *RWY* (discharge: 51%, area: 25%, *RWY* = 3.9).

[40] 3. For the temperate zone, shares in discharge are much higher for type III (90%) than for type IV (10%), although their shares in area differ far less (type III: 60%, *RWY* = 2.6; type IV: 40%, *RWY* = 0.5).

[41] 4. In steppe, arid, and subtropical zones, types I and II show a similar pattern as types III and IV in the temperate zone, however with a markedly higher *RWY* values for type I (5.2). Especially in view of strong seasonal variability of lowland runoff, these contributions are essential.

[42] Note that the predominance of types I and III complies with our definition of Earth system mountain types, as well as the absence of types I and II in the temperate zone and of types III and IV in the dry zones.

4.3. Mountains in Water Resources Context (Water Resources Contribution)

[43] Mapping the water resources contribution index *WRC* (Figure 5, bottom) finally illustrates the importance of mountains for human water needs. Critically important mountain regions are found in the Middle East, South Africa, parts of the Rocky Mountains and the Andes. Particularly marked is the importance of mountain water resources in the western and eastern Himalayas, which partly cannot compensate the large lowland deficits any more (*WRC* < −1). Striking is the frequent occurrence of overuse of mountain water resources which is found primarily in the dry mountain areas already mentioned.

[44] With the help of Figure 7 (left), it is revealed that over one third (37%) of global mountain area has a supportive role for lowland water resources (*WRC* between 0 and 1), which may also include important seasonal contributions, while about 7% are of essential significance

Table 4. Selected Mountain Ranges With Superior Relative Water Yield and Corresponding Major River Basins Which Benefit From the Disproportionally High Runoff[a]

Mountain Range(s)	Major Beneficiary River Basin(s)	q^*, mm a^{-1}
Andes, South	Chubut, Río Colorado[b], Río Negro[b]	1350
Drakens Mountains	Orange	219
Ethiopian Highlands	Blue Nile, Juba, Omo	901
European Alps	Danube, Po, Rhine, Rhone	1165
Great Dividing Range	Murray	590
Highland of Bihé	Okavango, Zambezi	565
Himalayas, East	Huang He	585
Himalayas, South	Ganges-Brahmaputra, Indus, Irrawaddy	4735
West Ghats	Krishna	2827
Jablonowy Mountains	Lena	929
Kolyma Mountains	Kolyma	515
Pamir, Altai, Hindukush, Tien Shan	Amu-Darya, Syr-Darya	682
Rocky Mountains, North	Mackenzie	1157
Rocky Mountains, South	Colorado, Rio Grande/Rio Bravo[c]	298
Taurus and Zagros Mountains	Euphrates and Tigris (Shatt al-'Arab)	535

[a]The q* is the maximum smoothed runoff (mean in circular-shaped neighborhood with radius of 1°) in the mountainous part of the respective beneficiary river basin(s), being representative for the highest runoff values which can be expected on the mesoscale. The rivers selected here have a basin area of more than 100,000 km^2 and an average *RWY* of more than 2.5.

[b]Argentina.

[c]United States/Mexico.

