HYDROLOGICAL PROCESSES
Hydrol. Process. **21**, 578–585 (2007)

(www.interscience.wiley.com) DOI: 10.1002/hyp.6268

Water resources in mountain regions: a methodological approach to assess the water balance in a highland-lowland-system

Rolf Weingartner,[1] Daniel Viviroli[1]* and Bruno Schädler[2]

[1] *Department of Geography, University of Berne, Hallerstrasse 12, CH-3012 Berne, Switzerland*
[2] *Swiss Federal Office for the Environment, CH-3003 Berne, Switzerland*

Abstract:

Mountains and highlands are typically areas that provide considerable quantities of water, the latter being an important resource for the lowlands. These run-off quantities remain discernible in the superior-scale river systems and significantly contribute to the global water resources. Therefore, mountain regions ought to be given specific consideration with regard to management endeavours. Although well known in principle, details of water resources originating from mountains remain under discussion. A new approach has been introduced, which depicts the water balance of Switzerland in a spatially distributed manner, based on catchments of about 150 km^2. The main feature of this approach is the areal precipitation, which is calculated using run-off, evaporation and storage change of glaciers, instead of being derived from gauged precipitation values. This methodology was selected because measurement and regionalization of precipitation remain subject to large uncertainties in mountainous areas. Subsequently, the view is widened to the European Alps, which, as compared with the surrounding lowlands, contribute considerably higher annual discharge, especially in the summer months. Finally, the focus is put on the hydrological significance of mountains in general. In dry regions, mountains, in particular, are indispensable contributors to the water resources downstream. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS water balance; water resources; Switzerland; European Alps; scales; highland-lowland; mountain regions

Received 3 May 2005; Accepted 29 November 2005

INTRODUCTION

The Rio Earth Summit in 1992 being an important milestone, mountains have gained increasing attention in science and politics. Especially the mountain-specific Chapter 13 in Agenda 21 (UNCED, 1992) underscores the global role that mountains play in the debates on environment and development issues (Funnell and Price, 2003). With regard to hydrology, the symbolic term 'water tower' has emerged (e.g. Mountain Agenda, 1998) and is now widely adopted, expressing the importance of mountains in providing freshwater for the adjacent areas downstream. With the International Year of Mountains 2002 and the following International Year of Freshwater 2003, the concerns of mountain areas have obtained further legitimacy.

Although the principles of the hydrological highland-lowland linkage recognized for a time long since—especially in glaciology and meteorology (*cf* Marcinek, 1984)—and are irrefutable, accurate figures for the hydrological importance of mountains on a global scale remain disputed. While earlier estimates vaguely expected up to 80% of the world's freshwater to originate in mountain watersheds (e.g. Mountain Forum, 1995), a recent study focused on an estimate of 32% (Meybeck *et al*., 2001). The considerable difference between the two estimates underscores the necessity for further research into the hydrological role of mountains for water supply. On the basis of case studies and results from global run-off models, this paper presents new figures on the hydrological significance of mountain regions. Not only does the role of mountains need to be clarified but so does the water balance of mountains, which still remains uncertain. This particularly applies to inferior scales (mesoscale), where the water balance terms are difficult to resolve owing to sparse gauging networks (Rodda, 1994) and large errors revealed especially in precipitation measurements Kirchhofer and Sevruk (1992). A further hindrance is the high spatial heterogeneity of hydrological, meteorological and climatological patterns in mountains. Although closer knowledge about mountain run-off is required 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).

WATER BALANCE IN MOUNTAINOUS AREAS: CASE STUDY OF SWITZERLAND

As resumed in the introduction, spatially detailed insights into both the water balance and, consequently, the water resources of mountain areas are not easily gained. The present section provides a suitable method to meet

---

* Correspondence to: Daniel Viviroli, Department of Geography, University of Berne, Hallerstrasse 12, CH-3012 Berne, Switzerland.
E-mail: viviroli@giub.unibe.ch

this challenge. The case study of Switzerland described (Schädler and Weingartner, 2002) is based on the current hydrometeorological measuring networks and deals with the idea of an optimal use of the information available, carefully considering the relevant measurement error, however. In this respect, emphasis must be placed on the fact that within global comparison Switzerland has one of the densest measurement networks, a fact that limits the range of applicability of the method in question to other mountain regions.

The water balance describes the hydrological character of the catchments. Its components are areal precipitation (P), areal run-off (R), areal evaporation (E) and change in water storage (dS): Under particular hydrogeological conditions, in particular, in karst areas, natural underground inflow and outflow (I) must also be taken into account. The equation for the water balance is therefore:

$$P = R + E + dS - I \qquad (1)$$

In earlier studies on the water balance of selected catchments in Switzerland (Binggeli, 1974; Leibundgut, 1978), major inaccuracies were observed in drawing up the balance, with the result that it did not appear to be possible to carry out a detailed, small-scale analysis of the water balance for the whole of Switzerland.

