General Characteristics of Alpine Waters

Bernhard Wehren, Rolf Weingartner, Bruno Schädler, and Daniel Viviroli

Abstract The elements of the water balance, namely precipitation, runoff, evapotranspiration, and storage change, their interaction and special attributes in the mountains are presented using the example of the European Alps, with particular reference to Switzerland. Strong differentiation in the alpine climate over time and space exerts a significant influence on the water cycle. This chapter therefore discusses each of the elements of the water balance with particular reference to the influence of mountains and their measurement, as well as the spatial differentiation characteristics. The analysis of the water balance is accompanied by a discussion on the attributes and differences at different altitudes and in different climatic regions. Finally, the importance of alpine water resources for water supplies in the adjacent lowlands is examined.

Keywords Alpine hydrology, Precipitation, Runoff, Water balance, Water towers

Contents

1 Introduction 18
2 Precipitation 18
  2.1 Introduction 18
  2.2 The Formation of Precipitation 19
  2.3 Precipitation in the European Alpine Region 25
3 Runoff 30
  3.1 Introduction 30
  3.2 Mean Water 34
  3.3 Floods 38
  3.4 Low Water 40

B. Wehren, R. Weingartner (✉), B. Schädler, and D. Viviroli
Hydrology Group, Institute of Geography, Oeschger Center for Climate Change Research, University of Bern, Hallerstrasse 12, 3012, Bern, Switzerland
e-mail: wein@giub.unibe.ch

U. Bundi (ed.), *Alpine Waters*, Hdb Env Chem (2010) 6: 17–58,
DOI 10.1007/978-3-540-88275-6_2,

4 Water Storage and Water Balance 42
4.1 Introduction 42
4.2 Evapotranspiration 43
4.3 Storage Changes 46
4.4 Water Balance 48
5 The Alps: Europe's Water Tower 49
5.1 Introduction 49
5.2 The Significance of the Alps for Downstream Hydrology and Water Resources 49
5.3 The Global View 50
5.4 The Future Role of Mountain Water Resources 53
5.5 Need for Knowledge 53
References 54

1 Introduction

Mountains play a special role in the hydrological cycle of continents. On the basis of their altitudinal distribution and orographic structure, highly disparate hydrological regimes can be observed over a relatively small area. They act as a fixed obstacle to the atmospheric flow, resulting in heavy precipitation on one side of the mountains and dry regions on the other. With their ability to store reserves of snow and ice at cold higher altitudes, they also play an important role in providing water supplies for surrounding low-lying regions. Through analysis of the water balance and its components, the following sections present a quantitative analysis of water resources in the Alps.

2 Precipitation

2.1 Introduction

Mountain chains such as the European Alps constitute an important factor in atmospheric circulation [1]. They trigger a variety of climatic and meteorological effects and cover a wide range of the spatial scale [2]. For example, they are manifested in the modification of the inner-continental climate zones or in the small-scale distribution of precipitation. Both can be important for the hydrology of alpine catchments.

One significant feature of mountain ranges is their barrier effects which can block or alter entire wind systems, the consequences of which can be observed not only in the mountains themselves but also much further afield. As a natural barrier, the Alps trigger convective and advective cloud formation, particularly in their peripheral areas. Hence they exhibit much more humid conditions than their adjacent environment [3]. As regards the small-scale distribution of precipitation in the mountains themselves, the differences between windward and leeward in terms of the prevailing wind directions and the effect of local wind systems are of decisive importance. Hence it is possible to determine a correlation between altitude above sea level and precipitation volumes, particularly if observed over a longer term.

2.2 The Formation of Precipitation

2.2.1 The Main Aspects of Precipitation Formation

Water is present in three aggregate states: solid, liquid and vapor. Of the estimated global water resources of 1386 million cubic kilometers, however, only 0.001% or 0.013 km^3 is stored in the atmosphere as water vapor (Table 1, [4]). If fully released, this volume of water would produce 25 mm of precipitation depth globally. Given an average annual and global precipitation of 972 mm [5], the water vapor in the atmosphere must therefore be completely replenished at least 39 times per year or approximately every nine days.

The water vapor available in the air plays a decisive part in the formation of precipitation. The amount of water that can be retained in the air in the form of vapor is primarily dependent on the temperature: Warm air masses can absorb more humidity than cold air masses, whereby there is an exponential correlation between temperature and saturation humidity (Fig. 1, [4]).

In the conditions described by the curve ("dew point temperature"), dew or clouds are formed, i.e. the water vapor condenses. If the conditions shown in the part above the curve are achieved, the condensed water vapor falls in the form of precipitation. In the conditions below the curve, water vapor enrichment or a cooling-off may occur without causing any formation of dew or precipitation. Since the air temperature is substantially determined by relief and altitude, these factors also have an impact on the maximum possible water vapor content in the air. In principle, precipitation is formed when air masses cool down, the consequences of which can be either dynamic (orographical and frontal induced precipitation) or thermal (convective induced precipitation) (Fig. 2, [6]).

Table 1 The global distribution of water [4]

		Volume	Depth
Total global water resources	100%	1,386 Mill. km^3	2,718 m
of which present in:			
Atmosphere	0.001%	0.013 Mill. km^3	0.025 m
Living creatures	< 0.001%	0.001 Mill. km^3	0.002 m
Waterways and inland seas	0.013%	0.19 Mill. km^3	0.4 m
Soil water	0.001%	0.017 Mill. km^3	0.03 m
Groundwater	1.69%	23.4 Mill. km^3	45.88 m
Polar ice	1.76%	24.4 Mill. km^3	47.85 m
Fresh water, total	3.47%	48 Mill. km^3	94.18 m
Salt water seas, salt lakes	96.53%	1,338 Mill. km^3	2,642 m

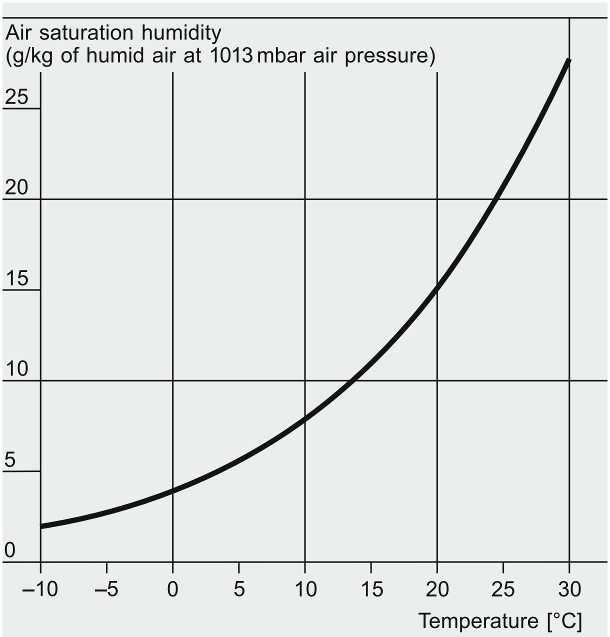


Fig. 1 Correlation between temperature and saturation vapor pressure [4]

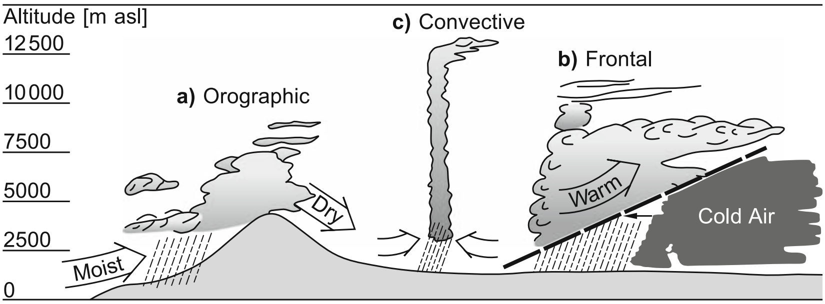


Fig. 2 Precipitation triggered by orographic, convective, and frontal processes [6]

Orographic Induced Precipitation

When humid, warm air masses are transported towards a chain of mountains by the prevailing wind systems, they are forced upwards and simultaneously cooled by the natural barrier. If, in the process, the temperature reaches or falls below dew point, clouds are formed on the windward side of the mountain range. The intensity of the precipitation triggered by this process exhibits a high spatial variability, with precipitation rates primarily dependent on the uplift distance, uplift velocity and the water vapor content in the air [7]. On the leeward side of the exposed mountain range, this situation usually gives rise to strong fall winds (such as the “Föhn”). Precipitation systems of this type are often the cause of mountain-induced dry and humid zones (Fig. 2a).

Frontal Induced Precipitation

Triggered by planetary pressure gradients, large-scale transfers of air masses occur which differ in terms of their energy or humidity content. When they collide, this creates frontal zones as the warmer, lighter (or even more humid) air rises above the colder air. This process can result in condensation and longer-lasting precipitation (Fig. 2b).

Convective Induced Precipitation

The sun warms the layer of air closest to the ground, and the heated air masses are expanded and forced upwards. As this happens, the air cools down and the water vapor retained in the air condenses. Convection flows of lengthy duration can induce cloud formations, leading to short, intensive precipitation. In the alpine region this process occurs primarily in the summer, in the form of heavy thunderstorm-induced rain, particularly if the atmospheric conditions are unstable (cold over warm, Fig. 2c; [8]).

2.2.2 The Influence of Mountains on Precipitation Formation

In addition, the processes discussed in Sect. 2.2.1 are specifically modified in mountainous regions, where the influence of the relief on atmospheric circulation can be thermal, mechanical or a combination of the two [9]. [10] has broken down these effects using the spatial scale (Fig. 3).

At this juncture, two highly typical examples of the European alpine region are discussed in more detail: On the one hand it is possible to observe on a micro scale (within the single kilometer range) the formation of local wind systems triggered by the disparate warming of the valley sides (valley-slope circulation). On the other hand, advective conditions are frequently modified at the upper meso scale (100-km range), which ultimately can result in “lee cyclogenesis” [11]. Both systems significantly affect the local and supra-regional distribution of precipitation:

Slope-Valley Circulation

Slope-valley circulation, which is exclusively dependent on thermal factors, occurs as a result of spatially differentiated insolation (Fig. 4, [12]). During the day, slopes

Influence \ Scale	Global or macro scale	Synoptic or upper meso scale	Lower meso to micro scale
Mainly mechanical	Barrier effect (wave deformation)	Windward blocking of cold air, front deformation, lee cyclogenesis	Channeling, mountain waves, fall winds
Mainly thermal	Plateau effect (large circulation systems, e.g. plateau monsoon)	Mountain-foreland circulation systems	Slope, mountain and valley winds

Fig. 3 Influences of mountains on atmospheric circulation – broken down according to spatial scale [10]

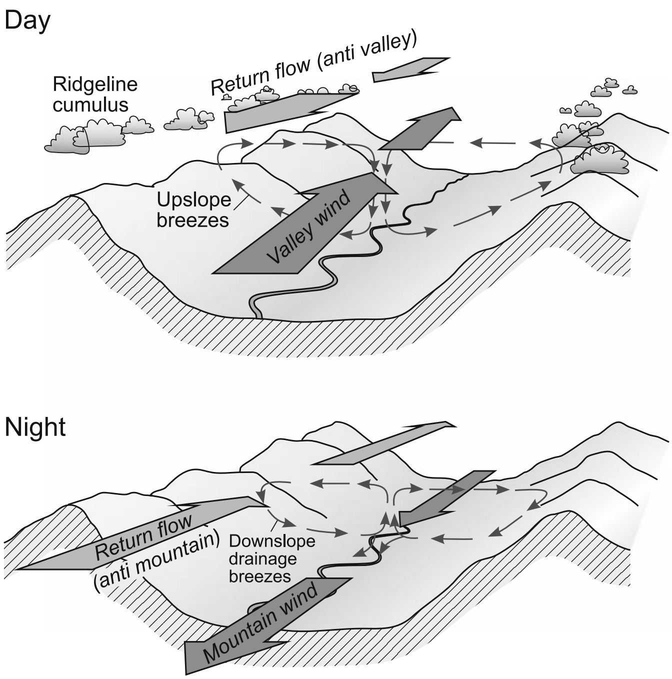


Fig. 4 Slope-valley circulation in the course of a day (vantage: valley upwards) [12]

at a higher altitude are exposed to stronger insolation than the lower-lying regions and the valley floor. The resultant warming triggers a slope upwind in all valleys, which can result in convective cloud formation and possibly precipitation in the upper slopes, particularly in the afternoons, due to the confluence of air masses. Stronger outgoing radiation during the night results in cooler air masses on the slopes, which sink towards the valley centre and outwards. This has a dissipating effect on the clouds above the mountain tops. Because of the conservation of mass balance, a vertical compensation flow is triggered over the valley centre, which can result in light cloud cover or fog above the valley floor. Because of this varying local wind system in the course of the day, valley slopes are often more humid than the valley centre.

Lee Cyclogenesis

One specific form of the mechanical effect of atmospheric circulation in the alpine region is lee cyclogenesis, which is linked to the passage of a cold front from North to South (Fig. 5, [10]). In the initial stage, the cyclones drifting in from the North trigger local southerly winds ("south Föhn"). If this process continues, the cold polar air is unable to flow over the Alps due to a lack of kinetic energy, and is forced to flow around the mountain range. This situation frequently gives rise to two divergent flowpaths which are subsequently manifested as the Mistral, Bise and Bora. In the final stage, a lee vortex is formed behind the alpine arch – typically within hours – which can strongly affect weather and precipitation volumes on the southern side of the Alps, especially in spring and autumn [10]. The approximately 30 lee cyclones which occur on average each year continue in two main directions:

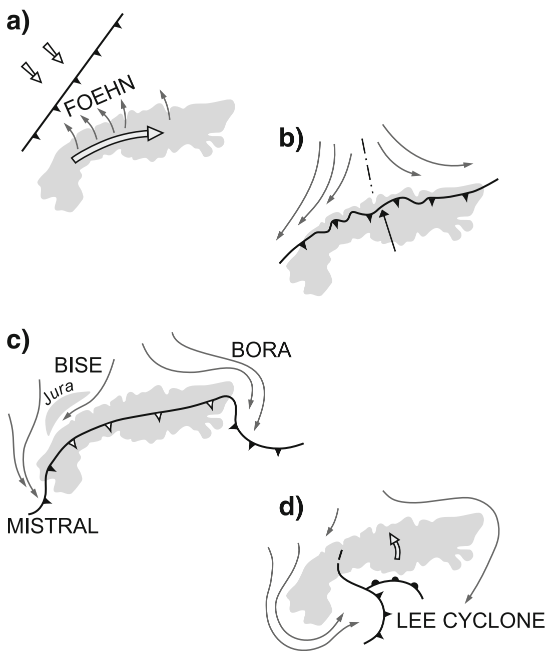


Fig. 5 Formation of a lee cyclone [10]

Either over the eastern Alps towards the interior of Eastern Europe, or along the North coast of the Mediterranean towards the Balkans [13].