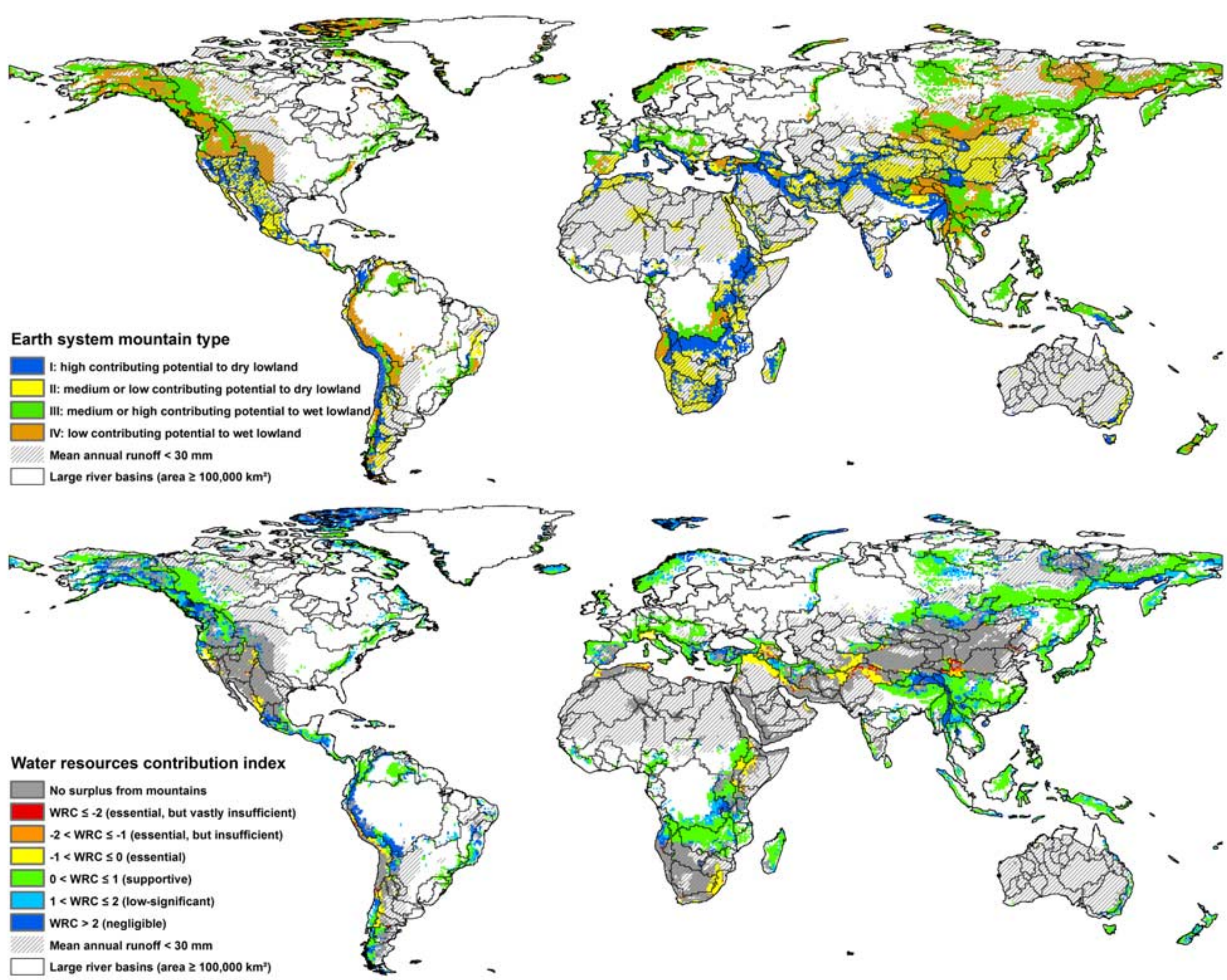

Figure 5. Global map of Earth system mountain types (top, cf. Figure 2) and of water resources contribution index *WRC* (bottom, cf. Table 2). Areas with an annual runoff of less than 30 mm are subject to increasing uncertainty and therefore displayed in hatch marks.

(*WRC* < 0). Following our classification, we expect mountain type I to show highest significance for lowland water supply; this is corroborated through Figure 7 (right), where the distribution of *WRC* noticeably shifts toward lower values, indicating a greater importance for the lowlands. Around the critical value of *WRC* = 0, a stronger concentration is found, with 27% of type I mountains being very important (*WRC* < 0) and 48% providing additional resources (*WRC* between 0 and 1). This indicates a vital importance of type I mountains for water resources supply, particularly in the densely populated subtropical regions. Note that the assumed per capita need of 500 m^3 a^{-1} represents a minimum value and that with assumption of higher values, the resulting *WRC* index would become smaller (i. e. even more in favor of mountain water supply).