For the present study, the large river basins of Switzerland whose water balance is well known (Schädler and Bigler, 1992) were divided into 287 medium-scale catchments (100–200 km^2). The main part of these catchments provides sufficient run-off data. Initial analyses of this measured annual run-off were carried out by Schädler and Weingartner (1992). These analyses served as a starting point for determining the water balance for all medium-scale catchments. The period covered by the study was the standard 1961–1990 period used by the World Meteorological Organisation (WMO), and the corresponding mean values for this period were used.

In Switzerland, precipitation and run-off are recorded in relatively dense networks. However, the network density decreases with altitude. This results in marked differences in the accuracy of figures for the water balance components, especially in catchments in the alps. As far as evaporation is concerned, excellent data has been provided by Menzel (1997). On the basis of individual, representative glaciers, for which annual figures for changes in mass are available (Müller-Lemans *et al.*, 1994) assertions can be made concerning change in water storage in glaciated basins. Overall, information can be obtained on water balance components for all the medium-scale catchments, although of varying quality, which is very important for the explanations given below. In many catchments, the collation of this information on water balance gives results that are not plausible. For example, in alpine catchments the difference between precipitation and run-off, taking into account change in water storage often gives a figure for evaporation which cannot be explained physically (Figure 1). As the analyses showed, in most cases these problems are caused by imprecision with regard to areal precipitation, which can be explained by difficulties in measuring, as well as spatial interpolation and extrapolation. In view of these uncertainties, Lang (1985) recommended that precipitation in mountain areas should be seen as the remaining element in the water balance, i.e. in concrete terms, that precipitation should be calculated on the basis of run-off, evaporation and change in water storage, instead of using explicit precipitation measurements. This approach was used for the present study and additional steps were incorporated that allow precipitation values obtained in this way to be checked in the context of regional water balances, and corrected if necessary.

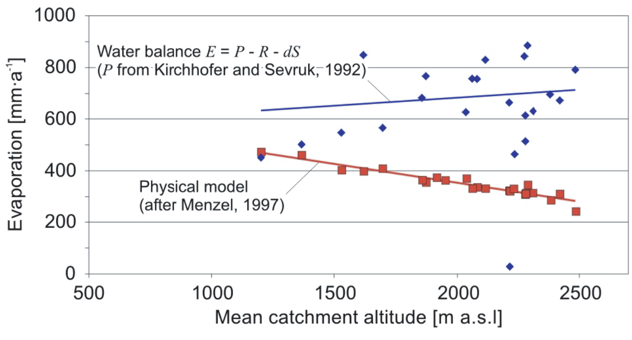


Figure 1. Calculated evaporation of medium-scale catchments in the alpine basin of the Rhine River above Chur, based on regionalized precipitation from Kirchhofer and Sevruk (1992). The results from a physical evaporation model (after Menzel, 1997) are shown for comparison

METHODS

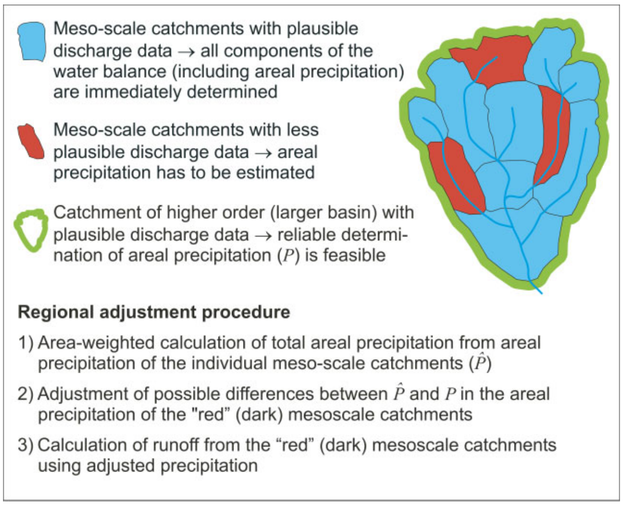
The precipitation of each medium-scale catchment is calculated from run-off, evaporation and change in water storage by glaciers (*cf* Equation (1)). For the sake of precision, inaccuracies in run-off data must be given careful consideration, since in most parts of Switzerland run-off represents the larger part of the precipitation calculated. Evaporation figures are much lower than those for precipitation and run-off; this means that any inaccuracies in evaporation figures have only a minor effect on errors in calculating precipitation. Although the relative errors in estimating changes in mass balance of glaciers are comparatively large, in absolute terms they have little influence on the accuracy of areal precipitation figures.

