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The relevance of glacier melt in the water cycle of the Alps: an example from Austria

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Abstract

This paper gives an overview on available methods how the contribution of glacier melt to runoff can be calculated with and without glaico-hydrological models. Further we applied an approach, which shows the potential of glacier melt contribution during the extreme hot and dry summer of 2003 by calculating the quotient q_{A03} of the mean monthly August runoff in 2003 and the long-term mean August runoff. The extreme summer 2003 was worth to be analysed as from the meteorological and glaciological point of view an extraordinary situation was observed. During June and July nearly the entire snow-cover melted and during the hot and dry August mainly ice melt of glaciers contributed to runoff. The mean runoff in August 2003 was calculated from observed mean daily runoff data of a selected period in August 2003 (3 to 27 August). This was done for 27 Austrian gauging stations in the glacierized basins of the rivers Inn, Salzach and Drau with a degree of glaciation between 2 and 76%. The quotient q_{A03} was calculated between 0.63 and 1.82, which means for the lower value that only 63% of the long-term mean August runoff and for the higher value 82% more than the long-term mean August runoff was observed in 2003. Additionally two stations at river Danube (0.4 and 1% glacierized) and further six gauging stations in catchments with no glacier cover were investigated to define q_{A03} quotients for non-glacierized basins. These q_{A03} quotients were calculated between 0.31 and 0.54. Hence, it was possible to qualitatively visualize the decreasing impact of glacier melt for a decreasing degree of glaciation. Nevertheless, for the accurate calculation of the glacier melt contribution for a certain catchment scale and time a glaio-hydrological model is needed.

1 Introduction

For mountain hydrologists the contribution of snow- and glacier melt to river runoff is of outmost interest. Especially under climate change conditions water managers would like to know what could happen if glaciers disappear and what the consequences could be. Is there a possibility for floods due to increasing glacier melt? Will reduced glacier melt caused by retreating glaciers affect and lower low flow during dry spells? Concerning basins in the European Alps we can already respond to some of these questions. But, a basic fact is that there is no constant factor of how much glaciers contribute to runoff. In a former study (Koboltschnig et al., 2008) we found out that for a small 5% glacierized catchment in a year with nearly stable glacier mass balance the annual glacier melt contribution was 1% and in the year 2003 with extremely negative glacier mass balances it was 15% of the total runoff. Comparing the glacier contribution during August of these two different years for the balanced year we calculated 4% and for 2003 we calculated 58%. Hence, the central question is: at which scale, for which degree of glaciation and for which meteorological situation (cold summer – hot summer) do we want know the contribution? The question of impacts can only be answered behind all that.

2 A review on different applied studies and their results

Kuhn (2004) investigated based on a simple air temperature and precipitation scenarios approach the reaction of the mean monthly runoff of glacierized and non-glacierized catchments. As these scenarios do not take into account the change of glacier surfaces they are not valid for future changes. Schaefli et al. (2005) applied a semi-lumped conceptual glacio-hydrological model for the joint simulation of daily discharge and annual glacier mass balance to Swiss catchments. The model was calibrated using daily discharge and annual glacier mass balance data. The model of Schaefli et al. (2005) has the main advantage of incorporating a glacier surface evolution model. Using this model applying climate change scenarios Schaefli et al. (2007) simulated the potential future of a catchment of a hydro power station in Switzerland. A decrease of 36% of the annual hydropower production was calculated for the future prediction period (2070–2099) – mainly because of the decrease in precipitation and ice melt and the increase in evapotranspiration. At the same time the simulated glacier surface reduced