2.2.3 Altitude Dependency of Precipitation

The dependency of precipitation on altitude was the subject of numerous studies in the twentieth century, the findings of which were widely disparate (e.g. [5, 14–20]).

In theory, since the absolute water vapor content of air reduces as the temperature sinks or the altitude rises, the volume of precipitation should decline. Yet the opposite is the case, particularly in mountainous regions in the temperate latitudes: here the annual volumes of precipitation generally tend to rise with the altitude. This is the result, on the one hand, of higher wind speeds at higher altitudes, which cause a relatively large shift in humid air masses. On the other hand, precipitation occurs more frequently and often at a much greater intensity.

Today the assumption is that there is no direct causal correlation between altitude and precipitation volumes. Rather, the influence exerted by the relief on approaching air masses is of decisive importance for precipitation volumes [19]. These effects also vary depending on weather conditions, climate region and season. Moreover, the correlation between precipitation volumes and altitude becomes significantly weaker the shorter the duration of the event ([21], cf. also Fig. 10).

The data available on altitude zones in the Alps with the highest average annual precipitation also varies widely (e.g. [16, 18, 19, 22]). Although this area cannot be precisely determined due to the lack of measurements or due to unreliable statistics, and despite the fact that major spatial differences have to be taken into account, current studies indicate an altitude between 3,000 and 3,500 m ASL [20].

2.2.4 Forms of Precipitation

Precipitation can occur in solid or liquid form. There are also differences in the size of particles or droplets, and hence in fall velocity [1]:

Solid: Snow, hail, ice, snow pellets, frost pellets, hoar frost, rime

Liquid: Rain, drizzle, fog deposition

In addition to liquid precipitation, snow in particular is an important contributor to the water balance in alpine catchments, since it acts as a temporary storage depot. Snow is formed in clouds as a result of condensation at temperatures below zero degrees Celsius. The aggregation of humidity at solid (ice) particles creates large crystals which fall to the ground in the form of snowflakes given the right conditions. Snow falls only at low speed, and is therefore usually carried by the wind over wide areas away from its atmospheric place of origin.

However, fog can also contribute to precipitation. This so-called fog deposition occurs as a result of drifting fog and clouds, whereby the volume of precipitation is determined by the drift velocity, density of droplets and the attributes of the vegetation which "filters" the water from the air. Thus, the most common abundant fog deposition can be expected in alpine forests, at high altitudes, on ridges and peaks, and is probably the most common source of water at altitude zones between 2,000 and 3,000 m ASL. Fog deposition often occurs as transient precipitation, i.e. a substantial portion is re-evaporated.

Locally, fog deposition can account for a significant proportion of the total volume of precipitation (e.g. [23, 24]). Yet a high local variability in fog deposition characteristics must be assumed, particularly in the alpine region. Hence the water balance in larger alpine catchments is only slightly distorted if fog deposition is not taken into consideration [5].

2.2.5 Measuring Precipitation

In principle, capturing and measuring precipitation is a simple matter. But its measurement is strongly influenced by the wind field prevailing at the measuring device and in its vicinity. In addition, losses due to splashing, evaporation from the device and inaccuracies in readings affect the quality of the measurement. In winter the loss of captured precipitation increases as the proportion of snow increases or due to its low fall velocity and its wind drift. This is the reason for the relatively large systematic precipitation measurement errors exhibited by mountainous regions: Errors of up to 15% have been recorded for higher altitudes and more than 50% if the proportion of snow is large [25].

Another problem encountered when registering precipitation in mountainous regions is the spatial distribution of measurement stations (e.g. [26]). The volume and intensity of precipitation in mountainous regions is highly variable even over small areas. Yet these very regions often suffer from a lack of dense precipitation measurement networks, since measurement stations are mainly to be found in valleys. Consequently, up to now the data collected in order to measure the spatial variability and volume of precipitation in higher-altitude regions has been insufficient.

2.3 Precipitation in the European Alpine Region

On an international scale, the Alps are a middle-sized chain of mountains which, due to their situation in the central latitude of Europe, are influenced by maritime as well as continental factors. Humidity is generally transported by the west and south winds flowing from the Atlantic or the Mediterranean towards the mountain chain. With altitudes of up to 4,500 m ASL, the Alps present an enormous barrier to the air masses being transported in this way, and this barrier effect reinforces European meridional temperature gradients [10].

2.3.1 General Characteristics of Precipitation

The spatial distribution of average annual precipitation for the period 1971–1990 (Fig. 6, [27]) clearly illustrates the significant role that the Alps play in the regional distribution of precipitation: The volume of precipitation already starts to rise in the lower regions adjacent to the Alps compared to regions with the same altitude above sea level further afield [28].

The two vertical profiles through the Swiss Alps on the precipitation map (Fig. 7, [29]) also illustrate the correlation between annual precipitation and altitude, particularly in the peripheral areas of the northern alpine region, and to some extent also the southern alpine region. Towards the main alpine ridge, however, average precipitation volumes decline again despite the increase in altitude [27]; in specific inner-alpine regions, even lower precipitation volumes than along the alpine periphery have been measured. The shielding effect of the mountains is particularly evident in the dry valleys, which are influenced by flanking lee effects (Switzerland: Valais, Engadine; Italy: Vintschgau).

The large-scale multi-year precipitation patterns for the European alpine region as shown in Figs. 6 and 7 can be summarized as follows [5]:

- Precipitation is greater in the outermost areas of the alpine arc than in the inner-alpine areas; moreover, precipitation declines in the western Alps towards the

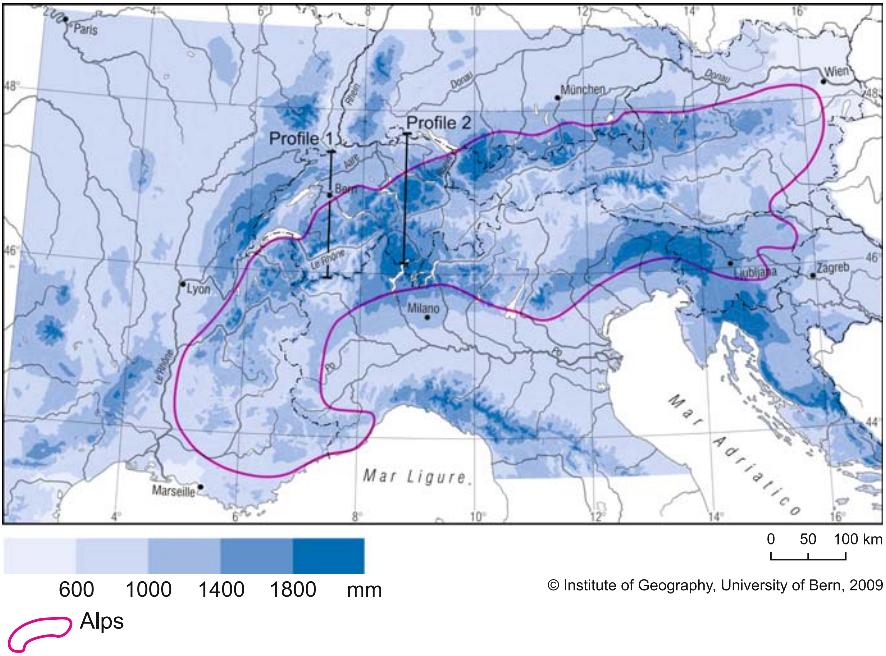


Fig. 6 Distribution of average annual precipitation in the European alpine region (1971–1990) [27]. Profiles 1 and 2 see Fig. 7

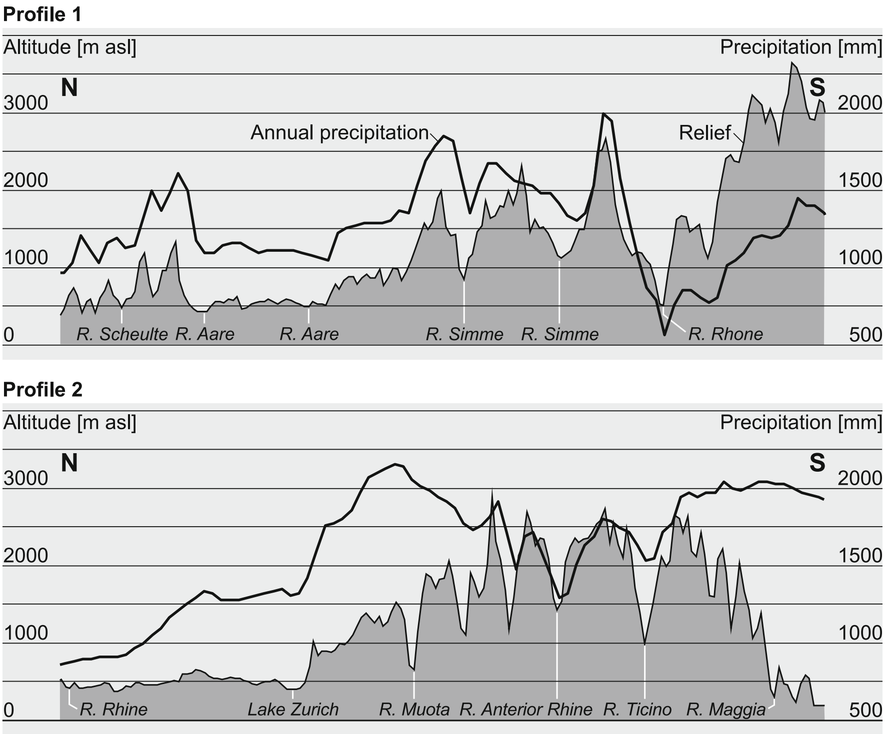


Fig. 7 Precipitation profiles through the Swiss Alps (average annual precipitation totals, 1971–1990), data: [27], [29]. Location of profiles see Fig. 6

south-west and in the central Eastern Alps towards the east. The southern periphery of the Alps has regions that exhibit particularly high precipitation volumes or maximum volumes for the Alps.

- The low-precipitation zone of the central Alps covers a larger area in the east than in the west, and is interrupted in the Gotthard massif by a region of maximum precipitation. The reason for the varying spatial distribution of dry zones is that narrow valleys predominate in the west, while the relief in the east is less pronounced; producing larger connected regions with low precipitation.
- While Figs. 6 and 7 show the correlation between orography and annual precipitation, this correlation is far from constant over larger areas and is subject to major local variations.

The following spatial patterns are evident from the seasonal distribution of precipitation (Fig. 8) [30]:

- Winter (e.g. January): In contrast to other seasons, precipitation over the entire alpine region is relatively low, and the central alpine regions are particularly dry. The low mountain ranges on the western side of the northern Alps

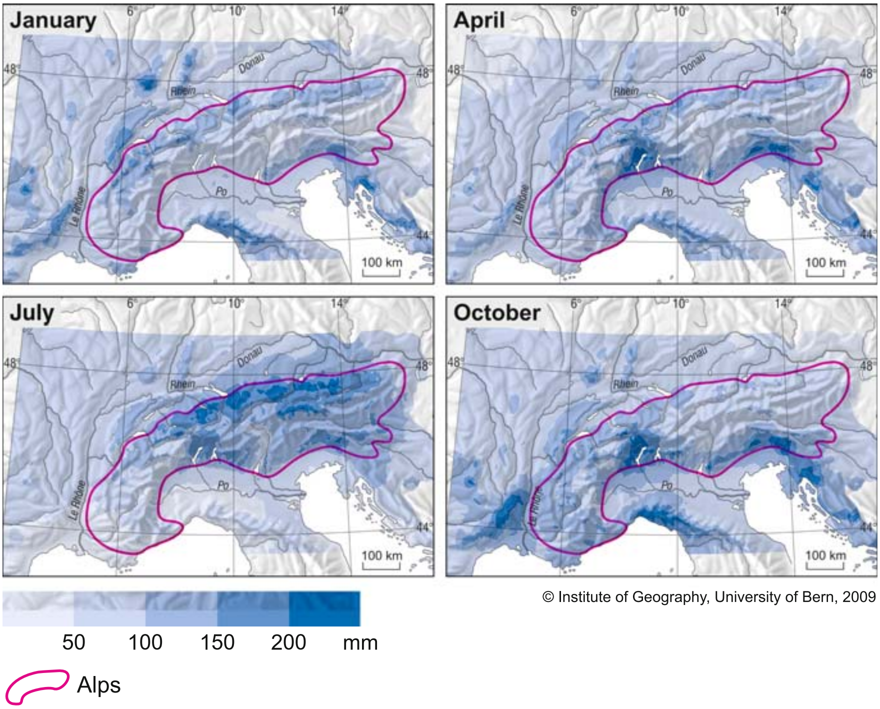
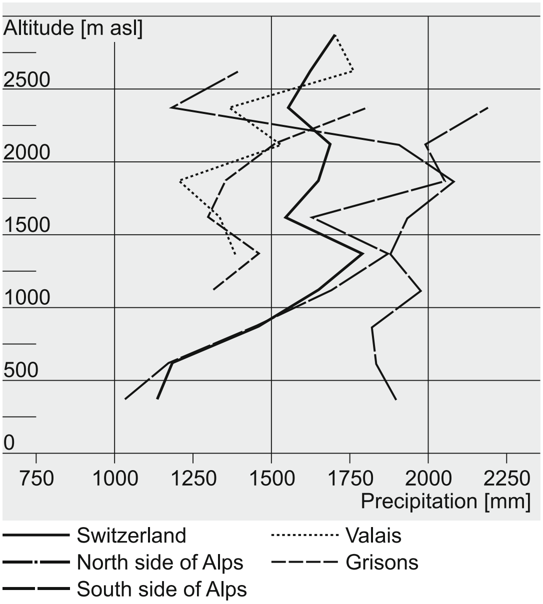


Fig. 8 Distribution of selected average monthly precipitation in the European alpine region (1971–1990) [3]

(Jura, Black Forest, Vosges), however, receive more precipitation than during other seasons.

