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1.6 Mountain glaciers and water supply

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***SUMMARY:** In glaciers and snow cover, precipitation is stored over months or years. Although mountain glaciers comprise only 0.1 % (vol.) of the worlds freshwater distributed in climate regimes from Alaska to New Zealand, they have a considerable effect on a reliable water yield. In the past, glacier melt not only contributed to water supply in arid regions, but also in the Alps during summer, where the influence of glacier melt on runoff is demonstrated for the river Rhine and the Vernagtbach stream. A further shrinkage of glaciers and the reduction of snow cover leads to stream flow being primarily driven by rainfall and less by melting, resulting in a higher temporal and quantitative variability in discharge. Water shortages from missing glacier runoff will influence the economy of numerous countries.*

The freshwater supply of alpine regions benefits from the combination of increased precipitation, reduced evaporation and most of all from temporary storage of precipitation in form of snow and ice. In this contribution the global distribution of snow and ice and the recently registered changes of glaciers and snow cover are presented. The formation and influence of melt-water in alpine and pre-alpine regions and the possible effects due to fluctuation of snow cover and glaciers are also discussed.

World-wide distribution of snow and ice

The temporal and spatial distribution of snow and ice masses is determined by the proportion of solid to total precipitation. On a global average 3% of the total precipitation falls in solid form. The distribution of perennial snow cover results from the relation between height above sea level and the geographic position. Its maximal extension is approx. 57 million km^2 on continents towards the end of the northern winter period and minimal with 16 million km^2 at the end of the southern winter. On the northern hemisphere the climatic snowline reaches sea level north of the 80° N line, on the southern hemisphere already at 65° S. Its highest altitude is reached in the Andes at about 6,800 m a.s.l. (above sea level) where on a climatic average precipitation falls as rain even at altitudes higher than 6,000 m a.s.l. (BAUMGARTNER & LIEBSCHER 1990). In contrast, for mid-latitudes this value is between 3,000 and 3,200 m a.s.l. (WILHELM 1975).

More than 99% (volume) of freshwater supplies in form of snow and ice lie in the polar regions and only 0.1% in non-polar mountain glaciers of North and South America, Central Asia, Iceland, Scandinavia, the Alps and New Zealand. The length and area of selected valley glaciers are presented in *Table 1.6-1*, including the largest non-polar Hubbard glacier in Alaska and the Vernagtferner as the smallest one in this compilation, which is, however, still allotted to the »larger« European ones as approx. 90% of the 5,000 glaciers of the Alps are smaller than 1 km^2.

Measured mass changes of alpine glaciers

It is difficult to obtain temporally well-resolved long-term data on changes in mass and volume of large glaciers outside the Alps due to their location and extent. Thus, the following

Table 1.6-1: Length and area of selected mountain glaciers (*: data from 1975–1980, **: 1985–1990, ***: 1995–2000).

Glacier	*Length (km)*	*Area (km²)*
Hubbard-G. (Alaska, US) **	122	3,400
Fedtschenko-G. (Pamir, Tadzhikistan) *	77	750
Pio XI (Chile) ***	64	1,265
Columbia-G. (Alaska, US) **	61	1,100
Baltoro-G. (Karakoram, Pakistan) *	59	1,286
Bruarjökull (Iceland) ***	45	1,700
Moreno-G. (Patagonia, Argentina) **	30	257
Tasman-G. (New Zealand) *	29	98
Grosser Aletsch-G. (Wallis, Switzerland) *	25	82
Khumbu-G. (Himalayas, Nepal) *	18	34
Mer de Glace (Mont Blanc, France) *	12	33
Franz Josef-G. (New Zealand) *	10	33
Nigardsbreen (Norway) ***	10	48
Abramov-G. (Kyrgyzstan) ***	9	26
Pasterze (Hohe Tauern, Austria) *	9	20
Vernagtferner (Oetztal Alps, Austria) ***	3	9

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is based mainly on results from glaciological, hydrological and climatological research on glaciers in the Alps.

In *Fig. 1.6-1* the cumulative specific mass balance data of eight glaciers, lying in Austria, France, and Switzerland are presented for the period from 1948 to 2004. The largest mass losses of more than 40 m water equivalent (w.e.) were measured for the Glacier de Sarennes, the smallest one of this collection. In contrast, the Silvretta glacier on the north alpine border showed no net mass loss between 1957 and 2004 as the reduction since 1985 was compensated by mass gains beforehand. The mass changes of the rest of the glaciers lie between these two extremes. The size of the individual glacier influences the cumulative mass balance to a large degree, as small glaciers, e.g. the Glacier de Sarennes with an area of 0.5 km² in 2000, react much faster to climate changes than larger ones, such as the Hintereisferner or Vernagtferner (8.7 and 9.2 km², respectively). For the majority of glaciers the summer 2003 displayed the largest mass losses within the series, caused by a long, uninterrupted series of sunny and exceptionally warm days without precipitation (c.f. next paragraph).