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by 40%. Driven by a regional climate model Huss et al. (2008) simulated the possible future runoff of three glacierized catchments in Switzerland (de Zinal, de Moming, and Weisshorn). With their glacio-hydrological model they took the glacier surface change into account by changing the glaciers extent and surface elevation. The model was calibrated and validated using DEMs of the past glacier surface and additionally monthly runoff observations. For the near future an increase of the glacier melt contribution was simulated because enough glacial storage was available. After a stable period runoff drops below the current situation (for all applied scenarios), which is due to the loss of glacial storage. Although Huss et al. (2008) did not explicitly calculate the contribution of glacier melt they simulated a substantial change of the runoff regime from glacial to nival shifting the runoff maximum from July/August to May/June. Studying long-term hydrographs Collins (2008) found out that glacierized catchments in the upper Rhone basin already reached the maximum runoff after the end of the Little Ice Age between 1940 and 1950. Runoff from glacierized basins increased gradually from the late 19th century before rising rapidly in the 1940s. After decreasing with falling temperatures to the late 1970s, rising runoff levels during the second warming period failed to exceed those attained during the first. Melt rates continued to increase, but it was insufficient to offset the shrinking glacier surfaces.

Although the results of Collins (2008) and Huss et al. (2008) seem to totally disagree it must be added that both results are valid if we know more about the catchment size, the degree of glaciation, which is nearly the same for both, and that there is a different physiographic setting and scale of the investigated glaciers.

Weber et al. (2009) reported on the application of the model DANUBIA, which was used to simulate the past and future glacier contribution for the river Danube and glacierized tributaries from the south (Inn and Salzach). They found out that the 35% glacierized catchment of Vent/Rofenache had a mean annual contribution of glacier melt of 36.9%, the 17% glacierized catchment Huben/Ötztalerache had a mean annual contribution of glacier melt of 26.5% and the 4% glacierized catchment Inn/Innsbruck had a mean annual contribution of glacier melt of 8.4% for the period 1991–2000.

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Future simulations were based on REMO and MM5 climate generators. Results showed a shift of the runoff regime for the higher glacierized catchments from glacial to nival but nearly no influence of the glacier retreat was shown for the largest catchment Achleiten/Donau (76 600 km^2, actually 0.5% glacierized) as the actual glacier melt contribution is already quite low (1.6%). For two western Austrian basins Lambrecht and Mayer (2009) calculated the excess discharge, which additionally contributes to runoff during periods of glacier retreat. The calculation is based on two glacier inventories in 1969 and in 1998, on annual glacier mass balance data and a degree-day approach. They computed the additional amount of runoff, which originates from glaciers. For the entire period from 1969 to 1998 the excess was between 1.5 and 9% depending on the degree of glaciation (4–40%). The fraction increased for summer months to 3–12%. In a highly glacier covered catchment the excess reached a maximum value of 40%. The excess discharge is not directly comparable to other results of studies investigating glacier melt contribution as during years of positive or even zero mass balance no excess discharge is calculated. Melt during steady state conditions cannot be considered.