- Spring (e.g. April): Compared to winter, the distribution of precipitation on the northern side of the Alps is much more balanced during this season. Particularly high volumes of precipitation occur along the southern periphery of the Alps.
- Summer (e.g. July): The southern lowlands (Po plain) exhibit extremely dry conditions, whereas high volumes of precipitation are recorded in the central and eastern Alps. The greatest volume of precipitation falls along the northern periphery of the Alps; precipitation in the northern lowlands is accordingly higher than at other times of the year. Precipitation is triggered primarily by storms.
- Autumn (e.g. October): While the distribution of precipitation is similar to that exhibited in spring, the Central Massif as well as the south-eastern periphery of the Alps exhibit particularly high precipitation. Because of more intensive evaporation of warm maritime surfaces, coupled with greater frequency of low-pressure zones above the Mediterranean at this time of the year, more

Fig. 9 Average annual precipitation in various regions and altitude zones in Switzerland (1961–1990) [31]



humidity is transported in the direction of the Alps, often manifesting itself in the form of heavy precipitation along the southern Alps.

The spatially variable influence of topography on average annual precipitation in the alpine region is also reflected in the altitude gradients of various climate regions of Switzerland (Fig. 9). In the study conducted by [31], the average annual regional precipitation was calculated as a remainder of the water balance. In general, the altitude dependency of precipitation occurs primarily in regions below 1,500 m ASL, although the correlation is not strong and can vary from one region to another. For regions above 1,500 m ASL, in most cases the relationship exhibits no linear progression; at times the average annual precipitation volume has even been observed to fall as the altitude increases. Moreover, the central alpine dry zones – illustrated here by the example of the Valais – are clearly evident. Furthermore, the precipitation gradient for the south side of the Alps is smaller compared to the northern side of the Alps, although overall it exhibits higher levels of precipitation.

The differences in precipitation characteristics to be observed on the north and south side of the Swiss Alps are largely a result of the different proportions of advective and convective precipitation events, as well as the differing intensity of precipitation. However, as mentioned above, topographical characteristics can also exert a significant influence [32]. Precipitation maps for the European alpine region (Figs. 6 and 8) have taken this fact into account by calculating around 10,000 local gradients in order to map precipitation altitudes.

2.3.2 Heavy Precipitation in the European Alpine Region

Heavy precipitation is defined as precipitation events of major intensity which therefore occur relatively seldom. A threshold value per station or climate region, or an exceeding probability, is frequently applied to determine heavy precipitation events [21].

The general principle is that the intensity of a heavy precipitation event weakens the longer it lasts. Observations in the Swiss alpine region show that the intensity of precipitation is slightly higher on the north side of the Alps than on the south, particularly for short-duration events. Conversely, the maximum heavy precipitation of long duration ($\geq$1 day), which is primarily triggered by advective conditions, is greater in intensity on the south side than on the north side of the Alps. The most intense precipitation occurs on the northern and southern peripheries of the Alps [29].

The pattern of altitude dependency in the case of heavy precipitation in the alpine region differs clearly from the average or monthly precipitation volumes. A comparison of transversal profiles through the Swiss Alps (Fig. 10, [21]), which include the extreme precipitation (here with a 100-year recurrence period) occurring in various observation periods ranging from 1 h to 1 year, as well as the average annual precipitation between 1901 and 1970, enables the following patterns to be determined: The altitude dependency, which is still clearly evident for average annual precipitation volumes, becomes weaker for heavy rainfall events with shorter observation periods, and virtually disappears in the range of hourly volumes. Within this time scale, topographic conditions in the close vicinity or further afield influence the precipitation process more strongly than is the case over longer observation periods [21, 33].

3 Runoff

3.1 Introduction

Runoff is a core element of the water balance, and as such has a reciprocal relationship with the community. On the one hand, river water – often referred to as “blue water” [34] – constitutes an important resource. For instance, it is essential for irrigation farming, which accounts for around 20% of the world’s food production. On the other hand, when it takes the form of high water or flooding, it presents a danger to humans and their infrastructure. High water and flooding account for around 30% of economic losses [35], and are ranked among the world’s most damaging natural disasters alongside earthquakes and storms. Both aspects—resource and natural hazard—are accorded particular importance in the alpine context.

Information on runoff characteristics in alpine regions provides the key to a comprehensive understanding of alpine hydrology. Runoff is both an expression of the complex interplay between precipitation, evaporation and storage changes, and of the close relationship with natural environmental conditions.

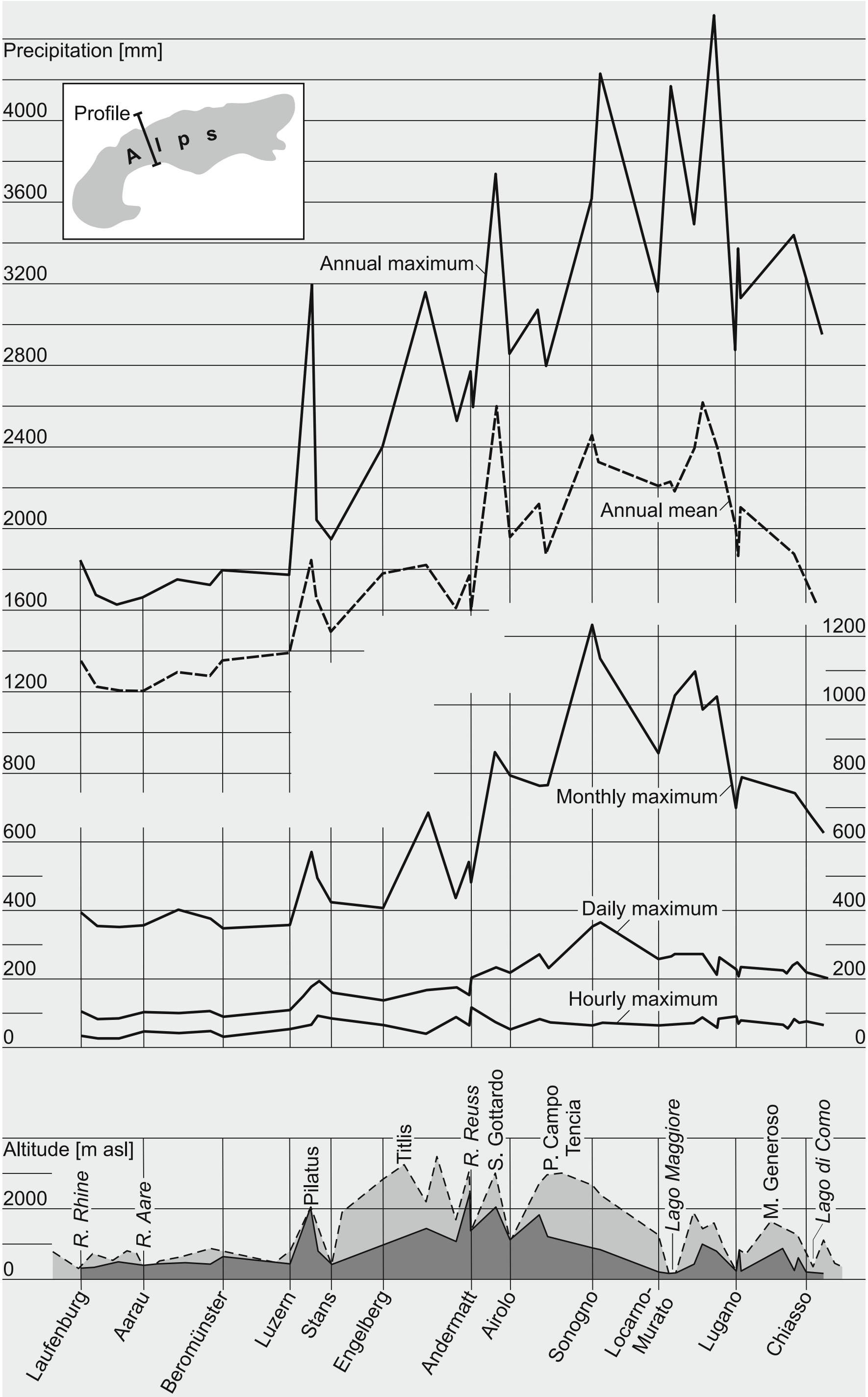


Fig. 10 Precipitation profile through the Swiss Alps (100-year heavy precipitation observed over periods of varying duration, and average total annual precipitation; 1901–1970 [21]

3.1.1 Measurement and Measurement Networks

Runoff is generally measured in two steps: (1) (continuous) recording of the water level, and (2) conversion of the water level to discharge using the rating curve, which relates the vertical depth of water in the stream to flow (volume per unit of time). To obtain the rating curve, it is necessary to determine the runoff discharged from different water levels directly. The hydrometric current meter is often used for this purpose, although more recently this has been replaced in larger rivers by the Acoustic Doppler Current Profiler (ADCP). The dilution method, which uses salt or fluorescence tracers, is ideal for smaller, turbulent alpine rivers and streams [29].

Runoff measurement stations are often expensive to install and operate in alpine regions. For example, the data collection points must be specially protected against derogation by solid matter, and streambed erosion as well as bed aggradation poses a major problem. Measurement of runoff in mountain torrents is particularly difficult and costly [36]. In general, the high cost of measurement and the inaccessibility of many data collection sites are the main reasons for the comparatively low density of measurement networks in alpine regions. Yet it is in these very regions, with their complex natural conditions, that a dense measurement network is essential in order to obtain a comprehensive overview of the hydrological conditions. In this context [37] states that it is a paradox that there is insufficient measured data on key hydrological areas. Runoff measurement networks in the Alps [38, 39], however, do not quite fit this picture. In fact, the volume of available data here is relatively good, although runoff at a great many stations is heavily influenced by hydropower production [40], see also Sect. 3.2.2

Fig. 11 illustrates this "hydrological paradox" [37] by comparing the altitude distribution of runoff measurement stations in Switzerland and Nepal: Nepal, a key hydrological mountainous country for the Indian subcontinent (cf. Sect. 5), has only

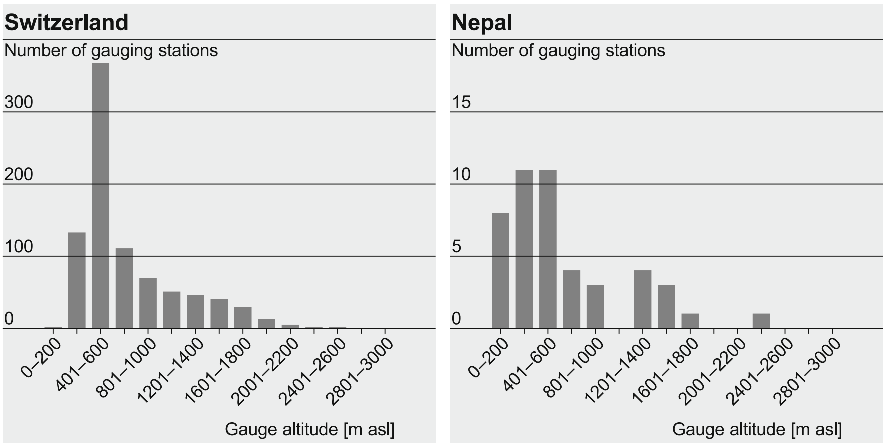


Fig. 11 Frequency of runoff measurement stations per altitude level (status 2005), *Left* = Switzerland, *Right* = Nepal (based on [38, 80])

a few runoff measurement stations. Indeed, the latter are all located at a lower altitude than data collection stations in Switzerland, despite the pronounced difference between the orography of Nepal and that of Switzerland. The Nepal example clearly illustrates what [41] is referring to when he complains that the mountains represent "the blackest of black boxes in the hydrological cycle."

3.1.2 Basin Characteristics

It is apparent from the above that only very few catchment areas in alpine regions have access to runoff data. Consequently, regionalization procedures need to be developed and applied for the purpose of estimating runoff characteristics [42]. In turn, however, the value of such estimates depends on the runoff data available for calibrating these models. This gives rise to the same dilemma mentioned above in connection with runoff measurement networks: In alpine regions with few runoff measurement stations it will be difficult to develop effective regionalization approaches.