Changes in volume of 15 glaciers in the Eastern Alps between 1890 and 2000 are presented in *Fig. 1.6-2* based on results obtained from cartographic surveys of glacier surfaces. In spite of the smaller temporal resolution, the phase of mass gain between 1960 and 1980 is well discernible, leading to a glacier surface heightening of 67 cm/year for the Waxeggkees in Zillertal, Austria, from 1959 to 1969. The neighbouring Hornkees, on the other hand, suffered from the largest decline of surface height of all the glaciers in the graph, amounting to an average of –118 cm/a for the period from 1989 to 1999.

Reasons for mass changes

The mass balance of a glacier represents the temporal and spatial integral between gain (accumulation due to snowfall, avalanches and snowdrift) and loss (ablation as a result from melting and evaporation, toppling of seracs). Temporally, we differentiate between the accumulation and ablation period, and spatially we divide the glacier area into an accumulation and ablation zone. A zero mass balance is characterised by an equilibrium between mass losses and mass gains averaged over the glacier area and mass balance year (October, 1 to September, 30). If the losses are predominant then the mass balance is negative, otherwise it is positive. There is a clear temporal distinction between periods of mass gains (winter) and losses (summer) for glaciers in mid-latitudes. In the tropics and subtropics, however, both processes can occur simultaneously, namely accumulation on higher parts and ablation on lower parts of glaciers, thus diminishing the seasonal differences.

Measurement data from the Alps show that mass gains in the form of snowfall have not significantly changed. For the Vernagtferner (c.f. *Fig. 1.6-1*), for example, the 40-year mass balance series (1964/65 to 2004/05) delivers an average of winter accumulation of 950 mm w.e. with a standard deviation of 220 mm w.e., whereas summer balance averages at –1,270 mm w.e. ± 508 mm w.e. (Escher-Vetter et al. 2005). The difference in the standard deviations illustrates that change of total mass balance is first and foremost due to changes in ablation i.e. changing of melting conditions on glacier surfaces. The largest part of melt-water production is due to the net radiation balance, which supplies 70–90 % of melt energy. Only 10–30% results from melting due to turbulent heat fluxes. Air temperature, however, plays a dominant role for the precipitation type and thus radiation absorption as fresh

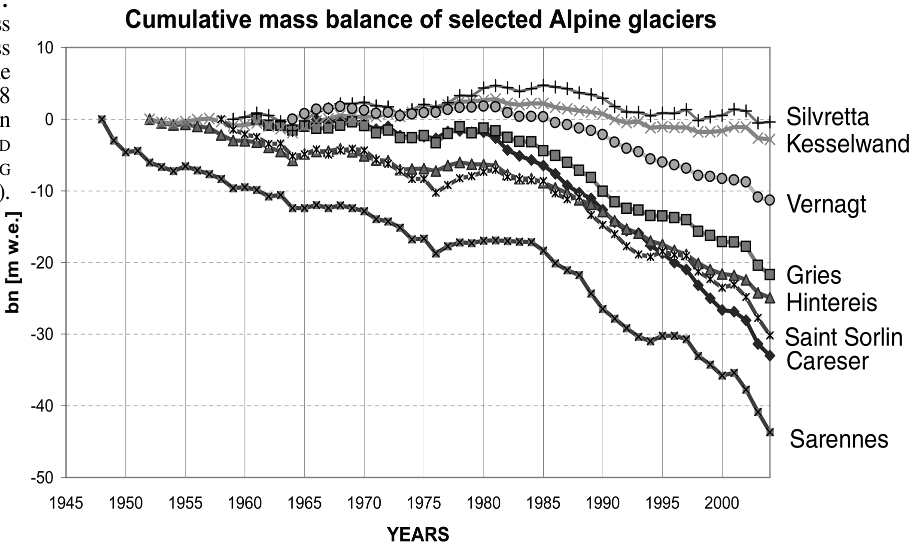

Fig. 1.6-1: Cumulative mass balance, i.e. total mass change of eight alpine glaciers between 1948 and 2004. Information provided by World Glacier Monitoring Service (WGMS).

snowfall reflects up to 90% of solar radiation, dark glacier ice only 10–30%. Thus, the frequency of summer snowfalls dominates the melt-water production: the more often snowfall periods occur in summer, the smaller the amount of melt-water production.

As snow falls at air temperatures below + 2° C, the largest capacity reached at around 0° C, and minimises at lower air temperatures, a rise in temperature due to climate change causes the snowfall zone to be shifted to higher altitudes and the snow cover duration is reduced. Research of the German Weather Service proves that regions in Germany from 400 m to 800 m a.s.l. show that the snow cover period was reduced by approx. 30–50% between 1951/52 and 1995/96 (DIETZER et al. 2001).