4.4. Importance of Different Relief Types

[45] With the rather extensive definition chosen for the delineation of mountains, it is possible to identify those relief types which actually function as a ''water tower''. Low and midaltitude mountains produce the highest discharge and make up the largest area in all four Earth system mountain types (Table 5). Highest runoff values are found for hills (770 mm a^{-1} in mountain type III and 550 mm a^{-1} in mountain type I) which is explained by the marked precipitation increase at the foot of mountain ranges, especially in humid areas. Values are only little lower for low- and midaltitude mountains (756 mm a^{-1} in type III, 408 mm a^{-1} in type I) and for high and very high altitude mountains (611 mm a^{-1} in type III, 409 mm a^{-1} in type I). Elevated Plateaux, on the other hand, produce significantly less runoff. However, it should be kept in mind that these values refer to an annual average. Seasonal and regional importance is therefore always subject to specific investigations.

5. Discussion

5.1. Mountain Types in Earth System Context

[46] Considering above results, the typology of mountains in Earth system context (cf. sections 3.2 and 4.2) is rephrased, now with focus on the ''water tower function'' instead of the mere contributing potential to lowland discharge. Table 6 summarizes our conclusions with regards to water resources and hydropower potential. This results in a revised type description:

Table 5. Characteristic Hydrological Values for the Relief Types [*Meybeck et al.*, 2001] Considered as Mountainous for this Article, Distinguished Into Earth System Mountain Types I to IV[a,b]

Relief Type	Mountain Type I: Dry Lowland Climate, High Contributing Potential			Mountain Type II: Dry Lowland Climate, Low or Medium Contributing Potential			Mountain Type III: Wet Lowland Climate, High or Medium Contributing Potential			Mountain Type IV: Wet Lowland Climate, Low Contributing Potential		
	A, 10^6 km^2	Q, km^3 a^{-1}	q, mm a^{-1}	A, 10^6 km^2	Q, km^3 a^{-1}	q, mm a^{-1}	A, 10^6 km^2	Q, km^3 a^{-1}	q, mm a^{-1}	A, 10^6 km^2	Q, km^3 a^{-1}	q, mm a^{-1}
Hills	1.3	732	550	2.2	140	63	5.4	4139	770	2.6	543	206
Low and midaltitude mountains	6.2	2529	408	7.9	198	25	8.5	6456	756	5.2	837	163
High and very high altitude mountains	2.5	1017	409	1.2	59	48	1.0	616	611	1.1	160	144
Elevated plateaux[c]	2.0	386	196	3.2	19	6	0.8	300	388	1.0	51	52
All relief types	12.0	4664	389	14.5	416	29	15.7	11,511	734	9.9	1591	161
Average relative water yield			6.0[d]			0.5[d]			1.5[e]			0.3[e]

[a]Cf. section 3.2.
[b]A: Surface area, Q: mean annual discharge, q: mean annual runoff. Total mountain area is 52.1 M km^2, total mountain discharge is 18,182 km^3 a^{-1}, and average mountain runoff is 349 mm a^{-1}.
[c]Medium, high, and very high altitude plateaux and midaltitude plains > 1000 m asl.
[d]Relative to average lowland runoff in dry zones (65 mm a^{-1}).
[e]Relative to average lowland runoff in wet zones (491 mm a^{-1}).

[47] 1. Earth system mountain type I: Essential water tower. Most of the discharge in the respective lowland basins originates from the mountain cells, which are therefore of superior importance. Examples: Ethiopian Highlands (Nile River), Taurus and Zagros Mountains (Euphrates and Tigris rivers), Pamir and Tien Shan (Amu-Darya and Syr-Darya rivers), southwest Himalayas (Indus River), Highlands of Lesotho (Orange River), and parts of the southern Rocky Mountains (Colorado River and Rio Grande).

[48] 2. Earth system mountain type II: Occasional water tower. Mountain cells may be essential for downstream discharge on the regional scale, either seasonally or in single years. Examples: Hoggar and Tibesti Mountains, central and northwest Himalayas.