As a rule, regionalization approaches are based on procedures to define the parameters of the catchment areas using basin characteristics, and modeling the relationships between these characteristics and the hydrological characteristics of interest [42]. Basin characteristics enable the numerical representation of climate conditions, topographical, pedological, and geological characteristics, land use and other aspects which impact runoff characteristics. Many of these key indicators are dependent on the altitude, giving rise in some cases to strong correlations between the hydrologically relevant key indicators. This must be taken into account when developing stochastic models. Fig. 12 shows the change in various basin parameters

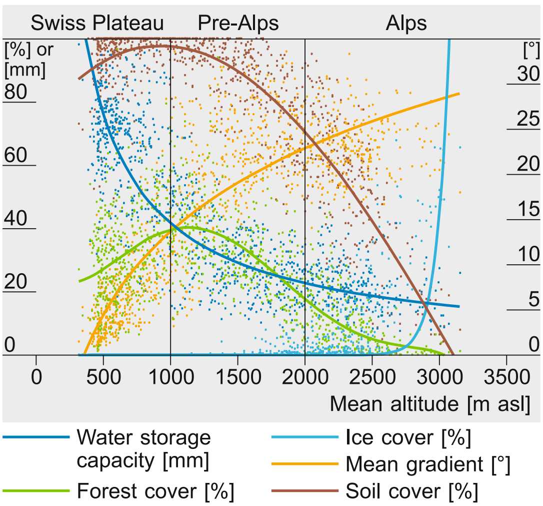


Fig. 12 Change in various hydrologically relevant basin characteristics with increasing mean altitude [81]. Points: Data from the 1,068 base regions in Switzerland. Line: Average change in key indicators with altitude

with altitude. This relationship can be used as the basis of fundamental considerations on the behavior of important basin characteristics in alpine regions:

The water storage capability serves as an indicator for the total water storage capacity of the soil and is based on the water available to the plant in the root zone. Fig. 12 shows how the soil's storage capacity drops off sharply the higher the altitude.

In Switzerland the greatest forest cover is located in the pre-alpine regions, i.e. between 1,000 and 1,500 m ASL. Forest cover has a significant impact on interception: [43] estimated, due to interception by forests in the Eastern Alps, 20–30% of annual precipitation does not reach the soil and is hence withheld from runoff. Moreover, the density of roots in the forest soil increases the stability of the slopes, which must be regarded as beneficial in terms of protection against natural hazards. In the case of flooding or high water, the impact of forests is a matter of dispute. [44] succinctly sums up the debate on the forest hydrological hypothesis as follows: "Forests presumably reduce flood flow and increase base flow. The debate about this forest hydrological hypothesis still goes on at the system scale of catchments. The investigations of [45] as well as newer aspects in soil hydrology at the process scale may help to differentiate: forest soils are more likely to control run-off than soils under any other land-use. However, not all the soils under forest bear the characteristics which support the forest hydrological hypothesis, and soils under various vegetation covers may show well developed properties to effectively mitigate peak run-off."

Soil cover declines sharply above 1,000 m ASL, giving way to increasingly large areas of debris and rock cover. Because of the high proportion of debris and rock cover and the soil's low water storage capacity, faster water turnover, higher runoff coefficients and, in general, extremely high volumes of runoff can be expected (see Sect. 3.3).

In Switzerland's alpine region, glaciers occur above around 2,500 m. This has a major impact, on seasonal flow regimes, among other things (see Sect. 3.2).

3.1.3 Structure of the Section on Runoff

The following discusses relevant aspects of flow characteristics in alpine regions, using the example of the European alpine region which in terms of data is well documented, and predicated on the classical mean water – high water – low water breakdown.

3.2 Mean Water

3.2.1 Mean Annual Runoff

Depth of runoff [mm a^{-1}] can be used to obtain a direct comparison of the mean annual flow rates from drainage basins or geographical regions of different sizes.

Table 2 Characteristics of runoff depth in regions and river basins in Switzerland (basis of data: [51])

Region	Runoff [mm a^{-1}] at 1,500 m asl.	Gradient [mm m^{-1}]	Coeff. of determination
Northern part of the Alps	1,166	0.55	0.51
Rhine	1,018	0.41	0.48
Aare (without Reuss and Limmat)	1,193	0.71	0.79
Reuss and Limmat	1,443	0.58	0.42
Inner alpine zone:			
Rhone (without Jura)	856	0.35	0.26
Inn (mean altitude $\geq$1500 m asl.)	(300)	0.70	0.3
Southern part of the Alps:			
Ticino	1,469	0.29	0.34
Switzerland	1,073	0.37	0.32

Table 2 provides an overview of the spatial variability of runoff depths in the Alps. A simple linear regression $D = f(\text{mA})$ (where D = Depth of runoff and mA = mean altitude) was derived for the regions shown in the table, on the basis of around 200 mesoscale catchments in Switzerland [46]. The significance of the correlation between altitude and runoff depth is derived from the coefficient of determination, providing a good to very good explanation of the spatial variation in runoff on the north side of the Alps. Here the runoff increases by an average of 0.4–0.75 mm m^{-1}. This behavior correlates with the distribution of precipitation, which is also altitude-dependent. Map 5.7 of the Hydrological Atlas of Austria shows that regional variations in runoff depth in the Eastern Alps are more pronounced than variations in precipitation, since "the distributions of precipitation and evaporation are generally contrary" [47]. According to studies conducted by [48], annual precipitation on the north side of the Alps is increasing by approximately 0.7 mm m^{-1} (cf. Sect. 2.2.3), and according to analyses performed by [49], annual evaporation is declining by 0.22 mm m^{-1} (cf. Sect. 4.4.2). As with precipitation, the role played by mean altitude in explaining the spatial variability in runoff in inner-alpine regions and south of the Alps is nonexistent or, at best, secondary.

According to [50], the lower border of the alpine-influenced catchments can be located (in Switzerland) at a mean altitude of around 1,500 m ASL. Above this altitude, flow characteristics are dictated by snow and glaciers (see below). Hence a comparison of runoff depths at the lower edge of the alpine region is shown in the second column of Table 2: the precipitation-related higher runoff on the south side of the Alps and the relative scarcity of runoff in inner-alpine zones is pronounced. Because of the varying gradients between the north and south side of the Alps, similar runoff depths can be assumed from mean altitudes of 2,500 m.

The influence of the mean altitude on mean runoff conditions can also be seen in a comparison of the two alpine states of Switzerland and Austria: Switzerland's mean runoff depth is around 1,000 mm a^{-1} [51] at an average altitude of 1,300 m ASL, while Austria's is 630 mm a^{-1} [47] at an average altitude of 770 m ASL.

3.2.2 Seasonal Runoff Characteristics

Seasonal runoff distribution can be used to determine the complex process of runoff generation. Regions with similar seasonal flow characteristics can be categorized by type. The best-known regime classification is from [52]. The criteria he used were (1) the dominant process of runoff origination (e.g. "glacial" i.e. fed by glaciers), (2) the number of maxima and minima for mean monthly discharges, and (3) the monthly dimensionless Pardé coefficients. The latter are calculated based on the quotients between the mean monthly and mean annual discharge. An overview of methods for classifying runoff regimes is provided by [50] and [53].

Seasonal fluctuations in runoff in alpine catchment areas are influenced by snow accumulation in early winter, the build-up of snow cover in winter, snowmelt processes in spring and early summer and – where applicable – glacier melt in summer (Fig. 13). The dominant role played by snow and ice in seasonal discharge volumes gives rise to single-peak regimes. Multiple-peak regimes, on the other hand, arise due to the alternating influence of precipitation, snow accumulation, snowmelt and evaporation. They typify northern alpine catchment at lower altitudes, as well as most southern alpine catchment areas which are influenced by the Mediterranean climate.

Because of the varying impact of snow and glaciers, six regime types have been classified for Switzerland [50]. These types differ primarily in terms of the flow characteristics during the months of May to September, i.e. the period during which ice and snow are melting (cf. Fig. 14). Discharges in May and June are largely dictated by snowmelt, while those in the July to September period are influenced by glacier melt. The highest monthly discharges occur in July and August in glacial regimes, and in May and June for nival regimes. The different types of regime are distinguished on the basis of the sequence of mean monthly discharges in the months May to September. In the winter half-year, minimum discharges with

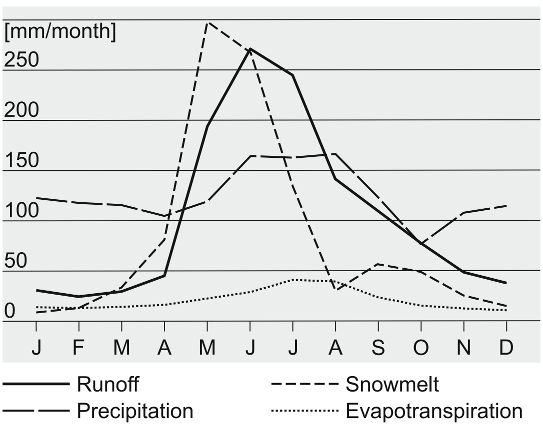
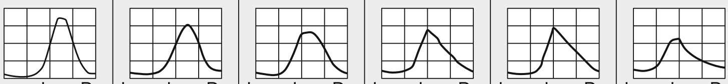


Fig. 13 Average seasonal course (1982–2000) of the main water balance elements in the alpine Dischma catchment simulated with PREVAH and the EMA snowmelt module. P: areal precipitation, R: runoff, ET: evapotranspiration and SN_M: snowmelt [82]

Regime	a-glaciaire	b-glaciaire	a-glacio-nival	b-glacio-nival	nivo-glaciaire	nival
	Jan Jun Dec	Jan Jun Dec	Jan Jun Dec	Jan Jun Dec	Jan Jun Dec	Jan Jun Dec
Rank	1. July 2. August 3. June 4. September	1. July 2. August 3. June 4. September	1. July 2. June 3. August 4. May	1. June 2. July 3. August 4. May	1. June 2. July 3. May 4. August	1. June 2. May 3. July 4. August
Cv (Jun)	21	21	16	17	16	20
Cv (Jul)	11	13	14	21	19	24
Basin characteristics	mA >2400 Gla ≥36	mA >2100 Gla 22–35.9	mA >2400 Gla 12–21.9	mA 1900–2300 Gla 6–11.9	mA 1550–1900 Gla 3–5.9	mA 1550–1900 Gla 0–2.9

Rank: Based on mean monthly flow [m^3/s] mA: Mean altitude [m asl]
Cv: Coefficient of variation [%] Gla: Glaciation ratio [%]

Fig. 14 Alpine regimes in Switzerland [83]. In their regime classification for Austria, [53] also distinguish between six single-peak regime types; however, their classification method differs from the one selected for regimes in Switzerland

Pardé coefficients <0.5 occur due to the storage of precipitation in the form of snow and ice. The seasonality of precipitation exerts only a minor influence on seasonal flow characteristics, since the greater volume of precipitation north of the Alps in the summer half-year is offset by higher evaporation during the summer.

Since snow and glaciers are particularly sensitive to any rise in temperature, climate change significantly influences seasonal flow characteristics [54, 88].

Not only does the dominant influence of snow and glaciers result in a single-peak regime; it also results in relatively low interannual runoff variability [55]. Figure 15 summarizes the classified Pardé coefficients for the four Swiss catchment areas over the observation period 1993–2006. The “colored carpets” enable the variability from year to year as well as the representativity of the mean seasonal course for a single year to be determined. In the alpine catchment area of the Rhône, the change in seasonal pattern from one year to another is minimal; the Pardé coefficients derived from monthly means over several years are therefore representative for any individual year. This regularity is less pronounced in catchment areas outside the alpine zone [56]. In terms of water management, these findings mean that even short-term measurements can provide meaningful information on seasonal flow characteristics in the alpine zone [57].

High discharge volumes, low runoff variability, and high relief energy provide the basis for major hydropower potential in the Alps. Around 70 TWh of electricity a year is generated from hydropower in Austria and Switzerland together. This corresponds to 50–60% of Switzerland’s total electricity production [58] and 60–75% of Austria’s (www.energyagency.at), depending on weather conditions and the demand structure. In some cases this use of hydropower causes massive changes in (seasonal) flow characteristics in the underlying water network. [40] and [42] have mapped and quantified the extent of this impact.

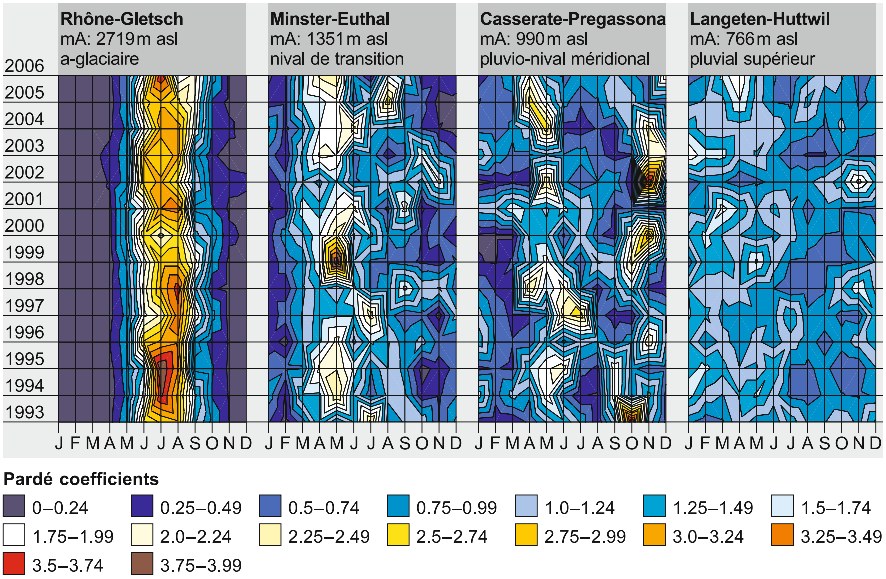


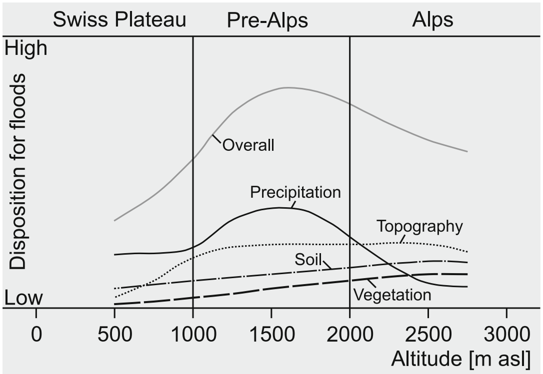
Fig. 15 Interannual variability of runoff regimes from 1993 to 2006, based on classified Pardé coefficients of selected catchment areas at varying mean altitudes [56]

3.3 Floods

Observation of flood disposition in alpine catchment areas – in other words the disposition of the region for high water [59] – provides a good starting point to the topic. [42] proposed a method for assessing the flood disposition of catchment using the quotients between the areas contributing to the flood and the total surface area of the region in question. The contributing areas are determined using an approach suggested by [60], by taking into account the density of the channel network and the topography. The runoff disposition of a catchment increases as the proportion of contributing areas rises, as has been illustrated by a comparison with the runoff coefficients of the most extensive floods measured in Switzerland. An alternative, descriptive method used to describe flood disposition is predicated on the fact that this disposition is decisively influenced by a few hydrologically relevant basin characteristics (Fig. 16).