3 Assessment of the glacier melt contribution based on observed discharge data of the extreme summer 2003

The basic idea of this study was to investigate possible methods to quantify the glacier melt contribution to river runoff and to evaluate at which degree of glaciation the contribution is still "visible". We decided to work with a simple approach without using models. For sure, the contribution of glacier melt to runoff is variable in time and space and mainly depends on the availability of the glacial storage and various meteorological frame conditions. In three former studies (Koboltschnig et al., 2007, 2008, 2009) we already applied a glacio-hydrological model to small and medium sized catchments in the Austrian Alps simulating the extreme summer of 2003. In the European Alps the summer of 2003 was reported as the hottest and driest summer ever observed since the beginning of meteorological observations (Beniston, 2004; Schär and Jendritzky, 2004). Even at elevated meteorological stations new records of highly positive temperatures were broken (Koboltschnig et al., 2009). In Fig. 1 it can be seen that there was no day below 0 °C during August 2003 in an elevation of 3100 m a.s.l. The effects of this summer on glaciers causing extreme ablation and an extraordinary reduction of snow covered areas and firn areas were reported in Paul et al. (2005) and Koboltschnig et al. (2009). Zappa and Kan (2007) evaluated the extreme heat and the runoff extremes in the Swiss Alps by using historical discharge records. They calculated that the 2003 summer runoff from alpine basins was only 60–80% (from the Swiss Central Plateau even less) of the long-term average runoff. For glacierized catchments the opposite was shown. In Koboltschnig et al. (2008) it was shown that especially in June but also in July the melt water contribution mainly originated from snow melt. Further it was calculated from a LANDSAT image, taken on 24 August 2003, that snow covered only 11% of the glaciers surface in the upper Salzach basin in the Austrian Alps. At elevated stations snow disappeared very early in the summer of 2003 (see Fig. 1). Sonnblick observatory (see Figs. 1. and 2) got snow-free in August 2003. Using satellite-based observations of the glacier surface albedo Paul et al. (2005) have shown that snow covered areas on glaciers were the lowest in August 2003 compared to other summer observations. Parajka and Bloeschl (2006) showed a composite MODIS image from June 2003 with nearly no snow cover over Austria. Glacier mass balance observations, which take the observation of the maximum ablation area extent into account, reported from the most extreme retreat of the snow cover in the summer of 2003 (WGMS, 2005).

Hence, there is a good possibility to take the chance of investigating the glacier melt contribution of the summer 2003 as nearly laboratory conditions were available. For sure, the outstanding meteorological situation of the summer 2003 is exceptional but comes close to what we expect when applying climate models for our near future.

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4 Methods

For this study we decided to show the contribution of glacier melt to runoff for the hot and dry summer in 2003. Therefore the mean runoff in the summer of 2003, observed at 35 stations in Austria, should be compared to the long-term mean, similar to the study of Zappa and Kan (2007). Considering the hot and dry meteorological situation, rivers without glaciation should show a quotient of far below 1 and rivers with high glaciation a quotient of above 1. Differently from our study Zappa and Kan (2007) decided to compare the summer 2003 discharge (from 1 June to 30 September) with the long-term mean summer discharge by taking the longest available discharge record for each station. Their goal was to show the runoff extremes (below and above the average). Within this study we tried to evaluate the contribution of glacier melt, which was the highest in August 2003 (Koboltschnig et al., 2008). Figure 1 shows that at four elevated meteorological stations in the northern, western and southern part of the Austrian Alps, August 2003 was the hottest and driest spell in the summer of 2003 with no day below 0 °C. Due to local thunderstorms and rainfall events in the beginning and the end of August the period between 3 and 27 August seemed to be the most suitable to be analysed. Even in the last days of August 2003 extreme floods were reported especially in the south of the Alps (Moser and Kopeinig, 2003).

To quantify and compare the effects, which the hot and dry summer of the year 2003 had in glacierized catchments the runoff quotient q_{A03} (see Eq. 1) was calculated. Therefore 27 gauging stations from the three main glacierized basins in the Austrian Alps Inn, Salzach and Drau (see Fig. 2), two stations at river Danube (low degree of glaciation) and six additional stations of rivers with non-glacierized catchments were selected (see Table 1). For the selected gauging stations the catchment area, the glacierized area, the degree of glaciation and the mean and maximum elevation of glaciers (if available) were derived using GIS (see Table 1). All analyses were done based on the Hydrological Atlas of Austria (BMLFUW, 2007) incorporating the maps of the latest Austrian glacier inventory, which was assessed for 1998 (Lambrecht and