In view of these errors, data for the medium-scale catchments must fulfil certain requirements. In particular, the plausibility of run-off was assessed carefully (Schädler and Weingartner, 1992). In catchments where the run-off data is reliable, the water balance is calculated directly and used as it stands for further analyses (*cf* Figure 2, light/blue catchments). In the other (dark/red) catchments, the water balance can only be determined approximately, owing to the unreliability of run-off data. For this reason, a regional adjustment procedure is made wherever possible. This necessitates larger basins that encompass several medium-scale catchments

DOI: 10.1002/hyp

Table I. Mean annual water balance components 1961–1990 for alpine and outer alpine regions as well as the whole of Switzerland: precipitation (P), run-off (R), evaporation (E), storage change (dS) and inflow (I)

Region	Mean elevation [m a.s.l.]	P [mm · a^{-1}]	R [mm · a^{-1}]	E [mm · a^{-1}]	dS [mm · a^{-1}]	I [mm · a^{-1}]
Alps	1664	1609	1192	421	−3	1
Lowlands	629	1171	610	560	−1	−2
Switzerland	1312	1458	991	469	−2	0



🟦 Meso-scale catchments with plausible discharge data → all components of the water balance (including areal precipitation) are immediately determined

🟥 Meso-scale catchments with less plausible discharge data → areal precipitation has to be estimated

🟩 Catchment of higher order (larger basin) with plausible discharge data → reliable determination of areal precipitation (P) is feasible

Regional adjustment procedure

1) Area-weighted calculation of total areal precipitation from areal precipitation of the individual meso-scale catchments ($\hat{P}$)

2) Adjustment of possible differences between $\hat{P}$ and P in the areal precipitation of the "red" (dark) mesoscale catchments

3) Calculation of runoff from the "red" (dark) mesoscale catchments using adjusted precipitation

Figure 2. Determination of the water balance of the mesoscale catchments using a regional adjustment procedure

and for which reliable run-off data is available. In all, 17 such larger basins can be used in Switzerland. In a number of regions, especially along the national borders, such larger basins cannot be identified, so that it is not possible to make regional adjustments. There are thus two methods for calculating the water balance:

1. Water balance calculations with a regional adjustment procedure: In the medium-scale catchments with plausible run-off data all water balance components, including areal precipitation, are incorporated as they stand. In the other catchments without (plausible) run-off data (dark/red catchments in Figure 2), areal precipitation is estimated on the basis of regional models or simple hydrological considerations. The sum of the areal precipitation figures for all medium-scale catchments must correspond to the areal precipitation figure for the larger basin. Any difference is compensated for only with respect to areal precipitation in the dark/red catchments. Subsequently, run-off of these catchments is calculated using adjusted areal precipitation.
2. Water balance calculations with no regional adjustment procedure: Without identified larger basins, a regional adjustment is not possible as it was mentioned before. In other words, estimated water balance figures must be used as they stand, even in cases where the quality of run-off data is low. The data cannot be verified and adjusted on a regional level.

The different ways of deriving the water balance allow for their plausibility to be estimated (Schädler and Weingartner, 2002) which, for approximately 60% of the catchments, is very high.

All in all, a closed hydrological system has been established, in which

- the components of the water balance are adjusted to each other and
- an upscaling of the water balance of the medium-scale catchments is possible. In other terms: the areal weighted sum of the water balances of the medium-scale catchments finally provides the water balance of the whole of Switzerland (Table I).

Apart from this spatial upscaling, a temporal upscaling is equally possible; i.e. water balances identified for the period 1961–1990 can also be converted to other twentieth-century time periods. This procedure paves the way to follow and discern long-term trends in the water balances of the twentieth century.

RESULTS

For each mesoscale catchment, an adjusted mean water balance is available for the period 1961–1990; run-off as an important part of this water balance is depicted in Figure 3. Revealing large differences over Switzerland, the water balances emphasize the productive capacity of alpine catchments, which—compared to the midland (Swiss Plateau) area—frequently show a multiple of areal precipitation and run-off. Maximum areal precipitation values exceeding 2300 mm · a^{-1} are observed in the Gotthard region within the central parts of the Swiss Alps. Run-off values around 2000 mm · a^{-1} are attained equivalent to a mean specific run-off of approximately 70 l · s^{-1} · km^{-2}. The lowest areal precipitation around 800–900 mm · a^{-1} and the equally smallest run-off depths (around 300 mm · a^{-1}) are observed in both the western and eastern parts of the Swiss Plateau. Water balance values also of the inner alpine catchments range in the same order of magnitude.

The north–south profile in Figure 4 again reveals these marked contrasts within inner-Switzerland. The Weisse Lütschine River is due to represent the glaciated mountainous catchments of the north side of the Alps (mean catchment altitude 2170 m); the Brig region stands for the relatively dry inner alpine basins. The Maggia River belongs to the southern alpine region with comparatively