With reference to the European Alps it can be said that there is a far greater likelihood of intense floods with high specific discharges in catchments above an altitude of 1,000 m. The upper limit of this critical zone lies at around 1,800 m, although it can vary considerably according to microclimatic and topographical conditions. Above 1,800 m, in most of the cases shortterm snow storage of precipitation reduces the hazard of floods. In other mountain areas these altitudinal limits vary according to general climatic conditions. However, the links between the elements which govern flood disposition mentioned here apply as a rule to other mountain areas, too.

Fig. 16 Flood disposition versus altitude [84]



Quick responses are typical for the most vulnerable zone between 1,000 and 1,800 m. They are produced by high rainfall intensity in combination with steep gradients and thin soils. In many cases an extensive network of streams ensures a high specific discharge. The processes of bedload mobilization and transport are stimulated by overland flow, which is an important component of runoff generation in this zone.

High runoff disposition in this zone is furthermore evident

- in the ratio between the 100-year and mean annual flood discharge: In this zone the 100-year discharge is only around two to two and a half times as much as the mean annual flood discharge [61];
- in the high runoff coefficient around 0.5 (median) that is based on the fact that the frequent precipitation, which often takes the form of convective rainfall in summer, may fall on soil which has only a limited capacity for storing water [61].

With regard to the last point, [62] rightly point out that the storage capacity of the soil and subsoil is not exhausted everywhere, even in the case of extreme precipitation: "It is therefore important to determine the limit beyond which a catchment is virtually incapable of storing any more water." However, steep mountainous catchments are only capable of storing low volumes of water and generally react rapidly. The authors [62] then use case studies to demonstrate that in many alpine catchments the response can also be slower, which ultimately results in major spatial variability in the flood characteristics of alpine catchments.

[63] for Austria and, on this basis, [64] for Switzerland, have analyzed and classified the occurrence of large floods in the alpine zone. Using various decision criteria as a basis, they obtained five event types: Flash floods, short-rain floods, long-rain floods, rain-on-snow-events and snow- (glacier-) melt events, which are shown in Fig. 17 for selected catchments in Switzerland. On the north-facing slopes of the Alps there is one clearly identifiable zone which is dominated by flash floods and short-rain floods. This zone is largely identical with the aforementioned zone of increased flood disposition. In the alpine zone itself, which, due to the use of

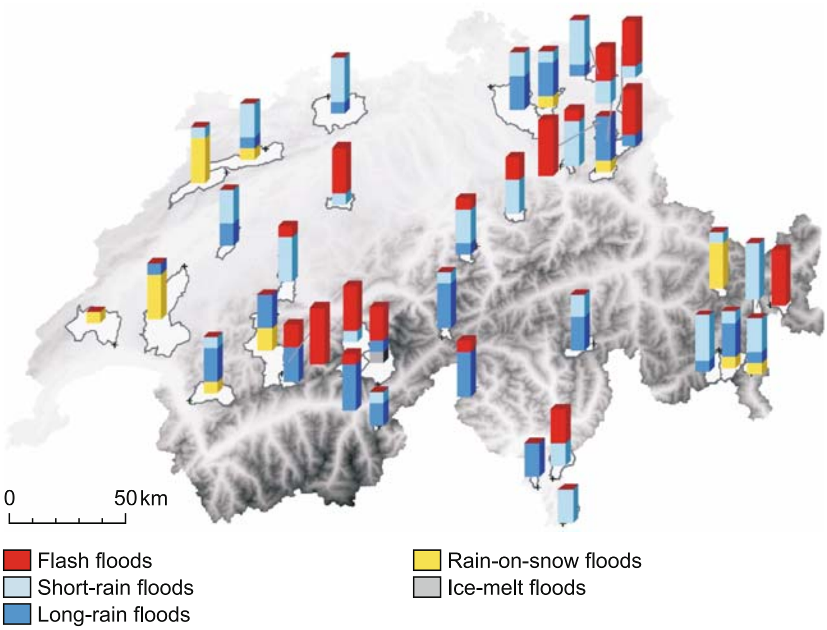


Fig. 17 Weighted frequency of the various process types [64]. Only flood events with a recurrence interval of more than 10 years are considered. These events are weighted as follows: A process type which results in an event with a recurrence more than 30 years is accorded the weighting 3. A recurrence of more than 20 but less than 30 years corresponds to a weighting of 2, and a recurrence of more than 10 but less 20 years corresponds to a weighting of 1. The weightings are then aggregated for each process type per catchment

hydropower, currently has only a few measurement stations with natural discharges (see above), the difference in frequency between the various process types is striking, and hence also the spatial variety of flood events. Long-rain floods are more relevant in the central and western regions of the Swiss Alps than in the eastern region, where short-rain floods are very frequent. Also notable is the fact that rain-on-snow events in the alpine zone are relatively rare; this is because flood peaks are more frequent in high summer, when the majority of catchments are free of snow and the zero degree line for the triggering precipitation event is relatively high, so that large areas are rained on and hence contribute directly to the runoff (Fig. 18). The opposite occurs in catchments outside the Alps, where the highest annual flood is spread evenly throughout the year.

3.4 Low Water

Low water refers to water levels which are below the limit defined as normal. As with high water, low water usually occurs at a specific time of the year depending

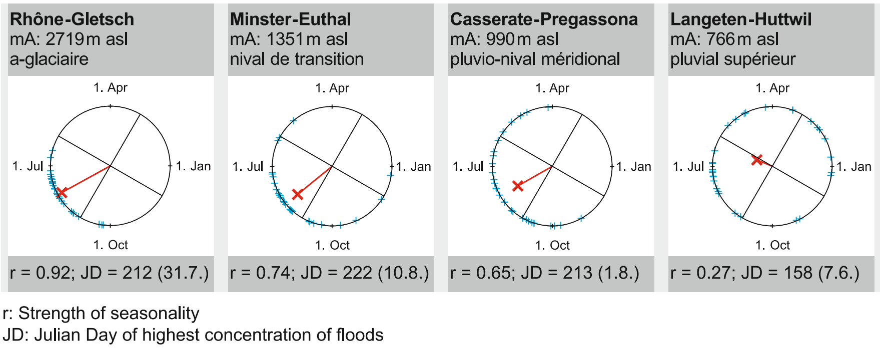


Fig. 18 Seasonal concentration of highest annual flood for various catchments in Switzerland [64]. $r =$ variability of occurrence between 0 (even seasonal distribution of flood) and 1 (flooding always occurs on the same day). r is represented as a vector (*red*). $D =$ mean date of occurrence (*red cross*)

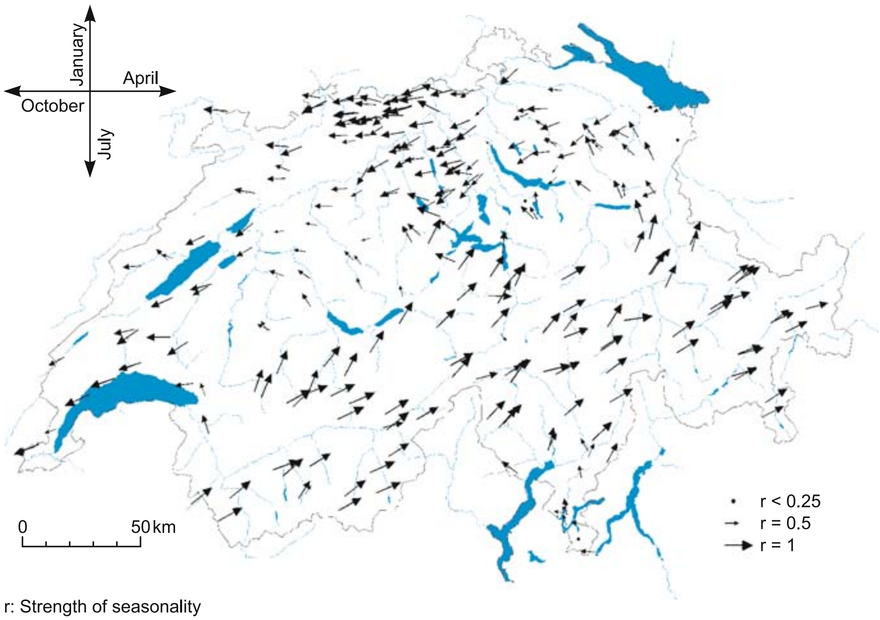


Fig. 19 Spatial representation of low water seasonality for selected runoff measurement stations [85]

on the region (cf. Fig. 19). As a general principle, there is a close correlation between the regime type (Sect. 3.2.2) and the seasonal occurrence of low water periods. In the alpine catchments the lowest flow rates usually occur in the winter half-year, when precipitation is stored in the form of snow.

On the north side of the Alps, the absence of low water during dry periods in summer is primarily attributable to snow and icemelt in the spring [65].

In inner-alpine areas – e.g. the Valais or the Tyrol – drought in summer can also produce low waters. Here drought can affect an entire valley side or even an entire region. The characteristic attributes of alpine catchments, particularly the low storage capacity of soil and subsoil, promote the occurrence of dry periods. This fact has long been recognized, and for centuries most surfaces have had to be irrigated by means of cleverly designed systems [66].

As mentioned several times above, natural low water characteristics in many alpine catchments are influenced by the effects of hydropower usage. Depending on the situation, entire sections of rivers can remain dry for several months, or their runoff regime can be severely altered, with the associated ecological effects (cf. Sect. 3.2.2). In Switzerland the Water Protection Law which came into force in 1991 requires a minimum residual water flow to be maintained in the affected watercourses. The residual flows are determined based on Q95, i.e. flow rates which are attained or exceeded on an average of 347 days (95%) per year. As evidenced by various studies, the legal minimum residual flows represent the absolute minimum from an ecological standpoint [67]. Solutions must be formulated that enable maximum ecological effectiveness and minimal constraints on production. The lessons which were learned in the European alpine region with regard to the hydrological impact of hydropower usage and the maintenance of optimal ecological effectiveness, must be transferred to other alpine regions where the development of hydropower is often the main priority.

4 Water Storage and Water Balance

4.1 Introduction

The water balance describes the elements of the hydrological cycle in a specific area over a specific period. It therefore provides an overview of the water resources which are available over the long term. The classic water balance equation is:

$$P - R - ET - \delta S - I = 0$$

Where

P Precipitation

R Runoff

ET Evapotranspiration

δS Storage change

I Natural subsurface inflow and outflow

The determination and attributes of the water balance elements precipitation and runoff have already been described and discussed in Sects. 2 and 3. The following takes a look at the elements evapotranspiration (ET) and storage change before describing the water balance per se.

4.2 Evapotranspiration

Evapotranspiration is a combination of two processes: evaporation und transpiration: Evaporation covers all water which is directly evaporated from open water surfaces (lakes, rivers, and streams etc.) or wet surfaces (roads, wet vegetation etc.) or sublimated from snow and ice cover. Transpiration covers water which is transported by root plants from the ground to their leaves, and from there is transferred to the atmosphere by the stomata.

Evapotranspiration plays a particularly important role since it links the hydrological cycle and energy budget of the atmosphere. For every kilogram of water that evaporates, 2.446 MJ of energy must be provided at an air temperature of 20° (latent heat of vaporization). This energy is either provided by net radiation or by the environment (atmosphere, soil) in the form of sensible heat. When evaporation condenses on cold surfaces (forming dew), the corresponding latent heat of vaporization is returned to the surrounding area.

Both processes – evaporation and condensation – are of particular importance in the mountains [68]: If snow- or ice-covered surfaces exhibit sublimation conditions due to extremely dry air, the energy used for sublimation is not available for melting. Since only around 12% of the sublimation energy (2.79 MJ kg^{-1}) is required for melting purposes (0.34 MJ kg^{-1}), the same amount of energy can either melt 8 mm of snow cover or sublimate only 1 mm. Conversely, particularly damp and windy conditions produce large volumes of energy available for the snow cover or glacial ice due to condensation: each millimeter of condensed water causes an additional melt of 7 mm of water equivalent snow or ice.

Evaporation is influenced not only by the amount of energy available but also by the amount of water available. If unlimited volumes of water are available in the soil and on surface areas, this is referred to as potential evapotranspiration, i.e. the highest possible evapotranspiration under given climatic conditions. The actual evapotranspiration is the evapotranspiration which can effectively be observed. This is always lower than potential evapotranspiration and is dependent on water availability, plant and surface attributes, net radiation, air humidity, and wind speed. In mountains with a great deal of barren soil and large areas of debris and rock cover which are unable to store water in any great quantities, and with fast-flowing water over steep terrain, actual evapotranspiration is very often limited and hence much lower than potential evapotranspiration.

4.2.1 Calculating Evapotranspiration

This description suggests that it is extremely difficult to measure actual evapotranspiration directly. Indeed, for individual points this can only be done using costly micrometeorological measurements in the lowest layer of the atmosphere, or with the aid of weighing lysimeters that enable evapotranspiration to be determined on a small area of plant-covered ground using the water balance equation: $E = P - R - \delta S - I$. The storage change δS is measured by weighing, the measured gravitational water at the lysimeter outlet corresponds to runoff, and precipitation is separately measured next to the lysimeter. There are no lateral underground inflows and outflows ($I = 0$).

A very similar process is used to calculate evapotranspiration in a hydrological catchment with well-defined hydrogeological conditions. Viewed over longer intervals (one or more years), $\delta S = 0$ can be assumed. $I = 0$ can also be assumed because the area is hydrogeologically verified. Thus, it is easy to calculate evapotranspiration by carefully measuring the areal precipitation (cf. "Precipitation") and runoff. Care must be taken to ensure that all errors in the calculation of individual components of the water balance equation are reflected in the result, for example evapotranspiration.