Kuhn, 2007). The degree of glaciation of catchment areas was calculated taking into account the real-hydrologic conditions, meaning that the area of diverted catchments was corrected (see grey entries in Table 1). The catchment area of the Inn basin was reduced by 201.6 km^2 and a glacierized area of 12 km^2 (Silvretta diverted into the Rhine basin in the west), the catchment area of the Isel and Drau basin was reduced by 15 km^2 and a glacierized area of 1.3 km^2 (Landeggbach diverted into the Salzach basin in the north) and the catchment area of the Salzach basin was increased by 85.7 km^2 and a glacierized area of 24.9 km^2 (diverted tributaries coming from the south from Margaritze and Landeggbach). The glacierized area of the Swiss part of the Inn basin was available from the Hydrological Yearbook of Switzerland (BAFU, 2010), but with a glacier extent for the year 1973 only. This value was reduced by an estimated value of 15% based on the mean reduction of Austrian glaciers (Lambrecht and Kuhn, 2007). Historical discharge data were online available from the Austrian Central Bureau of Hydrology (BMLFUW, 2010) back to 1951. Based on these time series of mean daily runoff from all selected gauging stations the quotient q_{A03} (see Eq. 1 and Table 1) was calculated as the quotient from the mean runoff in August 2003 ($MQ_{Aug\,03}$) and the mean long-term August runoff ($MQ_{Aug\,97-06}$).

$$q_{A03} = \frac{MQ_{Aug\,03}}{MQ_{Aug\,97-06}} \quad (1)$$

The mean runoff in August 2003 was taken as the mean of daily values from 3 August to 27 August, because of the above mentioned reasons. The mean long-term August runoff was calculated for the 10-year period from 1997 to 2006. As the length of available time series was very different from 12 to 56 years and the effect of shrinking glacier surfaces was not clear it was better to take only a 10-year period for comparisons. This decision was taken due to the paper of Lambrecht and Kuhn (2007), who reported that from 1969 to 1998 the glacierized area in Austria reduced from 567 km^2 to 471 km^2, which was a reduction of 17% in mean. The reduction was close to the mean for areas with high glaciation but highly variable from region to region, which is due to several components, which have an influence on melting and the different physiographic settings of glaciers. In that way the comparability of all calculated q_{A03} quotients should be better. The mean and minimum elevation of glaciers within the investigated catchments was calculated based on a 250 m digital elevation model. These values should help to compare the results of different regions.

5 Results

For non-glacierized catchments the August runoff quotient q_{A03} was calculated between 0.3 and 0.51 (see Table 1). Hence the mean runoff in August 2003 was only between 30 and 50 percent of the long-term mean. If not considering the shorter investigating period from 3 to 27 August the quotients would be much higher, between 5 and 28%, whereas the non-glacierized basins in the south would show 28% more for Gail, 7% more for Gurk and 12% more for Lavant river. This is due to the local thunderstorms in the end of August 2003. For the two stations Aschach and Wildungsmauer at river Danube, which have only a very small glaciation of 0.4 and 1%, the runoff quotient q_{A03} was calculated for 0.47 and 0.54.

The catchment area with the highest degree of glaciation of 76% is the Vernagtbach (nr. 19 in Table 1) and the Margaritze catchment area (nr. 2 in Table 1) with the largest Austrian glacier, Pasterze, has 33% glacierized area. The Inn basin at the station Kirchbichl shows a glacierized area of 320 km^2, which is, compared to the Drau and Salzach basin, the largest glacier surface. The diagram in Fig. 3, displaying the quotient q_{A03} vs. the degree of glaciation of a catchment, does not show a continuous decrease of the quotient q_{A03} for non of the three basins Inn, Salzach nor Drau if the degree of glaciation decreases. If the sub-catchments with the highest glaciation (nr. 1, 10 and 19) are compared it can be seen that for the Vernagtbach catchment (nr. 19) the mean and the minimum elevation is the highest. Nevertheless the quotient q_{A03} is the highest, which is the result of the hot summer 2003.

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6 Conclusions

For the European Alps already some approaches were applied to derive the glacier melt contribution to runoff. If historical glacier changes are considered in models then DEMs of glacier surfaces describing the three-dimensional change of the glacier surface must be available. For larger catchments glacier inventories are needed. If the future glacier melt contribution is investigated then a model, which is able to continuously adapt the glaciers surface should be applied. For small scale studies also the fluctuations of glaciers have to be considered. Hence not only the decreasing computing time and comfortable computer model surfaces but also a very good availability of different data sources makes simulations of past and future glacier melt easier to be realised.