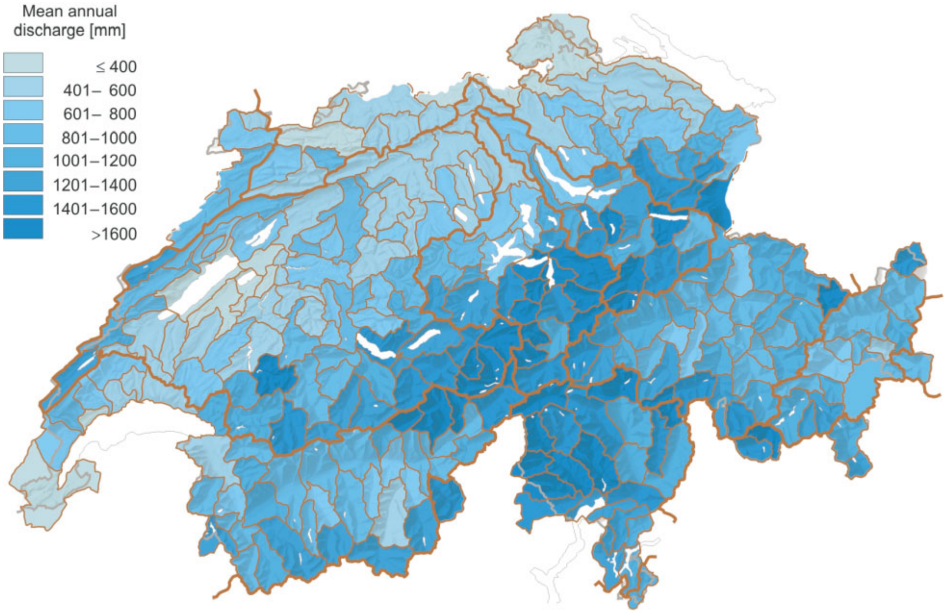


Figure 3. Mean annual discharge 1961–1990 in Swiss mesoscale catchments

high annual precipitation owing to pronounced spring- and autumnal precipitation values. The graphic also gives evidence that the evaporation for lower-lying catchments is around 500 mm $\cdot$ a^{-1} (Ajoie, Langeten) and that values as little as approximately 300 mm $\cdot$ a^{-1} are observed within alpine regions.

The following discussions focus on the alpine part of Switzerland, which has been spatially distinguished by means of various methods. For instance, a process-oriented definition following the discharge regimes has been presented by Aschwanden and Weingartner (1985). The geographical boundaries selected here follow Ives *et al.* (1997) in so far as all catchments with a mean elevation >1000 m a.s.l. are indicated as alpine, according to which definition approximately two thirds of the surface area of Switzerland are situated in the alpine region. These surfaces, however, contribute disproportionately to the total discharge of Switzerland. This high productivity of alpine catchments is also explained in a diagram depicting the ratio of surface, precipitation and discharge of different altitude zones (Figure 5). It is evident that for high altitudes, run-off contribution is superior to the relative proportion of surface area, as a result of higher precipitation and lower evaporation. Catchments between a mean altitude of 2000 to 2500 m a.s.l., for example, represent about 20% of the total Swiss surface area, while the respective contributions to precipitation and run-off amount to 22% and 25%, respectively. For mean altitudes of 500 to 1000 m a.s.l., by contrast, the share in surface area is 34%, while the respective shares are only 29% for precipitation and 24% for run-off.

Ultimately, the hydrological significance of the alpine region is equally emphasized in comparison with the hydrological balances of both the alpine and outer alpine regions (*cf* Table I).

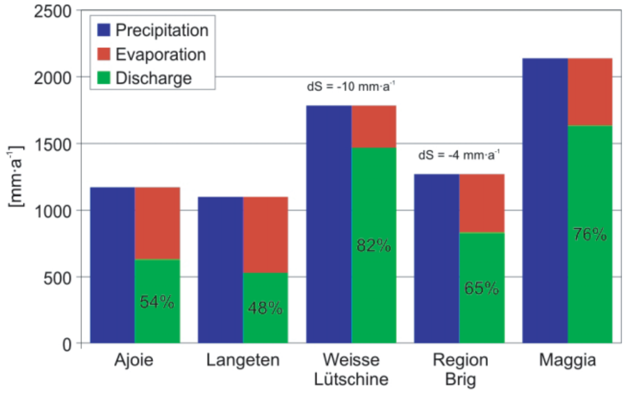


Figure 4. Typical mean water balance terms 1961–1990 of mesoscale catchments in a north-south profile from the Jura mountains (Ajoie) across the Alps (Weisse Lütschine, Region Brig) to the Ticino region (Maggia). dS marks the decrease in ice storage for the heavily glaciated Weisse Lütschine and Brig regions. The proportion of discharge to precipitation is indicated separately

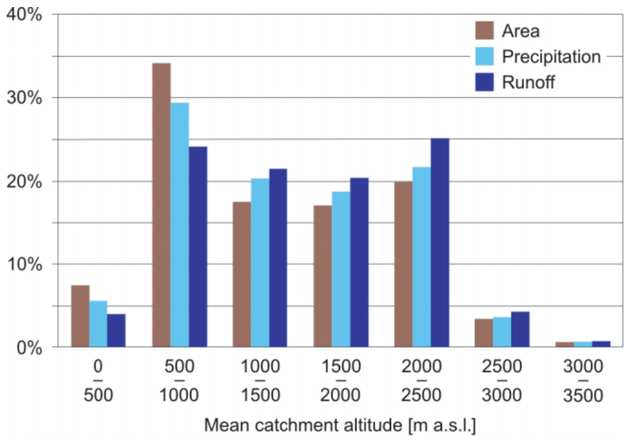


Figure 5. Percentages of surface area, precipitation and run-off of Swiss mesoscale catchments relative to mean catchment altitude