[49] 3. Earth system mountain type III: Supportive water tower. Mountain cells contribute considerably to downstream discharge and bear an essential hydropower potential. Examples: European Alps (Danube, Rhine, Rhone, and Po rivers), northern Rocky Mountains (Mackenzie), eastern Himalayas (Chang Jiang/Yangtse River).

[50] 4. Earth system mountain type IV: Limited water tower. Mountain cells are dryer than the lowland average and therefore of only limited or local value; potential for hydropower generation is available. Examples: northeast Andes (Amazon River), eastern Rocky Mountains (Mississippi River).

[51] The importance for geofluxes (fluxes of water and associated solid, gaseous, and dissolved material as well as thermal and mechanical energy) is summarized as well in Table 6. Geofluxes are essentially derived from wet mountain areas [*Milliman and Syvitski*, 1992], and if the potential for river transport is also high in the associated lowlands (such as in Earth system mountain type III downstream areas), geofluxes are generally high in the respective catchments. In Earth system mountain type I downstream areas, contrarily, transport may be limited because of lowland storage (except for large allochthonous rivers such as the Nile river capable of crossing large dry areas).

5.2. Climate Definition

[52] To test and assess climate definitions and more specifically average lowland dryness in a representative manner, various approaches were compared: precipitation [*New et al.*, 2002] < 400 mm a^{-1}; precipitation [*New et al.*, 2002] < 500 mm a^{-1} and precipitation variability > 75%; runoff [*Fekete et al.*, 2002] < 30 mm a^{-1}; *De Martonne* [1926] aridity index; *Köppen* [1936] dry climate zones; *Gorczynski* [1940] aridity index; *Holdridge* [1967] steppe, arid, and subtropical life zones.

[53] We are aware that the choice of thresholds and definitions in our methods influences the results to a certain degree. Assessing climate parameters such as precipitation-evaporation relationships, used for example for the *Holdridge* [1967] climate definition, is inherently difficult in mountain areas. While all methods have their particular benefits and shortcomings, the choice for the *Holdridge* life zone scheme was made because it produces the most plausible overall picture for the combined distributions of climate zones in general and of lowland dryness in particular.

[54] Capturing lowland dryness with a globally uniform definition is difficult, especially in lowland regions which are climatologically very heterogeneous. One of the most difficult cases is the Niger River. It originates from a hilly