If is frequently necessary to calculate evapotranspiration on the basis of climate and land use data. On the basis of the calculation of potential evapotranspiration, various procedures have been proposed with the aim of calculating actual evapotranspiration. There are a number of methods [68, 69].

4.2.2 Distribution of Evapotranspiration in the Alps

In the Alps [5] used an extensive range of water balance computations to determine evapotranspiration between 1931 and 1960 for an area covering 195,000 km^2 at an average altitude of 1,270 m ASL. The average value was 540 mm a^{-1}, although an increase from North to South was identified and the individual values vary widely depending on the region, with more than 700 mm a^{-1} recorded in the southern Alpine periphery and only 100 mm a^{-1} in the high alpine region. The reduction in evapotranspiration with increasing altitude fluctuates between 17 and 19 mm per 100 m of altitude.

A high-resolution spatial evaporation map covering the period 1973–1992 exists for Switzerland, which was calculated using modern evaporation models [49]. It shows major variability, on the one hand due to the large differences in altitude, but on the other hand also due to the spatial diversity of the vegetation. This variability is clearly visible in cross-sections through the Alps (Fig. 20). An average evapotranspiration of 484 mm a^{-1} was calculated for Switzerland as a whole (median altitude 1,300 m ASL). The average altitude gradient is around 22 mm per 100 m.

In Austria, which is significantly lower lying (cf. Table 3), the evapotranspiration amounts to 510 mm a^{-1}. On average the actual evapotranspiration is 90% of the potential evapotranspiration for the whole of Austria [70].

Since large areas of the Alps are virtually free of vegetation, evaporation is comparatively low. For the whole of Switzerland, evaporation was calculated at 156 mm a^{-1} for ice and firn, and 234 mm a^{-1} for rock cover [49]. Traffic areas also exhibit low evaporation (199 mm a^{-1}). By contrast, settlements and industrial areas (at 434 mm a^{-1}), agricultural and alpine farming areas (at 436 mm a^{-1}), and in particular forests (at 616 mm a^{-1}) exhibit much higher evapotranspiration, with lakes and rivers registering the highest average of 901 mm a^{-1}. The aforementioned areas also differ substantially over the course of the year (Fig. 21).

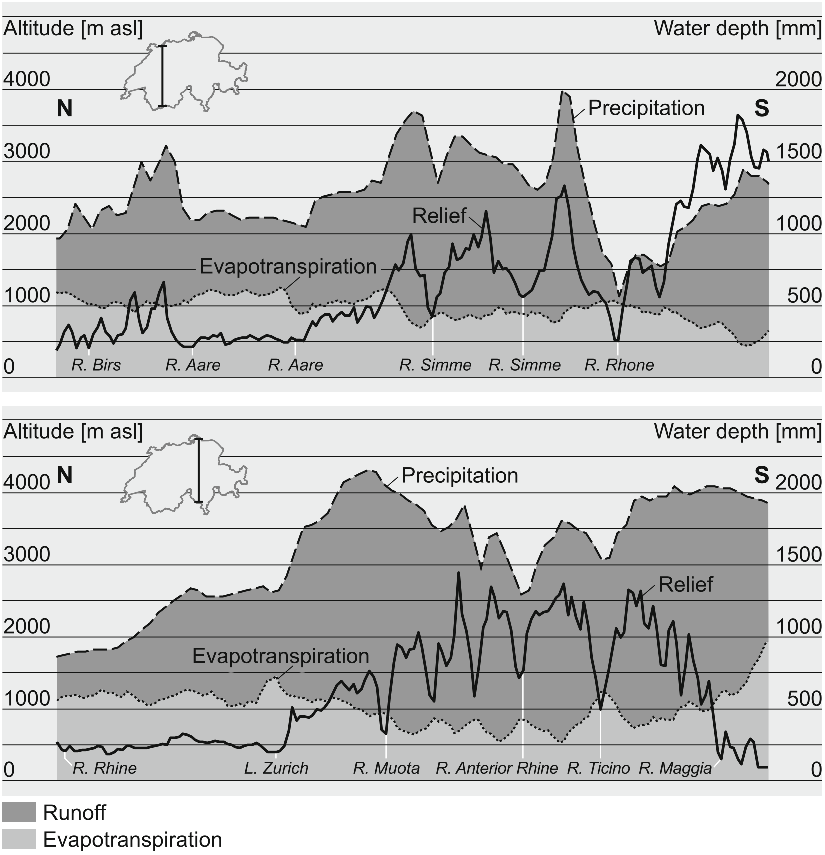


Fig. 20 North–south profiles indicating variation of mean annual precipitation, actual evapotranspiration and runoff (1973–1992) compared to relief. Profile 1 from Basel to Sion (Valais), profile 2 from Schaffhausen to Ascona (Ticino) [27, 29, 49]

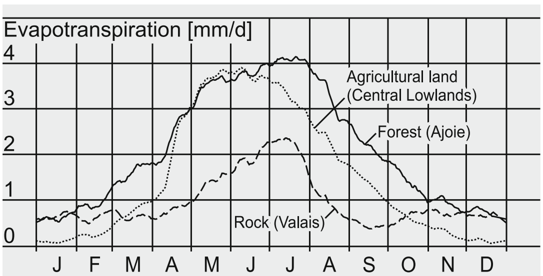


Fig. 21 Examples of mean daily evapotranspiration from varying surfaces [29, 49]

The development of evapotranspiration in Switzerland over time is presented in Fig. 2 of "Impact of Climate Change on Water Resources" [88]. A marked increase in evapotranspiration can be observed since the beginning of the twentieth century.

This is primarily attributable to rising temperatures but may also be due to the increase in agricultural productivity as a result of improved farming methods and fertilization, which has simultaneously increased the volume of transpiration.

4.3 Storage Changes

Water storage and changes in water storage are important elements in the water balance. Water storage provides a balanced supply of water for evapotranspiration and runoff over the short, medium, and long term.

Short-term storage of water for several hours can take the form of interception on the vegetal cover or depression storage in surface puddles. Water is stored over a slightly longer period (days – weeks) in the upper and lower soil. Artificial reservoirs can store water for weeks or even months. However, snow cover or groundwater storage levels as well as lake levels can also be subject to fluctuations that extend over several months (cf. Fig. 22). Glaciers as well as large groundwater reserves located deep underground are capable of storing water for years or even decades. Glacial fluctuations are discussed in Table 1 of "Impact of Climate Change on Water Resources" [88].

The effects of storage are reflected in the runoff regime (cf. Sect. 3.2.2). These storage depots help to offset shortages during dry periods. On the other hand, snow

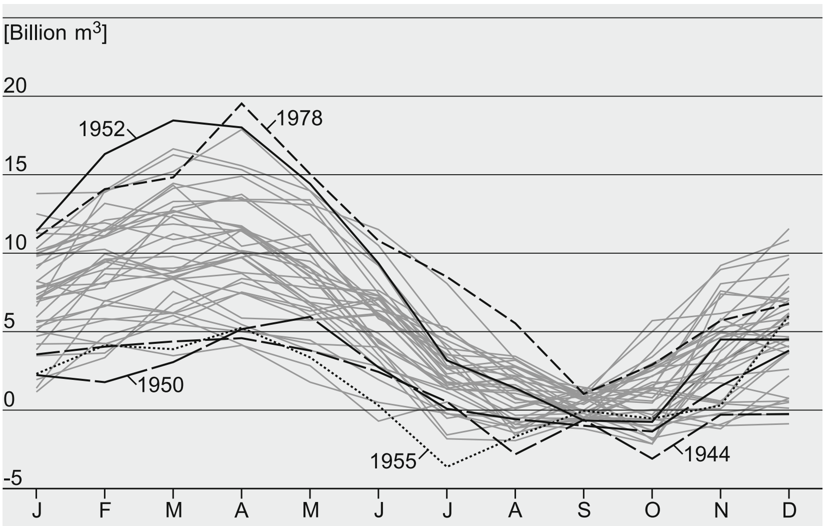


Fig. 22 Monthly variations in total water storage volumes in Switzerland from 1940 to 1981. Water storage volumes include medium-term changes in soil moisture, groundwater, snowpack, lakes, and reservoirs. Long-term changes in groundwater and glaciers are not taken into account [71]. Minimum and maximum years are indicated

stored in large quantities can also pose a threat if it melts rapidly at times of heavy precipitation.

Water storage in soil, groundwater, and snow cover is extremely difficult to quantify, whereas changes in lake and reservoir levels can be measured and calculated with relative ease. Figure 22 charts the total short- and medium-term storage volumes in Switzerland based on comprehensive water balance calculations [71]. Strong seasonal fluctuations in storage volumes are immediately identifiable. These are attributable not only to natural snow cover during the winter, but also to man-made reservoirs, which in Switzerland have a maximum storage capability of almost 4 billion cubic meters of water. Natural lakes play an important role in mitigating peak discharge. During flood periods, short-term fluctuations in the water level of lakes may be temporarily relevant. Today these fluctuations are generally much less severe than at the end of the nineteenth century [71], since most lakes are now artificially managed in order to safeguard against excessively low or high water levels.

When compared against the figures in Table 4, the maximum storage levels shown in Fig. 22 (with a peak in spring of almost 20 km^3) are striking, particularly given the fact that Fig. 22 shows the monthly averages rather than the maximum and minimum levels. Moreover, it is also worth remembering that this volume of stored water is replenished year after year. These impressive statistics also clearly explain why the Alps – like many other mountainous regions in the world – are of such importance for neighboring lowlands (cf. Sect. 5).

An analysis of the figures in Table 4 gives rise to some interesting comparisons. For example, the storage volume in reservoirs is the same as the average volume of water stored by snow cover on 1 April. While the water volume stored by snow cover is much larger than that contributed by glaciers, even in hot years, it is not available in the same months. Drinking water consumption accounts for only 2% of water supplies in Switzerland. Only a very small proportion of water is used for irrigation. However, these statements are generalizations, and conditions can vary widely depending on the region and season, thereby changing the impact of the individual components.

Table 3 Water balance in the Alps [5], Austria [87], Switzerland, and some of its alpine fluvial basins [51]

Region	Period	mA	Area	P	R	ET	δS
		[m ASL]	[km^2]	[mm]	[mm]	[mm]	[mm]
Alps	1931–1960	1,270	195,500	1,450	910	540	
Austria	1961–1990	770	83,875	1,144	634	510	
Switzerland	1961–1990	1,312	41,285	1,458	991	469	−2
Rhine-Chur	1961–1990	1995	3,270	1,465	1,123	343	−1
Rhone-Léman	1961–1990	2084	5,458	1,435	1,034	407	−6
Ticino	1961–1990	1483	3,352	1,943	1,458	485	0
Inn	1961–1990	2334	1,818	1,248	964	286	−2

4.4 Water Balance

To calculate the water balance it is necessary to obtain an overview of the various components in order to estimate their relevance and variability over time and space. Since it is not easy to determine the individual components, the water balance equation

$$P - R - ET - \delta S - I = 0$$

will never work out exactly. Often, therefore, one of the parameters is calculated as a remainder to which all errors are attributed. Alternatively, an attempt can be made to balance out the errors, as in the example of [5, 31]. Comparisons of different water balances are also difficult due to the fact that the climate is constantly changing. Various methods and intervals are applied.

The overview of water balances in the Alps shown in Table 4 prompts some interesting comparisons. While the overall figure for evaporation in the Alps is 37% of precipitation, the percentage of evaporation in Austria is 45% compared to only 32% in Switzerland. This is because it rains far less in Austria due to the country's more continental climate, and the country's lower altitude gives rise to more evaporation. Even within Switzerland there are major regional differences. Despite being situated at a much higher altitude, the Rhone, Rhine, and Inn basins record no higher precipitation than the average for Switzerland due to the inner-alpine location of these regions. Yet the volume of precipitation in the Ticino basin, in the south of Switzerland, is substantial.

These regional effects in the Rhone area (Valais with low precipitation and high evaporation) or in the Ticino area (high precipitation and low evaporation) are clearly expressed in the transversal profiles shown in Fig. 20. This diagram also

Table 4 Water storage volumes in Switzerland compared to flows in the water balance and water applications (from [86])

Storage volumes in Switzerland		
Lakes	130	km^3
Glaciers 1850	100	km^3
Glaciers 2007	45	km^3
Reservoirs	4	km^3
Useable Groundwater	11	km^3
Snow cover on 1 April (1961–1985)	5	km^3
Water flows		
Precipitation (1961–1990)	60	$km^3\ year^{-1}$
Evapotranspiration (1961–1990)	19	$km^3\ year^{-1}$
Runoff from Swiss area (1961–1990)	40	$km^3\ year^{-1}$
Total runoff from Switzerland (1961–1990)	53	$km^3\ year^{-1}$
Storage in glaciers 1974–1981	0.4	$km^3\ year^{-1}$
Melting of glaciers 1998–2006	0.9	$km^3\ year^{-1}$
Drinking water consumption 2005	1	$km^3\ year^{-1}$
Irrigation during drought summer	0.1	$km^3\ year^{-1}$
Water for artificial snowmaking	0.008	$km^3\ year^{-1}$

illustrates the major surplus of precipitation over evapotranspiration (green areas) which gives rise to the enormous resources of water in the Alps (cf. also Sect. 5).

The water balance is not only subject to significant regional and seasonal fluctuations but also to longer-term changes associated with climate change. Fig. 2 in "Impact of Climate Change on Water Resources" [88] charts the changes in the elements of the water balance in Switzerland since 1901. It shows the major fluctuations to which precipitation is subject, and suggests that precipitation has increased slightly over the years. At the same time, however, evapotranspiration has also been steadily increasing in line with rising temperatures. All in all, therefore, runoff – and hence water resources in Switzerland – appears to have remained virtually unchanged over the past 100 years. It would be a mistake, however, to assume that this trend will continue, since regional and local changes in the water balance have been identified and further changes must be expected (cf. "Impact of Climate Change on Water Resources" [88]).