Recording and modelling of glacial and nival runoff

Glacial runoff regimes show a prominent seasonal variability, as in strongly glacierized regions the highest runoffs occur during summer nice-weather periods. Nival catchments, i.e. those influenced by snow melt produce top amounts depending on altitude and season: the lower the area, the earlier the maximal runoff amounts can be expected. *Fig. 1.6-3* (VIVIROLI 2001, changed) shows as an example the averaged runoff of the river Rhine for the period from 1961 to 1990, the »upstream« part of which is strongly influenced by snow and ice-melt regions of the Swiss Alps, therefore reaching its maximum in June. For the part of the river between Rheinfelden on the Swiss-German border and Lobith on the German-Dutch border, referred to as »downstream«, the maximum discharge in the spring is generated by rain and snowmelt, the minimum in summer induced by higher evaporation. Although the runoff recorded at Lobith, referred to as »mouth« in *Fig. 1.6-3*, reaches its peak in winter, it would be even lower in summer without the melt-water from ice. Individual months as for example July 1976, which was characterised by extremely dry conditions in middle and west Europe, displayed much higher melt-water contributions to total runoff: approx. 90% of the discharge recorded at Lobith was generated by glacier melting in the alpine part of the catchment (ROHRER 1992).

The characterisation of »water tower« as a reliable, over-proportionally large, seasonally delayed runoff contribution was originally introduced as a term for the Alps, the Rhine drainage basin serving as a good example for European regions. In arid regions of continental type, the melt-water contribution to runoff compensates the lacking precipitation in summer to a much greater extent as in the alpine regions. For areas of Central Asia or North America which present a distinctly arid foreland this »water tower« effect is virtually a question of survival. The summer runoff due to melting processes in the Tienshan and Pamir for the Amu-Darya River is extremely important, and the runoff characteristic of the Colorado River in western US shows that winter precipitation storage in form of snow and ice is an important water contributor (VIVIROLI 2001).

Runoff models allow an estimation of the relative

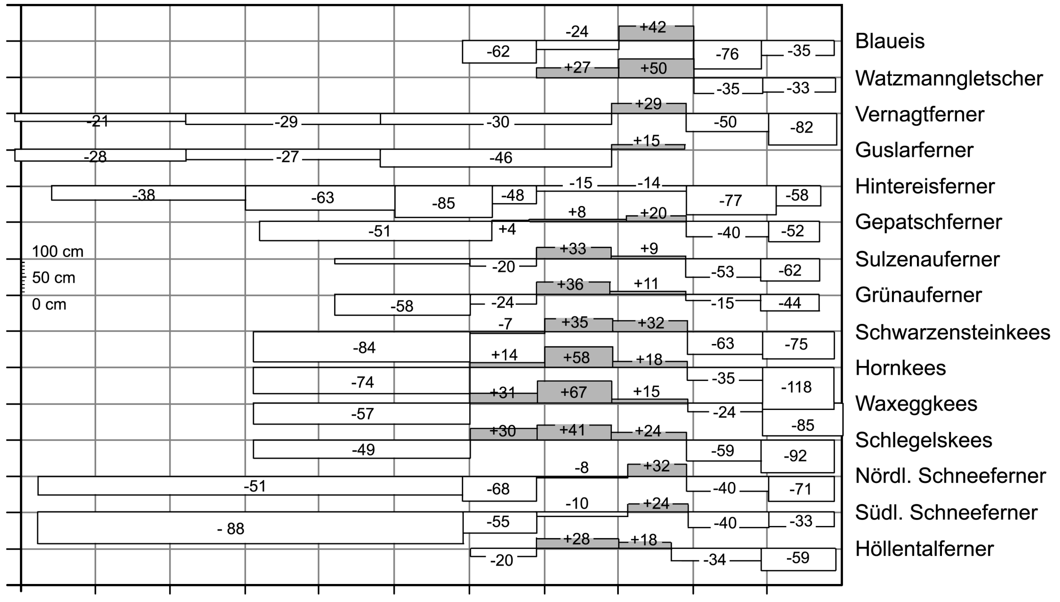

Fig. 1.6-2: Annual change in height of selected east-alpine glaciers between 1889 and 2000. Losses are marked in white, gains in grey. The figures give the specific volume change in cm per year for the marked time over the bar.