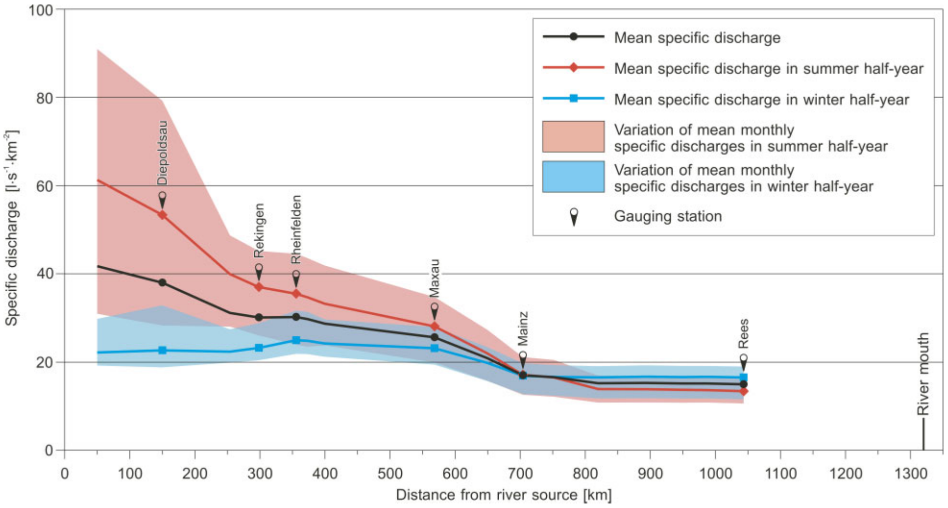


Figure 6. Specific discharges along the course of the river Rhine

The few figures inferred from a spatially differentiated description of the water balance verify and underline the hydrological significance of mountain regions in Switzerland. The subsequent chapter will highlight the importance of this alpine region for the water supply of the lowlands, before we again face the issue of the hydrological significance of mountains within the global frame.

HYDROLOGICAL LINKAGE OF HIGHLANDS AND LOWLANDS

As the water balance for a mountainous region has been resolved more clearly, the focus is put on the more general effect of run-off for the adjacent lowlands. Firstly, the region of interest spans the European Alps (with Switzerland as an important part) and will be extended to other regions worldwide.

Europe: the hydrological significance of the Alps

Since the climate of the Alps is influenced by seas from three directions (the Atlantic to the North and the West, the Mediterranean to the South) and the Alps are situated within a zone predominantly marked by westerly winds, the amount of humidity involved is considerable. Another decisive factor that contributes to the hydrological importance of the Alps is meltwater run-off from snow and ice over the summer months. Apart from providing significant amounts of water, this run-off is also highly reliable and therefore run-off variability downstream is decreased. The lower catchments of the Rhine, the Rhone, the Po and the Danube profit by this remarkably dependable summer run-off from the Alps.

In the case of the Rhine River, the alpine section (mainly situated within Switzerland) and the lower reaches are clearly discernible from a hydrological point of view. It is especially in the summer months (June to September) that the Alps play a distinct supportive role with regard to overall discharge. The mean alpine proportion of total discharge in June is thus 52%, despite the fact that the Alps represent only 15% of the total catchment of the Rhine. The specific discharge pattern of the Rhine (Figure 6) illustrates the increased supply of water from the Alps during the summer half-year (May to October). The high specific discharges in the upper section correspond to the water balance figures for Switzerland presented in the previous section. It is only downstream from Mainz that winter-specific discharge begins to exceed summer-specific discharge, indicating that the maritime influence (first of all characterized by winter rain) gradually increases while the influence of alpine meltwater run-off decreases.

The hydrological significance of the Alps for the three remaining streams (Rhone, Po, and Danube Rivers) shows a similar pattern in principle, while distinctions are to be made according to the relative position of the streams to the Alps. The Rhone and Po River run in permanent proximity to the alpine massif and therefore constantly benefit from tributaries originating in the Alps, which supply plentiful summer discharges. The Danube River, on the other hand, has its origin outside of the Alps and is under alpine influence through tributaries only. However, this influence is also considerable, as will be shown below.

A comparison between the proportion of discharge that can be expected on the basis of catchment size and the actual discharge measured demonstrates the marked hydrological significance of the Alps (Table II). With a mean contribution of 34% of the total discharge, the alpine regions of the Rhine River system supply 2·3 times more water than might be expected on the basis of surface area alone (disproportional influence). In the summer months of July and August, this proportion is considerably higher for all four river systems, ranging from 36% (Danube) to 80% (Po) (Viviroli and Weingartner, 2004a). It can be concluded, therefore, that the disproportional run-off contributions of the Swiss alpine regions (as presented above) are still relevant on a larger scale, showing a marked long-range effect on run-off patterns in downstream European river systems.