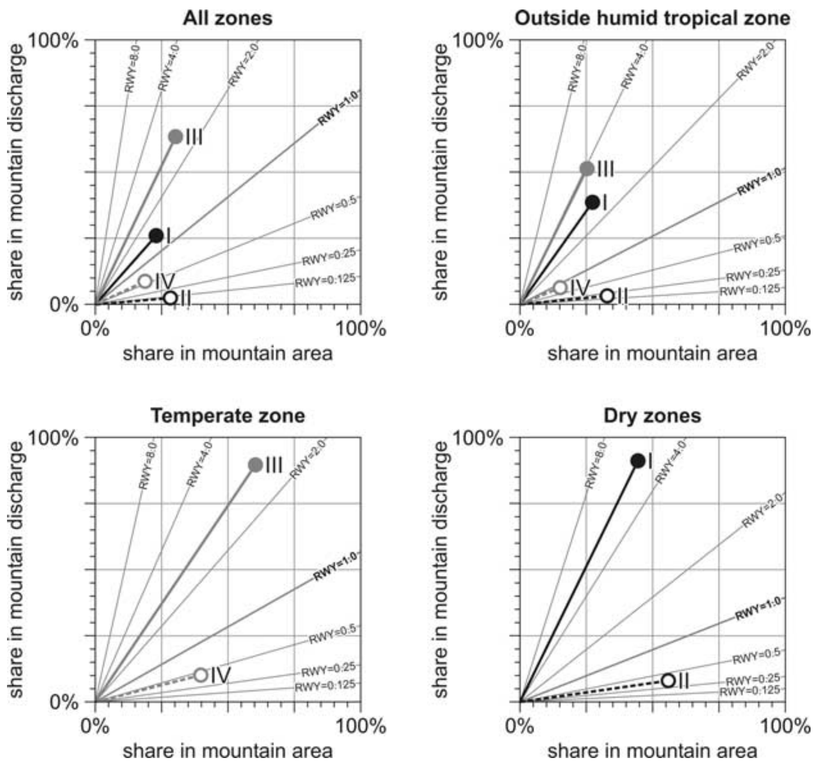

Figure 6. Share in mountain discharge (ordinate) compared to share in mountain area (abscissa), distinguished by predominant *Holdridge* [1967] life zone in the lowlands and by Earth system mountain types I to IV (cf. section 3.2). The diagrams thus refer to a mountain area contributing to the respective lowland life zone. Zone-specific relation to *RWY* is given for each diagram, determined from respective values of area and average runoff in the lowland and in the mountain section; the steeper the line for the mountain types, the greater *RWY* and therefore the importance in terms of runoff formation (cf. Figure 3). The thought line of unity where share in runoff is equal to share in area refers to an average *RWY* of 1.3 for all zones, 1.9 outside the humid tropics, 1.7 for the temperate zone, and 2.5 for dry zones. In compliance with our definition, Earth system mountain types I and II do not contribute to the temperate zone, and types III and IV do not contribute to the dry zones.

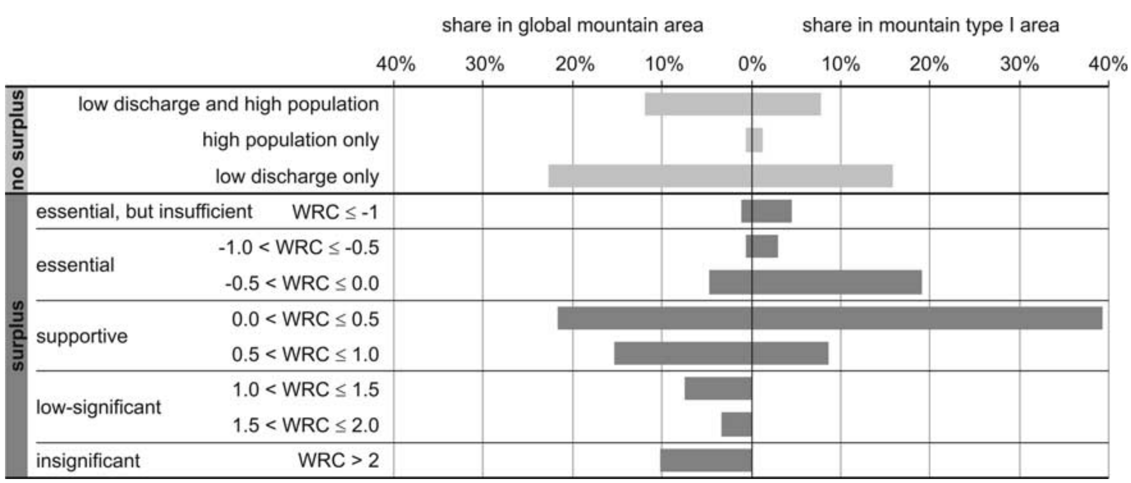

Figure 7. Importance of all mountain areas (left) and of Earth system mountain type I (right) for lowland water supply, assessed through occurrence of water resources contribution index *WRC*. Note that mountain type I shows no *WRC* values above 1 and therefore always has at least supportive function; this complies with its definition as a mountain area with high contributing potential to a dry lowland area (see also Table 2).

Table 6. Relative Importance of Mountains as Water Towers With Regards to Different Functions, Distinguished by Earth System Mountain Type[a]

	Type I	Type II	Type III	Type IV
Lowland water resources	++	+	0 to +	–
Hydropower potential	+	– to +	++	0 to +
Geofluxes	+ to ++	–	++	0 to +

[a]Compare with section 3.2; negative sign: very low; 0: low; plus sign: medium; double plus sign: high.

area (the Fouta Djalon) in a tropical monsoon climate, flows northeasterly to reach a hot desert area and then returns southeasterly to a tropical monsoon climate [cf. *Viviroli and Weingartner*, 2004a]. Additionally, it is joined in its lowest course by the Benue River which is located in a humid climate and therefore further masks the marked dryness which occurs in the middle course of the Niger River. In our analysis basin typology, this particular problem was eased by separating the Benue River from the Niger River and treating it as an individual basin.