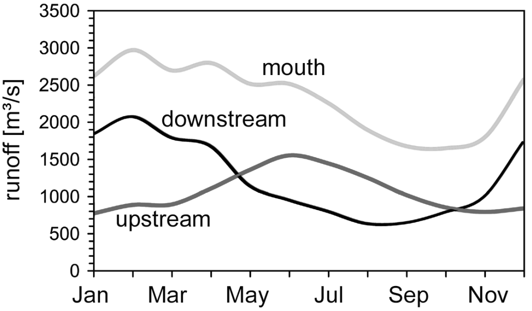

Fig. 1.6-3: Mean water flow of the river Rhine (1961–1990): »upstream« (Rheinfelden gauge), »downstream« and »mouth« (Lobith gauge on the German-Dutch border).

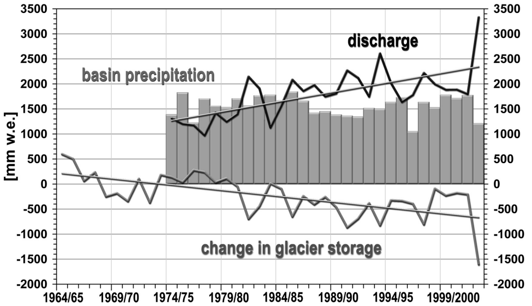

Fig. 1.6-4: Catchment area of the Vernagtbach gauging station, Oetztal Alps, Austria (2640 m – 3633 m a.s.l., 11.44 km^2, ca. 80% glacierized): selected terms of the water balance as based on direct measurements, for the period 1965 to 2003.

contributions of snow and ice-melt to the total runoff. The complexity of applied models is adapted according to available meteorological and topographical data and the entities to be modelled. For determination of runoff on daily to monthly basis in large catchment areas simple models are used, which rely on air temperature, precipitation data and a little differentiated surface structure. This type of model is calibrated with mapping, mass balances or partial runoffs (e.g. HAGG & BRAUN 2005; KUHN 2003). Temporally and spatially high resolved models (with typical scales: 1 hour, 100 m grid) are based mainly on energy balance approaches for melt-water production and linear storage concepts for runoff modelling (e.g. ESCHER-VETTER 2000).

Runoff measurements are available for very few glaciers. *Fig. 1.6-4* presents the increase in runoff and the annual sums of precipitation over the past 30 years for the 11.44 km^2, 80% glacierized Vernagtbach catchment in the Oetztal Alps, Austria. The 40-year series of the change in glacier storage derived from the mass balance analyses is also included. Since recording began in 1974 not only have the yearly sums nearly doubled, but also the hourly peak values have risen from 3 m^3/s to over 20 m^3/s. This is foremost due to negative mass balances and the resulting enlargement of the ice area in comparison to the firn and snow covered areas of the glacier. These top runoff values will continue as long as the glacier surface has not become distinctly smaller.

Economic importance of melt-water from snow and ice

The study by VERBUNT et al. (2003) shows that for the 195 km^2 Massa catchment in Switzerland, 85% of the water is contributed by the Large Aletsch glacier occupying 70% of the total area, and only the 2% glacierized Dischmatal (43 km^2) surprisingly enough 6% of the mean runoff between 1981–2000. With rising loss of ice mass and with a continuing reduction of snowfall amounts in mountain areas a diminishing contribution of glacier melt-water can be expected in the long run and not surplus due to floods. This is not only of increasing importance for shipping on the rivers Inn, Rhine or Danube, but even much more so for supplies of fresh drinking water in such regions as Tienshan in Central Asia. The capital of the Chinese Xinjang province, Urumchi with a population of more than 1 million derives the majority of its freshwater supply from the glaciers of the eastern foot-hills of these mountains. Water shortage in power-station reservoirs or lacking cooling water for thermal and nuclear plants here as well as in industrial countries can lead to a deficit in electricity supply.

If the climate development of the past decades continues, then only glaciers such as at present on the Zugspitzplatt will remain towards the end of the 21st century – i.e. small ice rests of 45 ha, where glacier areas of 300 ha existed in the middle of the 19th century. Not even covering parts of glaciers in the Alpine regions with white sheets, as practised in the past years will substantially prevent a further massive shrinkage, in spite of the hopes of ski resorts tourism managers as well as mountaineers, who prefer the present picturesque views to bare mountain sites without glaciers.

Conclusion

Since the post-glacial maximum in the middle of the 19th century, a distinct retreat can be observed for the glaciers of the Alps as well as for the majority of glaciers worldwide. This glacier shrinkage was shortly interrupted by mass gains around 1900, 1920 and between 1965 and 1980, but the mass gains could not reverse the secular trend. The reason for glacier retreat is primarily due to an increase in melting during the summer months and can lead to the disappearance of many small mountain glaciers, if the climatic development continues. The compensating effect of glaciers in their contribution to water supply will diminish, and in the middle and long run lead to reduction of runoff from alpine catchments especially in dry summer periods. In the short run an increase of runoff due to stronger melt-water production can be expected, which as in the past decades may lead to flooding catastrophes in alpine valleys.