Table II. Contribution of the Alps to total discharge of the four major alpine streams

	Rhine	Rhone	Po	Danube
Mean contribution of the Alps to total discharge [%]	34	41	53	26
Areal proportion of total alpine region [%]	15	23	35	10
Disproportional influence of the alpine region	2·3	1·8	1·5	2·6

Hydrological significance of mountains worldwide

Owing to the limited availability of discharge data, a global comparative assessment based on gauge records is limited to selected regions (Viviroli, 2001). For the following analysis, a set of catchments was selected to represent the most important mountain ranges outside the polar climate zones and omitting the strongly tropical Amazon and Congo River basins. The relation of mountain and lowland discharge is then examined on the basis of mean monthly values of run-off, revealing the proportion of discharge contributed to total discharge by mountain areas (Figure 7). Mountain contributions of more than 100% occur when lowland run-off is less than mountain run-off as a consequence of groundwater recharge or withdrawals for irrigation. In order to assess the disproportionality of the mountain contribution, the relative mountain area is also considered; a figure for the disproportional influence of mountain run-off as compared to surface area is calculated from annual run-off figures (*cf.* Table II).

Also on this scale, a distinct hydrological feature of mountains is recognized in the more effective discharge generation as compared to the lowlands. Four groups are distinguished: In a first group (a: Colorado, Nile, Orange, Euphrates, Niger, Amu-Darya, Río Negro and Indus Rivers), monthly run-off originating from the mountain section exceeds total run-off in almost all months, highlighting the essential role of mountains in the hydrology of dry climate zones. The contribution from mountains is vastly disproportional. For a second group (b: Cauvery, Tigris, São Francisco and Senegal Rivers), mountain run-off exceeds total run-off during at least one month. This still implies a vital importance of mountains for the lowland areas downstream during dry seasons, although the disproportionalities are lower, in general. The third group (c: Ebro, Saskatchewan, Columbia and Wisla Rivers) consists of basins where mountain run-off is clearly inferior to total run-off. The disproportionality of run-off contribution from mountains, however, reaches a factor of around 2—this means that mountains still contribute about twice the amount of run-off that could be expected on the basis of their relative area. Additionally, their influence is augmented seasonally as reliable meltwater run-off markedly contributes to summer run-off downstream. Apart form the Ebro River, all cases of this group are located in regions of humid climate. Finally, group number four (d: Mekong and Orinoco Rivers) is made up of river basins where run-off contributions from the mountains are lower than expected from surface area. This is due to the tropical influence, i.e. ample amounts of precipitation falling in the lowlands dwarf the influence of the mountains.

For a comparison, the alpine river basins examined in the previous section (*cf* Table II) are added to Figure 7. Clearly, these four cases match group c where disproportionalities of around two are observed. With this,

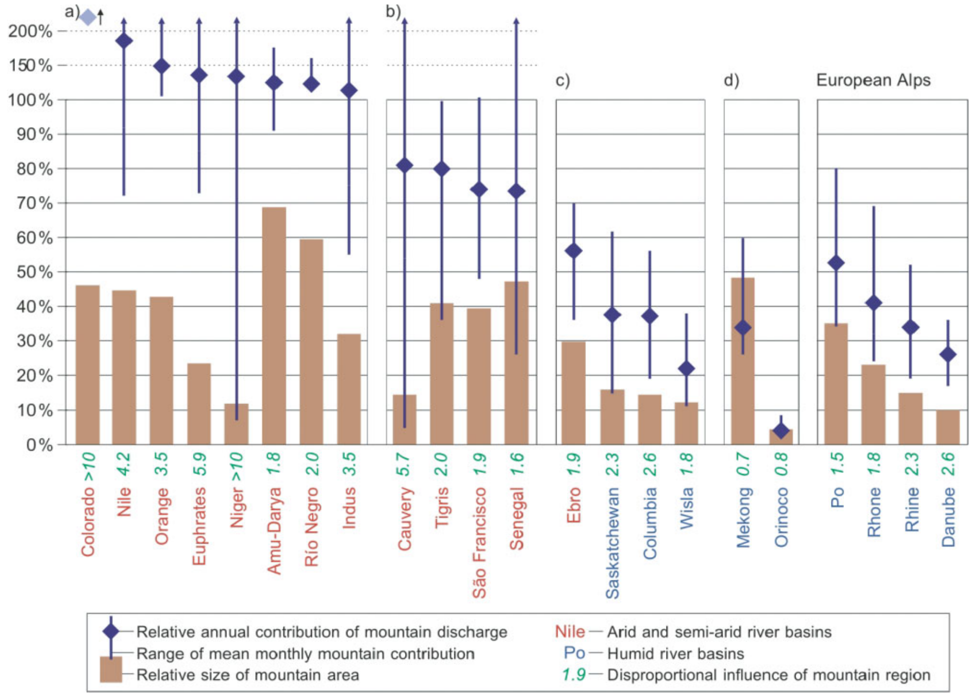


Figure 7. Proportions of run-off contribution and share of surface area for selected large river basins worldwide (a to d) and for the alpine river basins of Europe

the results from the global comparative assessment are corroborated—therefore, a consistent analysis of the hydrological importance of mountains is also feasible even if the data available are less extensive.