5 The Alps: Europe's Water Tower

5.1 Introduction

Mountains and highlands typically produce substantial volumes of water. The reason for this is that the air masses are forced to rise and subsequently cool, releasing humidity in the form of precipitation (orographic precipitation, cf. Sect. 2.2). Furthermore, evapotranspiration is reduced due to a lower rate of net radiation, lower temperatures, more frequent snow cover, and a shorter vegetation period. The discharge formed in mountain regions is subsequently transported to adjacent lower-lying areas via river systems. Downstream, the mountain water performs an important function for irrigation and food production.

One key contributor to the importance of mountains in their role as water towers is their ability to store winter precipitation – temporarily or over a longer period – in the form of snow and ice, which melt only in spring and summer, i.e. precisely when the water supply in the lowlands is at a minimum and agricultural demand for water is high. Moreover, the essential mountain contributions in summer are highly dependable. It is therefore generally agreed that mountain regions, with their disproportionately high discharge compared to lowlands, are of significant hydrological importance.

5.2 The Significance of the Alps for Downstream Hydrology and Water Resources

The Alps exhibit the general hydrological features typical of mountain areas. Additionally, they are exposed to the influence of seas in three directions (the

Table 5 Contribution of the alpine area to total discharge, respective shares in area and corresponding disproportionalities (annual mean and maximum monthly average)

	Rhine	Rhone	Po	Danube
Mean annual contribution to total discharge (%)	34	41	53	26
Maximum monthly contribution to total discharge (with month of occurrence) (%)	52(VI)	69(VII)	80(VIII)	36(VIII)
Share in total area (%)	15	23	35	10
Disproportional influence of the Alps (annual)	2.3	1.8	1.5	2.6
Disproportional influence of the Alps (maximum monthly)	3.5	3.0	2.3	3.6

Atlantic to the west, the North Sea to the north and the Mediterranean to the south) and lie in a zone of predominantly westerly winds. This enables sizeable amounts of humidity to be transported and subsequently extracted from the atmosphere. Because of their significantly higher annual discharge compared to the surrounding lowlands, the Alps are often referred to as the Water Tower of Europe [72]. With a mean contribution of 34% of the total discharge, the alpine regions of the River Rhine supply 2.3 times more water than might be expected on the basis of surface area alone. Table 5 lists the corresponding figures for all four major alpine rivers of Switzerland. The maximum contribution of the Alps occurs in the summer months, ranging from 36% (Danube, in August) to 80% (Po, in July). Since this summer runoff from the Alps originates from snow- and icemelt, it is highly reliable and mitigates the variability of the precipitation-driven flow characteristics downstream.

Figure 23 illustrates the high hydrological productivity of the Alps using specific discharge figures, i.e. discharge per unit area. For the Rhine and the Rhone Rivers, a clear pattern is evident with high specific discharges in the upper sections (typically 40–70 $\mathrm{l\,s^{-1}\,km^{-2}}$ or higher) and a steady decline as the catchment area grows in size and the influence of the Alps declines. The influence of the Alps is particularly visible in the Danube catchment which originates outside of the Alps and is subject to alpine influence via the River Inn (Fig. 23, Danube at a catchment size of about 75,000 $\mathrm{km^2}$).

5.3 The Global View

Building on the above concepts developed for the European Alps, studies were also conducted for other mountain regions worldwide.

A first approach was based on discharge gauge data from 20 case studies around the world to produce a representative assessment of mountain waters in different climatic conditions [73]. A study of the hydrological characteristics of these basins

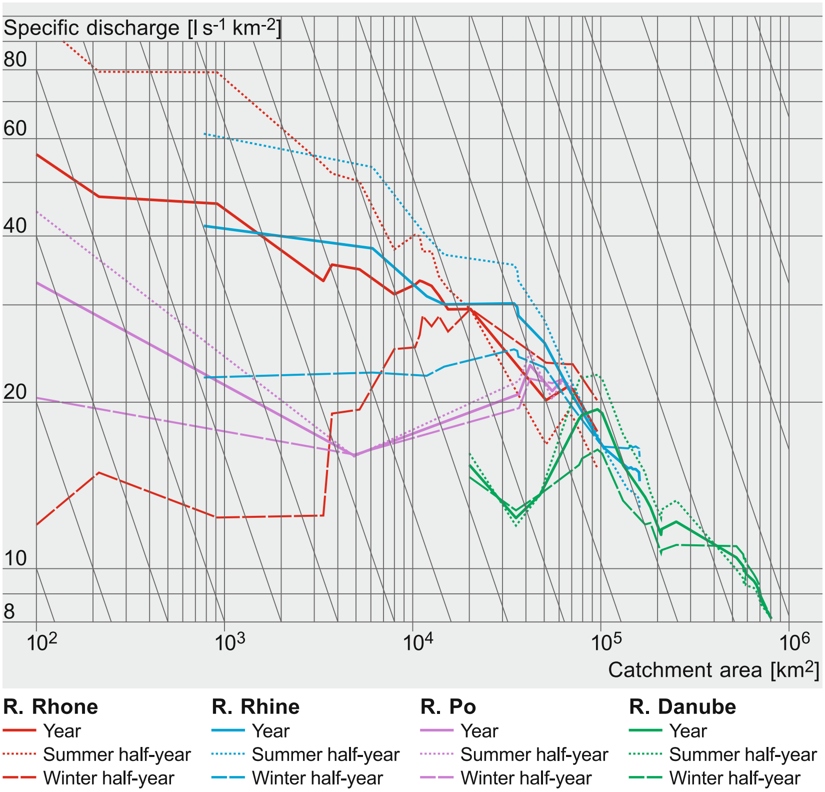


Fig. 23 Specific discharge for the four main alpine rivers Danube, Rhine, Rhone, and Po, annual mean as well as summer and winter half-year mean values

showed that the mountainous sections of rivers usually produce disproportionately high amounts of discharge. While mountain regions in humid climate conditions – such as in the Alps – produce about twice the discharge expected on basis of their share of the total basin area, mountain runoff may constitute 50–90% or more of total discharge in semi-arid and arid areas: the drier the lowlands, the greater the importance of the relatively humid mountain areas [74]. Since the runoff originating in mountains has a low year-to-year variability, its occurrence is highly reliable. Furthermore, it usually coincides with the dry period in the lowlands during summer.

The first spatially distributed assessment of the hydrological significance of mountains on a global scale was recently conducted by [75] on the basis of a hydrological model and a digital elevation model. Among other things, this analysis showed the disproportionately high runoff of mountain areas for the entire global land surface at a resolution of 0.5° × 0.5 (Fig. 24). Furthermore, by incorporating climate and population data, it found that more than 50% of mountain areas play an essential or at least supporting role for the water resources in the respective downstream regions.

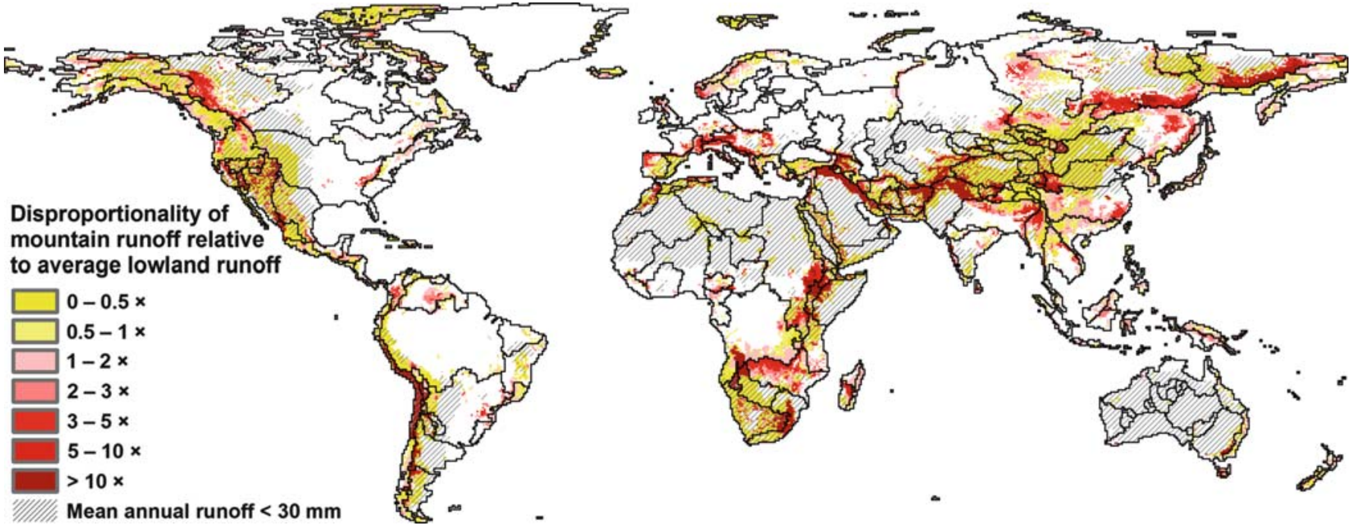


Fig. 24 Disproportionality of mountain runoff relative to average lowland runoff for mountain areas at $0.5 \times 0.5°$ resolution

5.4 *The Future Role of Mountain Water Resources*

5.4.1 Global

Since mountain regions are highly vulnerable to climate change [76], marked changes in snow and ice occurrence are to be expected. Since this means an alteration in seasonal storage rates, these changes will also affect seasonal discharge patterns.

Besides global climate change, mountain water resources are also influenced by demographic factors: population growth in critical lowland areas aggravates potential water scarcities and increases the pressure on streamflow originating in mountain areas. The growing demand for food and changes in dietary habits (e.g. increase in meat consumption) have the same effect. Furthermore, the future will see more intense competition for water for use in hydropower generation and industry.

The role played by changes in land use is less certain to predict. While population growth in mountains is likely to lead to intensified land use, with the resultant local soil degradation and erosion, the effects on downstream water resources are likely to be less marked.

5.4.2 Alps

As far as the European Alps are concerned, at first sight the situation does not appear too critical due to the abundance of water. The highest average areal precipitation figures, as observed in the Central Alps (Gotthard region), exceed 2,300 mm a^{-1} and the corresponding runoff is around 2,000 mm a^{-1}, equivalent to a mean specific runoff of approximately 70 l s^{-1} km^{-2} [77].

However, changes in the seasonality of snowmelt coupled with shifts in precipitation patterns may result in water shortages in the summer and autumn, especially in downstream regions. For the River Rhine, for instance, some scenarios show a decrease in total discharge of more than 50% at the German-Dutch border for the low-flow period in the autumn [78]. Moreover, the declining impact of snow and ice melt will increase the year-to-year variability of discharge in the summer and autumn.

5.5 *Need for Knowledge*

As the world's water towers, mountains will continue to play an essential role in meeting increased demands for food, drinking water, energy supplies, and industrial production in the twenty-first century. Thanks to their specific climatic and hydrological characteristics, mountains play a key role in the global water cycle. Water management must therefore start in mountain regions. Given the above considerations, it is essential to emphasize the importance of increasing our knowledge about mountain water resources [79]. Over the past decade the growing volume of available data, combined with the use of hydrological and climatological models, has driven progress in this field. However, due to the remoteness of the study area and the major strain placed on gauging devices, mountain hydrology is still a challenging field. While this is especially true for mountains in developing and emerging countries, reliable and long-term measurements at high altitude areas are relatively scarce even in the densely gauged Alps.

Further increasing our knowledge about mountain water resources will help us to understand the interaction between mountains and lowlands. It is this interaction that needs to be accorded high priority in terms of watershed management and in the interests of mitigating any conflicts that may arise over the distribution of this precious resource.

Acknowledgments The authors wish to thank Alexander Hermann for excellent support in preparing all figures.

References

1. Weischet W (1995) Einführung in die Allgemeine Klimatologie. Teubner, Stuttgart
2. Binder P, Schär C (1996) MAP mesoscale alpine programme. Design Proposal, Zürich
3. Rathjens C (1982) Geographie des Hochgebirges. Teil 1: Der Naturraum. BG Teubner, Stuttgart
4. Häckel H (1999) Meteorologie. Eugen Ulmer, Stuttgart
5. Baumgartner A, Reichel E, Weber G (1983) Der Wasserhaushalt der Alpen. Oldenbourg Graphische Betriebe GmbH, München
6. Gray, DM (1973) Handbook on the Principles of Hydrology. Water Information Center, Port Washington, New York
7. Barry RG (1992) Mountain weather and climate. Routledge, London, New York
8. Grebner D, Grubinger H (2004) Charakteristiken alpiner Niederschlagssysteme. Österreichische Wasser- und Abfallwirtschaft 56:51–58
9. Houze RA Jr (1993) Cloud dynamics. International Geophysics Series. vol 53. Academic Press, San Diego
10. Wanner H (1992) Ein Nussgipfel im Westwind. In: Müller JP, Gilgen B (Hrsg) Die Alpen – ein sicherer Lebensraum? Ergebnisse der 171. Jahresversammlung der Schweizerischen Akademie der Naturwissenschaften. Chur, 1991. Desertina, Disentis, S 50–69
11. Wanner H (1994) Die Alpen – Klima und Naturraum. In: Moser R, Svilar M (Hrsg) Lebensräume. Lang AG, Europäischer Verlag der Wissenschaften, Bern, S 71–106
12. Oke TR (1987) Boundary layer climates. University Press, Cambridge
13. Schär C, Davies TD, Frei C, Wanner H, Widmann M, Wild M, Davies HC (1998) Current alpine climate. In: Cebon P, Dahinden U, Davies HC, Imboden DM, Jaeger CC (Eds) Views from the Alps. Regional perspectives on climate change. MIT Press, Cambridge, Massachusetts
14. Lütschg O (1944) Zum Wasserhaushalt des Schweizer Hochgebirges. Beiträge zur Geologie der Schweiz. Geotechnische Serie. Hydrologie. Kümmerly & Frey, Bern
15. Uttinger H (1951) Zur Höhenabhängigkeit der Niederschlagsmenge in den Alpen. Theor Appl Climatol 2(4):360–382