[55] The typology established here holds valid for today's climate only. This is particularly relevant for the mountain areas that have a low contributing potential to a dry lowland area. The Hoggar and Tibesti Mountains, for instance, were important "water towers" for the Sahara Area in the humid Holocene, as can be deduced from Elephant bones and rock paintings discovered [cf. *Mauny*, 1956]. In a more humid climate, these mountain areas might be reactivated.

5.3. Global Runoff Model

[56] An important source of uncertainty is the underlying runoff model. In order to assess the accuracy and plausibility of runoff values, the continental water balances of the employed UNH model [*Fekete et al.*, 2002] were compared with outputs from the WaterGAP [*Döll et al.*, 2003] model, and the world water balance according to *Baumgartner and Reichel* [1975] (Table 7). The comparison generally shows a high degree of correspondence, with more notable differences for Africa and Australia. Altogether, uncertainties of modeled runoff are significantly larger in areas where the model could not be adjusted properly because of missing long-term gauge values [see *Fekete et al.*, 2002].

Table 7. Comparison of Mean Annual Runoff for Six Continents From Various Sources[a]

Continent	WWB, mm a^{-1}	UNH-GRDC, mm a^{-1}	WGAP, mm a^{-1}	A, 10^6 km^2
Africa	114	151	119	30.1
Asia	276	294	251	44.0
Australia	269	235	236	9.1
Europe	282	286	270	9.9
North America	242	279	235	22.5
South America	618	659	633	18.0
Overall	278	304	270	133.6

[a]WWB: world water balance by *Baumgartner and Reichel* [1975], UNH-GRDC: composite runoff fields [*Fekete et al.*, 2002], WGAP: WaterGAP [*Döll et al.*, 2003], A: Surface area; glaciated parts of Greenland and Antarctica are excluded.

Table 8. Comparison of Modeled Mean Annual Runoff From Mountain Areas For Six Continents[a,b]

Mountains of continent	UNH-GRDC$_M$, mm a^{-1}	WGAP$_M$, mm a^{-1}	A_M, 10^6 km^2
Africa	194	140	10.3
Asia	354	296	23.4
Australia	1002	913	1.3
Europe	468	420	2.8
North America	309	270	9.3
South America	491	500	5.0
Overall	349	302	52.1

[a]Broad sense, based on *Meybeck et al.* [2001].
[b]UNH-GRDC$_M$: composite runoff fields [*Fekete et al.*, 2002], WGAP$_M$: WaterGAP [*Döll et al.*, 2003]; A_M: Mountain surface area; glaciated parts of Greenland and Antarctica are excluded.

[57] In mountain areas, however, higher uncertainties must be expected because of the high heterogeneity of hydroclimatological patterns and the sparser gauging network. The comparison of runoff from mountain areas for the UNH-GRDC and WaterGAP models in Table 8 shows that, with the exception of South Africa, the UNH-GRDC model produces higher runoff values from mountain areas, most clearly for Asia and Africa. On a smaller scale, comparisons for the densely gauged region of the European Alps (model: 822 mm a^{-1} [*Fekete et al.*, 2002], reference: 910 mm a^{-1} [*Baumgartner et al.*, 1983]) and Switzerland (model: 1061 mm a^{-1} [*Fekete et al.*, 2002], reference: 991 mm a^{-1} [*Schädler and Weingartner*, 2002]) suggest that at least in areas with extensive measurements, water balance in mountains is represented with reasonable accuracy. While the underestimation for the European Alps was expected because of the smoothing effects in models, the overestimation of strongly mountain influenced Switzerland is rather surprising.