Besides the disproportional contribution of mountains to total run-off, a compensatory effect is discernible as total discharge variability is reduced through the influence of the more reliable mountain run-off. This effect generally corresponds with disproportionate mountain run-off contribution. When taking into account further aspects, such as detailed climate conditions and human usage in a quantitative scheme (Viviroli *et al.*, 2003), it is revealed that in many cases, mountains are indeed of great importance for the hydrology of the lowlands. Comparing the location of the hydrologically extremely important mountain ranges to the distribution of arid and semi-arid areas suggests that mountains function as wet islands within comparatively drier areas. It has already been shown for the European Alps that mountains contribute significantly to total run-off, even in a temperate, humid area. The metaphorical term 'water towers' applies in even much more marked terms to dry zones where mountains supply essential volumes of freshwater which are transported downstream in the respective river systems.

It can be deduced that an important factor in the interaction of upper mountain reaches and lowland areas is the uplift of air and the subsequent cooling and condensation in mountains which generates substantial amounts of moisture that are extracted from the atmosphere as precipitation (orographic effect). This is coupled with a reduced evapotranspiration. Through cooler temperatures, the temporary storage of precipitation in the form of snow and ice during the winter half-year becomes important, since it leads to increased discharge during the melting period in spring and summer, exactly when demand in the lowlands is greatest. On the whole, precipitation and temperature patterns in the mountain areas result in an important contribution to total discharge, which is traceable in the run-off figures presented in the present analysis.

CONCLUSIONS

The hydrological importance of mountainous regions has been analysed on three different scales. On a regional scale (Switzerland), marked contrasts in water balance terms are observed across very short distances, especially for precipitation and run-off. This results from the typical heterogeneity of physiographic conditions in complex terrain. Examination of the subcontinental scale (European Alps and adjacent lowland areas) reveals that the disproportional run-off volumes observed on the inferior regional scale (mountainous upstream catchments) may contribute markedly to run-off of large river systems. This is also true on the global scale, even more in dry climate zones. In summary, it may be concluded that mountains contribute essential run-off volumes for supplying a great part of the continental areas with freshwater (so-called 'blue water', Falkenmark, 2005), the respective river systems functioning as a means of transport that is able to couple even far-apart arid regions to this vital resource (Steffen and Tyson, 2001).

GIS-based analysis of mountain water resources (Viviroli *et al.*, submitted) reveals that outside of the humid tropical climate zones, mountain run-off is about 1·9 times higher than lowland run-off. This global figure corresponds well to the figures presented above, while the existence of significant variations and specific features on smaller scales was highlighted in this article (see also Viviroli and Weingartner 2004b).

With regard to global water resources, it is of paramount importance to consider mountainous regions as well as the lowland regions depending on them in the management of the available resources and to find sustainable and well-balanced solutions. This requires consideration of the contrasting conditions upstream and downstream, as well as the varying demands of rural and urban areas and the requirements of the agricultural, industrial and domestic sectors (Mountain Agenda, 2000). Climate change is another important term in the equation as mountain regions show a distinct vulnerability in this respect (Messerli *et al.*, 2004). Ultimately, human pressures are about to reach a state where the continental aquatic systems can no longer be considered as being controlled by earth system processes only (Meybeck, 2003). Therefore, future management of river systems should also consider long-term anthropogenic impacts on the hydrological system, such as river damming, large-scale water transfers and expanding irrigation (Clarke and King, 2004) all of which result in a general decrease of river flow quantities, coupled with increasing water quality problems.

REFERENCES

Aschwanden H, Weingartner R. 1985. *Die Abflussregimes der Schweiz*, *Publikationen Gewässerkunde 65*. Department of Geography, University of Berne: Berne, Switzerland.

Binggeli V. 1974. *Hydrologische Studien im zentralen Schweizerischen Alpenvorland, insbesondere im Gebiet der Langete*, *Beiträge zur Geologie der Schweiz–Hydrologie 22*. Kümmerly und Frey: Berne, Switzerland.

Clarke R, King J. 2004. *The Atlas of Water*. Earthscan: London, England.

Falkenmark M. 2005. *Towards Hydrosolidarity: Ample Opportunities for Human Ingenuity*. Fifteen-Year Message from the Stockholm Water Symposia. Stockholm International Water Institute: Stockholm, Sweden.

Funnell DC, Price MF. 2003. Mountain geography: a review. *The Geographical Journal* **169**(3): 183–190.

Ives JD, Messerli B, Spiess E. 1997. Introduction. In *Mountains of the World: A global Priority*, Messerli B, Ives JD (eds). Parthenon: New York, London.

Kirchhofer W, Sevruk B. 1992. Mean annual corrected precipitation depths 1951–1980. In *Hydrological Atlas of Switzerland*, *Plate 2·2*, Weingartner R, Spreafico M (eds). Swiss Federal Office for Water and Geology: Berne.

Kundzewicz ZW, Kraemer D. 1998. Striving towards assessment of mountain water resources. In *Proceedings of the International Conference on Ecohydrology of High Mountain Areas*, Chalise SR, Herrmann A, Khanal NR, Lang H, Molnar L, Pokhrel AP. ICIMOD: Kathmandu, Nepal: 175–185; 24–28, March 1996.