16. Havlik D (1969) Die Höhenstufe maximaler Niederschlagssummen in den Westalpen. Nachweis und dynamische Begründung. Geographische Institute der Albert-Ludwigs-Universität, Freiburg i. Br
17. Fliri F (1974) Niederschlag und Lufttemperatur im Alpenraum. Wissenschaftliche Alpenvereinshefte. Heft 24. Deutscher und Österreichischer Alpenverein, Innsbruck
18. Lauscher F (1976) Weltweite Typen der Höhenabhängigkeit des Niederschlags. Wetter und Leben 28:80–90
19. Blumer F (1994) Die Höhenabhängigkeit des Niederschlags im Alpenraum. Dissertation, Eidgenössische Technische Hochschule (ETH), Zürich
20. Schwarb M (2000) The alpine precipitation climate. Evaluation of a high-resolution analysis scheme using comprehensive rain-gauge data. Dissertation, Eidgenössisch Technische Hochschule (ETH), Zürich
21. Geiger H, Zeller J, Röthlisberger G (1991) Starkniederschläge des schweizerischen Alpen- und Alpenrandgebietes: Intensitäten und Häufigkeiten. Grundlagen, Einführung, Methoden, Spezialstudien. Band 7. Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft (WSL), Birmensdorf
22. Fliri F (1975) Das Klima der Alpen im Raume von Tirol. Monographien zur Landeskunde Tirols. Folge 1. Universitätsverlag Wagner, Innsbruck, München
23. Turner H (1985) Nebelniederschlag. In: Sevruk B (Hrsg): Der Niederschlag in der Schweiz. Bericht der Arbeitsgruppe «Niederschlag» der Hydrologischen Kommission. Schweizerische Naturforschende Gesellschaft (SNG), Kümmerly & Frey, Bern, S 159–164
24. Grunow J, Tollner H (1969) Nebelniederschlag im Hochgebirge. Arch Met Geoph Biokl B17:201–218
25. Sevruk B (1985) Fehlerquellen, Genauigkeit, Korrekturmöglichkeiten. In: Sevruk B (Hrsg) Der Niederschlag in der Schweiz. Bericht der Arbeitsgruppe "Niederschlag" der Hydrologischen Kommission. Schweizerische Naturforschende Gesellschaft (SNG), Kümmerly & Frey, Bern, S 65–86
26. Konzelmann T, Wehren B, Weingartner R (2007) Precipitation networks. Hydrological Atlas of Switzerland. Plate 2.1^2, Bern
27. Schwarb M, Frei C, Schär C, Daly C (2001) Mean Annual Precipitation throughout the European Alps 1971-1990. Hydrological Atlas of Switzerland. Plate 2.6, Bern
28. Veit H (2002) Die Alpen. Geoökologie und Landschaftsentwicklung. Ulmer, Stuttgart
29. Spreafico M, Weingartner R (2005) Hydrologie der Schweiz. Ausgewählte Aspekte und Resultate. Berichte des BWG, Serie Wasser. Band 7. Bundesamt für Wasser und Geologie (BWG), Bern
30. Schwarb M, Frei C, Schär C, Daly C (2001) Mean seasonal precipitation throughout the European Alps 1971-1990. Hydrological Atlas of Switzerland. Plate 2.7, Bern
31. Schädler B, Weingartner R (2002) Ein detaillierter hydrologischer Blick auf die Wasserressourcen der Schweiz. Niederschlagskartierung im Gebirge als Herausforderung. Wasser-Energie-Luft 94:189–197
32. Lang H (1985) Höhenabhängigkeit der Niederschläge. In: Sevruk B (Hrsg) Der Niederschlag in der Schweiz. Bericht der Arbeitsgruppe «Niederschlag» der Hydrologischen Kommission. Schweizerische Naturforschende Gesellschaft (SNG), Kümmerly & Frey, Bern, S 149–158
33. Zeller J, Gensler G (1980) Starkregenprofile durch die östlichen Schweizer Alpen. Tagungspublikation der Forschungsgesellschaft für vorbeugende Hochwasserbekämpfung (Interpraevent). Heft 1: Naturraum-Analysen. Bad Ischl, Klagenfurt, S 203–213
34. Falkenmark M, Rockström J (2006) The new blue and green water paradigm: breaking new ground for water resources planning and management. J Water Resour Plng Mgmt 132(3) 129–132
35. Munich Re Group (2008) Topics Geo: Naturkatastrophen 2007 – Analysen, Bewertungen, Positionen. Edition Wissen, München

36. Kienholz H, Keller H, Ammann W, Weingartner R, Germann P, Hegg Ch, Mani P, Rickenmann D (1998) Zur Sensitivität von Wildbachsystemen. vdf-Verlag (NFP-31-Projekt), Zürich
37. Rodda JC (1994) Mountains – A hydrological paradox or paradise? In: Beiträge zur Hydrologie der Schweiz 25:41–51, Bern
38. Kan C(2004) Hydrometric Networks. Hydrological Atlas of Switzerland. Plate 5.1^2, Bern
39. Hydrologisches Zentralbüro (2003) Water level and discharge gauging stations. Hydrological Atlas of Austria, Plate 5.1, Wien
40. Margot A, Schädler B, Sigg R, Weingartner R (1992) Influence on rivers by water power stations (>300 kW) and the lake control. Hydrological Atlas of Switzerland. Plate 5.3, Bern
41. Klemes V (1990) Foreword. In: Molnar L (ed) Hydrology of mountainous areas. IAHS Publication No. 90
42. Weingartner R (1999) Regionalhydrologische Analysen – Grundlagen und Anwendungen. Beiträge zur Hydrologie der Schweiz, Nr. 37, Bern
43. Markart G, Kohl B, Perzl F (2007) Der Bergwald und seine hydrologische Wirkung – eine unterschätzte Größe? In: LWF-Wissen 55, S 34–43
44. Germann P (1994): Do forests control run-off? In: Beiträge zur Hydrologie der Schweiz, Nr. 25:105–110, Bern
45. Burger H (1927) Physikalische Eigenschaften von Wald- und Freilandböden. Mitt. Eidgenössische Forschungsanst. Wald Schnee Landsch 14(2):201–250
46. Schädler B, Weingartner R (1991) Natural Runoff 1961–1980. Hydrological Atlas of Switzerland. Plate 5.4, Bern
47. Kling H, Nachtnebel HP, Fürst J (2005) Mean annual depth of runoff using water balance data. Hydrological Atlas of Austria, Plate 5.7, Wien
48. Sevruk B (1997) Regional dependency of precipitation-altitude relationship in the Swiss Alps. Clim Change 36(3–4):355–369
49. Menzel L, Lang H, Rohmann M (1999) Mean annual actual evaporation 1973–1992. Hydrological Atlas of Switzerland. Plate 4.1, Bern
50. Aschwanden H, Weingartner R (1985) Die Abflussregimes der Schweiz. Publikation Gewässerkunde Nr. 65, Bern
51. Schädler B, Weingartner R (2002) Components of the natural water balance 1961–1990. Hydrological Atlas of Switzerland. Plate 6.3, Bern
52. Pardé M (1933) Fleuves et rivières. Paris
53. Mader H, Steidel T, Wimmer R (1996) Abflussregime österreichischer Fliessgewässer – Beitrag zu einer bundesweiten Fließgewässertypologie. Umweltbundesamt, Monographien, Band 82, Wien
54. OcCC (2007) Klimaänderung und die Schweiz 2050 – Erwartete Auswirkungen auf Umwelt, Gesellschaft und Wirtschaft, Bern
55. Aschwanden H, Weingartner R, Leibundgut Ch (1986) Zur regionalen Übertragung von Mittelwerten des Abflusses, Teile I und II. Deutsche Gewässerkundliche Mitteilungen 30 (2/3):52–61;(4):93–99
56. Pfaundler M, Weingartner R, Diezig R (2006) "Versteckt hinter den Mittelwerten" – die Variabilität der Abflussregimes. Hydrologie und Wasserbewirtschaftung 50(3):116–123
57. Aschwanden H (1990) Einsatz von Kurzzeitmessungen zur Bestimmung der Abflussmenge Q347. Gas–Wasser–Abwasser 70(1):20–28
58. Bundesamt für Energie (2008) Stand der Wasserkraftnutzung in der Schweiz am 1. Januar 2008, Bern
59. Kienholz H (1990) Zur Beurteilung und Kartierung von Naturgefahren in Gebirgsregionen. Geographisches Institut der Universität Bern, Bern
60. Düster H (1994) Modellierung der räumlichen Variabilität seltener Hochwasser in der Schweiz. Geographica Bernensia G44, Bern
61. Merz R, Blöschl G, Humer G (2008) Hochwasserabflüsse in Österreich – das HORA-Projekt. In: Österreich. Wasser- und Abfallwirtschaft, 9-10, 2008:129–138, Wien

62. Naef F, Schmocker-Fackel P, Margreth M, Kienzler P, Scherrer S (2008) Die Häufung der Hochwasser der letzten Jahre. In: Bezzola GR, Hegg Ch (Hrsg) Ereignisanalyse Hochwasser 2005, Teil 2, Bern und Zürich
63. Merz R (2002) Understanding and estimating flood probailities at the regional scale. Winer Mitteilungen, Wasser Abwasser Gewässer, Bd. 181, TU Wien
64. Diezig R (2006) Hochwasserprozesstypen in der Schweiz - Eine prozessorientierte Typisierung grosser Hochwasserereignisse in ausgewählten schweizerischen Einzugsgebieten. Diplomarbeit, Geographisches Institut, Bern
65. Laaha G, Godina R, Lorenz P, Blöschl G (2005) Low Flow. Hydrological Atlas of Austria, Plate 5.5, Wien
66. Reynard E (2008) Les bisses du Valais, un exemple de gestion durable de l'eau? In: Rev l'association pour la sauvegarde du Léman 69:1–8
67. BUWAL (1989) Wasserentnahme aus Fliessgewässern: Gewässerökologische Anforderungen an die Restwasserführung. Schriftenreihe Umweltschutz, Nr. 110, Bern
68. Lang H (1978) Zum Problem der räumlichen und zeitlichen Variabilität der Verdunstung in der Schweiz. In: Die Verdunstung in der Schweiz. Beiträge zur Geologie der Schweiz – Hydrologie, Nr. 25, Bern
69. Ward AD, Elliot WJ (1995) Environmental Hydrology. Lewis Publishers, New York
70. Kling H, Nachtnebel HP, Fürst J (2005) Mean annual areal actual evapotranspiration using water balance data, Map 3.3, Wien
71. Schädler B (1985) The water balance of Switzerland. Communication of the Swiss Hydrological Survey No 6a
72. Viviroli D, Weingartner R (2004) The Hydrologcial Significance of the European Alps. Hydrological Atlas of Switzerland, Plate 6.4. BWG (Bundesamt für Wasser und Geologie), Bern
73. Viviroli D, Weingartner R, Messerli B (2003) Assessing the hydrological significance of the world's mountains. Mt Res Dev 23:32–40
74. Viviroli D, Weingartner R (2004) The hydrological significance of mountains – from regional to global scale. Hydrol Earth Syst Sci 8:1016–1029
75. Viviroli D, Dürr HH, Messerli B, Meybeck M, Weingartner R (2007) Mountains of the world – water towers for humanity: typology, mapping and global significance. Water Resour Res 43:W07447. doi:10.1029/2006WR005653
76. Messerli B, Viviroli D, Weingartner R (2004) Mountains of the world: vulnerable water towers for the 21st century. Ambio Special Rep 13:29–34
77. Weingartner R, Viviroli D, Schädler B (2007) Water resources in mountain regions: a methodological approach to assess the water balance in a highland-lowland-system. Hydrol Processes 21:578–585
78. Lenderink G, Buishand TA, van Deursen WPA (2007) Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach. Hydrol Earth Syst Sci 11:1145–1159
79. Kundzewicz ZW, Kraemer D (1998) Striving towards assessment of mountain water resources. In: Chalise et al SR (eds) Ecohydrology of high mountain areas, proceedings of the international conference on ecohydrology of high mountain areas, Katmandu, Nepal, 24–28 March 1996, pp 175–185, ICIMOD, Katmandu, Nepal
80. ICIMOD (1996) Climatic and hydrological atlas of Nepal. Kathmandu
81. Breinlinger R, Gamma P, Weingartner R (1992) Characteristics of Small Basins. Hydrological Atlas of Switzerland. Plate 1.2, Bern
82. Zappa M, Pos F, Strasser U (2003) Seasonal water balance of an alpine catchment as evaluated by different methods for spatially distributed snowmelt modelling. Nordic Hydrol 34(3):179–202
83. Weingartner R, Aschwanden H (1992) Abflussregimes als Grundlage zur Abschätzung von Mittelwerten des Abflusses. In: Hydrologischer Atlas der Schweiz, Tafel 5.2, Bern
84. Weingartner R, Barben M, Spreafico M (2003) Floods in mountain areas – an overview based on examples from Switzerland. In: J Hydrol 282(1–4):10–24

85. Pfaundler M, Wüthrich T (2006) Saisonalität hydrologischer Extreme. Das zeitliche Auftreten von Hoch- und Niederwasser in der Schweiz. Wasser Energie Luft 98(2) 77–82
86. Schädler B (2008) Climate change – Are we running out of water? gwa 10/2008, pp 763–769
87. Kling H, Nachtnebel HP, Fürst J (2005) Water balance regions, climatic water balance and runoff characteristics. Hydrological Atlas of Austria, Plate 7.1, Wien
88. Wehren B, Weingartner R, Schädler B, Viviroli D (2009) General characteristics of alpine waters. In: Bundi U (ed.) Alpine Waters. Handbook of Environmental Chemistry, vol. 6. Springer, Heidelberg