[58] Although global runoff models now under development will be improved using full calibration instead of adjustment methods, mountain runoff will presumably remain hard to assess because of the inherent difficulties concerning representativity and accuracy of the gauging networks.

[59] As consequence of the current uncertainties, the maps presented should not be interpreted on basis of single pixels, but rather in the regional and global patterns they produce. We assume larger uncertainties for low runoff values and the figures derived from them, respectively, and suggest cautious interpretation for areas with a mean annual runoff of less than 30 mm (shown in hatch marks in the relevant world maps). This applies especially to the "occasional water towers" (type II) as defined above where precipitation and runoff are low, but highly variable from year to year. Consequently, the validity of mean annual values is limited, while interannual variability causes a significant vulnerability for crises in water resources [cf. *Viviroli et al.*, 2003].

6. Summary and Outlook

[60] An exhaustive assessment of mountain areas with regards to water resources supply for the adjacent lowlands was presented, providing the basis for identification of critically important regions on a global scale. The signifi-

cance of mountain areas was assessed first in a hydrological and ecological context, ranging between essential (23% of global mountain area), supportive (30%), occasional (28%) and limited (19%) importance. When lowland water users are considered, 7% of global mountain area has an essential role in water resources, while another 37% provide important supportive supply. The distinction of climate zones in typology and analysis was indispensable since significant findings may be masked in global average values. With the resulting maps, the disproportionality of mountain runoff is identified on a cell-by-cell basis, and statements for individual basins, climate zones and relief types are summarized from this data. The methods that have been established could serve as a starting point for more detailed investigations, for instance with increased spatial (regional) and temporal (seasonal) resolution.

[61] Studies rooted in regional analysis (e.g., *Barnett et al.* [2005] on possible changes in snowmelt-dominated regions) are able to provide higher spatial accuracy, and specific regional analyses (such as *Bales et al.* [2006] for the western United States) may point more clearly to research issues such as the combination of remote sensing and ground-based data. Similar analyses will only be feasible at global scale with highly improved global hydrological modeling efforts, but they are inherently hampered by the lack of accurate monitoring data in many regions of the world.

[62] Within the next decades, effects of climate change and population growth are expected to worsen water resources supply significantly, particularly through altered discharge patterns from mountains [see *Messerli et al.*, 2004] and increasing demand for food production. This will affect most heavily regions prone to scarcity already today, such as arid regions or also the monsoon belts, especially when seasonal deficits occur which nowadays are attenuated by mountain supply. Since at least 40% of the world's population lives in a river basin shared by two or more countries [*Wolf*, 2002], a considerable conflict potential exists about sharing water between upstream and downstream neighbors. To date, more than twice as much positive interactions are reported than negative ones [*Wolf et al.*, 2003], but with increasing pressure, basin-wide agreements are likely to meet harder challenges. The expansion of human water resources appropriation (today 56% of global accessible discharge [*Postel et al.*, 1996]) will foster the construction of dams and river transfers, which will also have serious ecological, economical and social costs [*Gleick*, 2003]. The most severe problems are to be expected in developing regions of the tropics and subtropics, where water resources management is hindered by the lack of reliable and long-term data sets, missing technical, scientific and financial resources as well as political instability. At the same time, dependency on mountain water resources is increased by demographic pressure as well as by strong urbanization and industrialization processes.

[63] An integrated approach is necessary for sustainable water management, with an adequate monitoring network and the best possible assessment of the resource as basis for decision making [*WWAP*, 2006; *Oki and Kanae*, 2006]. This applies especially to water resources originating from mountain areas which are essential for mitigation of seasonal and regional deficits, and there particularly to the developing world. In these regions, the data available today are not yet sufficient for a long-term successful water resource management which is necessary for the benefit of the rapidly growing population and the urgently needed increase of food production. Furthermore, climate and hydrology modelers should focus on a better representation of the even more uncertain mountain areas, because they represent highly relevant areas for today's and tomorrow's water resources.

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