The results of our study have shown that there is a good correlation between the quotient q_{A03} and the degree of glaciation if outliners are neglected. For sure there cannot be a linear correlation as the melt contribution of glaciers depends on many meteorological and physiographic parameters. Nevertheless, results of glacierized catchments compared to the results of non-glacierized catchments show that there is a threshold of the quotient q_{A03} from which on the influence of glacier melt is insignificant. Although at this study for some glacierized catchments the quotient q_{A03} was below 1, which means that the August runoff in 2003 was below the long-term mean, the results of Koboltschnig et al. (2008) should raise awareness. It was shown that for the catchment of Mittersill (6% glacierized and q_{A03}=0.78, see nr. 14 in Table 1) the contribution of glacier melt in August was 58%. For the decision if there is valueable contribution or impact of glaciers the q_{A03} threshold value should be set to 0.5, which was about the maximum value of six non-glacierized catchments.

For the determination of the glacier melt contribution the application of a sophisticated glacio-hydrological model makes sense, as it is able to simulate all runoff components. Even the excess-melt approach of Lambrecht and Mayer (2009) is on the one hand very good because it is easily applicable, assuming necessary data is available,

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but on the other hand misleading. It gives the impression that glaciers only contribute to runoff during periods of negative mass balances. But, the results of Huss et al. (2008) and Weber et al. (2009) have shown that the ongoing retreat of glaciers will in future lead to a shift of the runoff regime from glacial to nival, especially for small and highly glacierized catchments (degree of glaciation more than 10%). Therefore glaciers are not only contributors to runoff – the effect of compensation during the annual water cycle is also of the same importance. The predicted change of the runoff regime seems to be the most effective impact, which the retreat of glaciers will have on water management in the European Alps. If we try to consider the impact, which retreating glaciers could have on water resources and water management, it is from now on possible to seriously think about and calculate the effects, as models and methods are reliable enough. Some studies concerning the impacts of the drought in summer 2003 have shown "a shape of things to come" (Beniston, 2004) but did not take into account that in the Alps still glaciers were available to compensate for the lack of precipitation. Eybl et al. (2005) reported that the hydropower production at river Danube in Austria was reduced during August 2003 by one third. On the other hand the hydropower production was enhanced in glacierized catchments.

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Table 1. Overview and results of investigated basins and stations (grey background indicates corrected catchment area and glacierized areas).