Lang H. 1985. Höhenabhängigkeit der Niederschläge. In *Der Niederschlag in der Schweiz*, *Beiträge zur Geologie und Hydrologie der*

Schweiz 31, Sevruk B (ed.). Kümmerly und Frey: Berne, Switzerland; 149–157.

Leibundgut C. 1978. Die Berechnung der Verdunstung aus der Wasserbilanz von Einzugsgebieten. *Die Verdunstung in der Schweiz*, *Beiträge zur Geologie der Schweiz–Hydrologie 25*. Kümmerly und Frey: Berne, Switzerland.

Marcinek J. 1984. *Gletscher der Erde*. Edition Leipzig: Leipzig, Germany.

Menzel L. 1997. *Modellierung der Evapotranspiration im System Boden-Pflanze-Atmosphäre*, *Zürcher Geographische Schriften 67*. Department of Geography, Federal Institute of Technology: Zurich, Switzerland.

Messerli B, Viviroli D, Weingartner R. 2004. Mountains of the world: vulnerable water towers for the 21st century. Contribution to the Royal Colloquium on Mountain Areas, Abisko 2003. *AMBIO Special Report* **13**: 29–34.

Meybeck M. 2003. Global analysis of river systems: from Earth system controls to Anthropocene syndromes. *Philosophical Transactions of the Royal Society: Biological Sciences* **358**(1440): 1935–1955.

Meybeck M, Green P, Vörösmarty CJ. 2001. A new typology for mountains and other relief classes: an application to global continental water resources and population distribution. *Mountain Research and Development* **21**(1): 34–45.

Mountain Agenda. 1998. *Mountains of the World–Water Towers for the* 21st *Century. A Contribution to Global Freshwater Management*. Department of Geography, University of Berne: Berne, Switzerland.

Mountain Agenda. 2000. *Mountains of the World–Mountain Forests and Sustainable Development*. Department of Geography, University of Berne: Berne, Switzerland.

Mountain Forum. 1995. *International NGO Consultation on the Mountain Agenda: Summary Report and Recommendations to the United Nations Commission on Sustainable Development*. The Mountain Institute: Franklin, WV; Document available on-line: http://www.mtnforum.org.

Müller-Lemans H, Funk M, Aellen M, Kappenberger G. 1994. Langjährige Massenbilanzreihen von Gletschern in der Schweiz. *Zeitschrift für Gletscherkunde und Glaziologie* **30**: 141–160.

Rodda JC. 1994. Mountains–a hydrological paradox or paradise? *Hydrologie kleiner Einzugsgebiete*, *Beiträge zur Hydrologie der Schweiz 35*. Swiss Hydrological and Limnological Society: Berne, Switzerland; 41–51.

Schädler B, Bigler R. 1992. Water balance of river basins. In *Hydrological Atlas of Switzerland*, *Plate 6·1*, Weingartner R, Spreafico M (eds). Swiss Federal Office for Water and Geology: Berne, Switzerland.

Schädler B, Weingartner R. 1992. Natural runoff 1961–1980. In *Hydrological Atlas of Switzerland*, *Plate 5·4*, Weingartner R, Spreafico M (eds). Swiss Federal Office for Water and Geology: Berne, Switzerland.

Schädler B, Weingartner R. 2002. Components of the natural water balance 1961–1990. In *Hydrological Atlas of Switzerland*, *Plate 6·3*, Weingartner R, Spreafico M (eds). Swiss Federal Office for Water and Geology: Berne, Switzerland.

Steffen W, Tyson PD. 2001. *Global Change and the Earth System: a Planet under Pressure*, *IGBP Science 4*. International Geosphere-Biosphere Program: Stockholm, Sweden.

UNCED (United Nations Conference on Environment and Development). 1992. *Agenda 21. United Nations Conference on Environment and Development Held in Rio de Janeiro*, Brazil. Document available online: http://www.un.org.

Viviroli D. 2001. *Zur hydrologischen Bedeutung der Gebirge*, *Publikationen Gewässerkunde 265*. Department of Geography, University of Berne: Berne, Switzerland.

Viviroli D, Dürr HH, Messerli B, Meybeck M, Weingartner R. Mountains of the world - water towers for humanity: typology, mapping and global significance. *Water Resources Research* (submitted).

Viviroli D, Weingartner R. 2004a. The hydrological significance of the European Alps. In *Hydrological Atlas of Switzerland*, *Plate 6·4*, Weingartner R, Spreafico M (eds). Swiss Federal Office for Water and Geology: Berne, Switzerland.

Viviroli D, Weingartner R. 2004b. The hydrological significance of mountains: from regional to global scale. *Hydrology and Earth System Sciences* **8**(6): 1016–1029.

Viviroli D, Weingartner R, Messerli B. 2003. Assessing the hydrological significance of the world's mountains. *Mountain Research and Development* **23**(1): 32–40.

DOI: 10.1002/hyp