Basin	nr.	HZB-ID	Station name	Catchment name	Catchment area (km^2)	Glacierized area (km^2)	Min. elev. glaciers (m)	Mean elev. glaciers (m)	Glaciation (%)	q_{A03} quotient (3–27 Aug)
	1	212 068	Innergschloess	Gschloessbach	41	15	2320	2995	36	1.18
	2		Margaritze	Moell	71	24	2325	2975	33	1.53
	3	212 076	Matreier Tauernhaus	Tauernbach	65	15	2320	2990	23	1.06
	4	212 043	Hinterbichl	Isel	107	16	2615	3025	15	0.98
	5	212 092	Brühl	Isel	502	48	2320	3005	10	0.96
Drau	6	212 167	Lienz	Isel	1182	64	2320	3005	5	0.84
	7	212 316	Lienz/Peggetz	Drau	1854	64	2320	3005	3	0.82
	8	212 324	Oberdrauburg	Drau	2084	64	2320	3005	3	0.82
	9	212 357	Sachsenburg	Drau	2535	64	2320	3005	3	0.84
	10	203 893	Kees/Obersulzbach	Obersulzbach	22	13	2415	2885	58	1.72
	11	203 034	Sulzau	Obersulzbach	81	17	2415	2910	21	1.18
	12	203 042	Neukirchen	Untersulzbach	41	6	2320	2855	15	0.89
	13	203 596	Habach	Habach	46	4	2565	2845	8	1.19
	15	203 125	Bruck	Salzach	1252	83	2320	2875	7	0.91
Salzach	14	203 075	Mittersill	Salzach	590	37	2320	2875	6	0.78
	16	203 901	Wallnerau	Salzach	2229	102	1955	2895	5	0.82
	17	204 032	Werfen	Salzach	3037	102	1955	2895	3	0.77
	18	203 398	Salzburg	Salzach	4506	104	1955	2890	2	0.63
	19	202 689	Vernagt	Vernagtbach	11	9	2990	3200	76	1.85
	20	201 350	Vent	Rofenache	98	37	2755	3145	38	1.50
	21	230 300	Gepatschalm	Fagge	58	22	2225	3115	37	1.40
	22	201 376	Obergurgl	Gurglerache	63	21	2700	3105	34	1.19
	23	201 392	Huben	Ötztalerache	516	99	2630	3125	19	1.16
Inn	24	201 434	Tumpen	Ötztalerache	785	114	2630	3110	14	0.99
	25	230 342	Brunau	Ötztalerache	870	114	2630	3110	13	1.11
	26	201 525	Innsbruck	Inn	5569	246	2225	3090	4	0.75
	27	201 889	Kirchbichl	Inn	9105	320	2225	3055	4	0.99
Donau	28	207 035	Aschach	Donau	78 190	424	1955	3010	1	0.54
	29	207 373	Wildungsmauer	Donau	103 993	430	1955	3000	0.4	0.47
	30	212 787	Federaun	Gail	1307					0,54
	31	213 041	Gumisch	Gurk	2554					0,36
	32	213 090	Krottendorf	Lavant	953					0.31
without glaciers	33	211 573	Graz m. MK	Mur	6986					0.30
	34	205 252	Roitham	Traun	1486					0.40
	35	209 171	Hardegg	Thaya	2382					0.49

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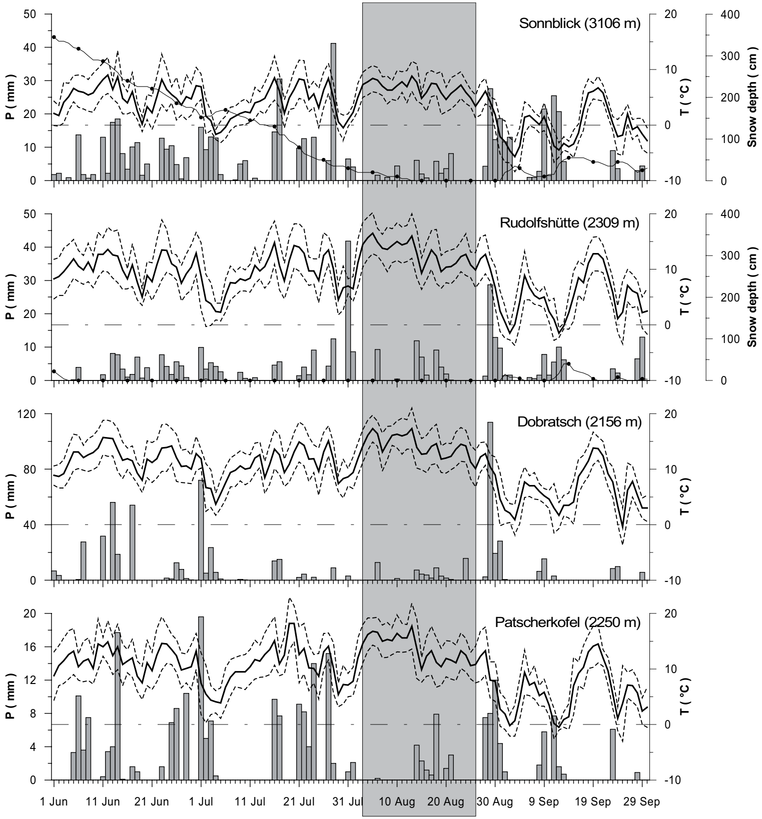

Fig. 1. Meteorological observations from four elevated stations in Austria (the location can be seen in Fig. 2) from 1 June to 30 September 2003. The dark black line is the daily mean air temperature and the grey dashed lines are the corresponding daily minimum and maximum air temperatures. Grey bars are the daily precipitation amounts and the black dotted lines at the two uppermost diagrams are the observed snow depths. The grey zone indicates the investigated time span from 3 to 27 August 2003.

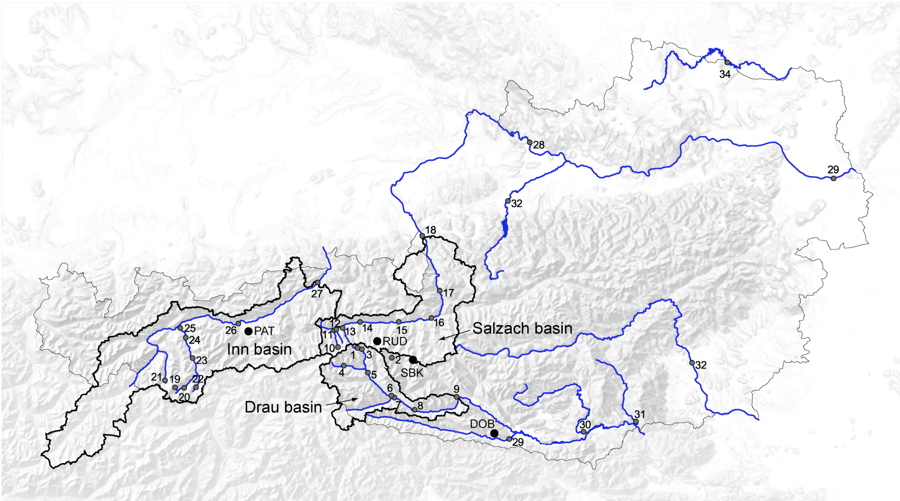

Fig. 2. Overview of investigated gauging stations (grey dots). Station numbers according to Table 1. Black dots indicate elevated meteorological stations: DOB = Dobratsch, PAT = Patscherkofel, RUD = Rudolfshuette, and SBK = Sonnblick (see Fig. 1). Black fat lines show the three main glacierized basins Inn, Salzach and Drau (data source HAO, 2007).

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Relevance of glacier melt in the water cycle of the Alps

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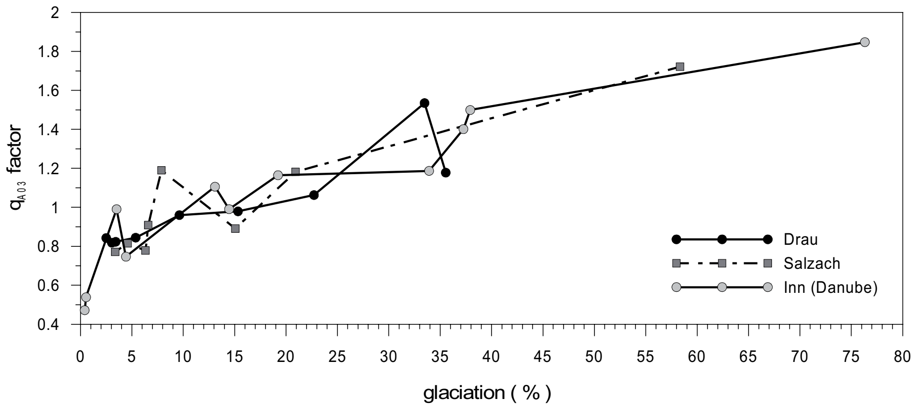

Fig. 3. Calculated August 2003 quotient (q_{A03}) vs. degree of glaciation of investigated catchments (see Table 1).