Projet SIE

Contribution potential of glaciers to water availability under climate change conditions in Valais, Switzerland

Flavio Finger
Master student in Environmental Engineering
EPFL

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Under the guidance of Dr. Bettina Schäfli and Prof. Andrea Rinaldo, Laboratory of Ecohydrology, ENAC - EPFL.

Glaciers influence the runoff regime of the catchments they are located in due to accumulation on to the ice surface in winter and ablation in summer. In this study we estimate the contribution of seasonally delayed glacier melt water to total runoff for current and future climate conditions. We find that the influence of glaciers on total runoff in the highly glaciated catchment of the Rhone river in Valais, Switzerland is high under current climate conditions and that a considerable decrease can be expected until year 2085, where it becomes nearly negligible compared to seasonal precipitation fluctuations.

1 Introduction

According to Kuhn and Batlogg [1998] the runoff regime in alpine catchments and in particular the peak flow during the summer months are strongly affected by the degree of glacierization. Global climate change continuously causes the Alps glaciated surfaces to decrease [Paul et al., 2007; Farinotti et al., 2011; Huss, 2011; Kaser et al., 2010; SSHL and CHy, 2011]. Kaser et al. [2010] thus state that considerable detrimental changes for water availability in rivers originating in glacierized mountain regions are expected due to shrinking glaciers.

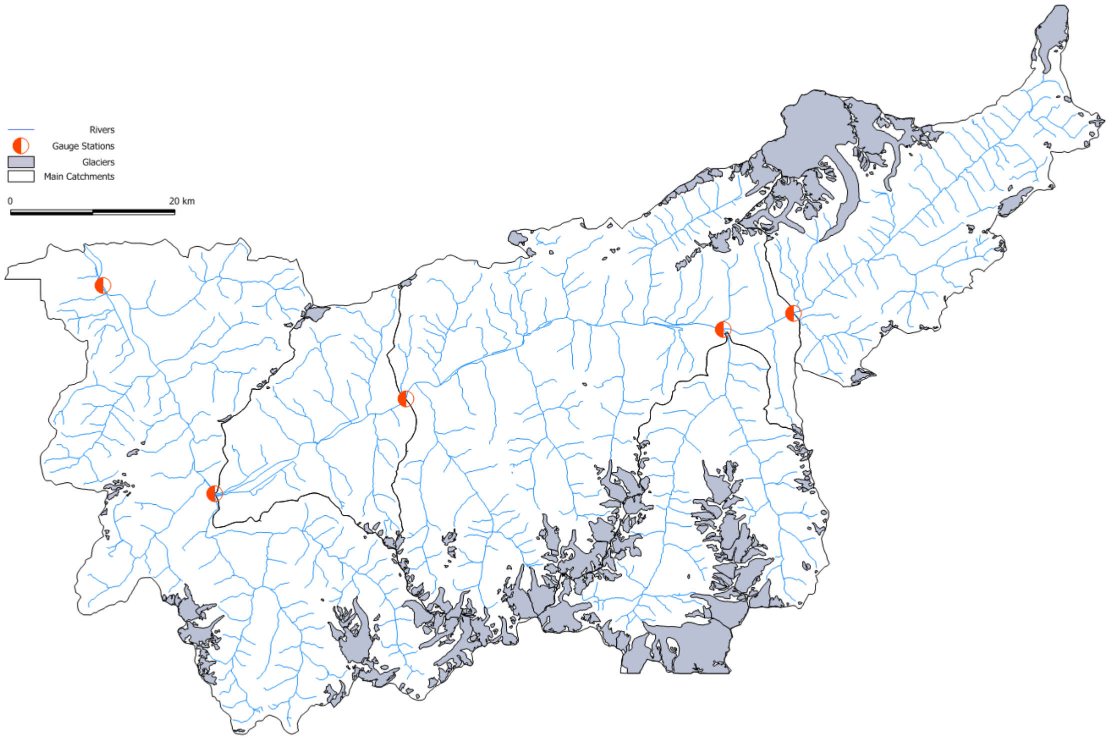

Figure 1: The Rhone river catchment upstream of Lake Geneva. It is divided into five subcatchments. The grey areas are glaciers, the river network is shown as blue lines and the red symbols represent the gauge stations at the subcatchment outflows.

Water has a very high socioeconomic importance in Switzerland and particularly in the canton of Valais. As a matter of fact, about 56% of Switzerlands electricity is produced by hydroelectric power plants [SSHL and CHy, 2011]. It is thus of big importance to be aware of the seasonal contribution of glacier melt water to the total runoff in the Rhone river and its variations due to climate change.

This project aims to quantify the present amount of glacier runoff in the Rhone river catchment upstreams of Lake Geneva according to the first-order approach used by Kaser et al. [2010]. Further we will repeat the analysis under climate change conditions by the means of three scenarios based on the CH2011 [2011] report. In order to compare the glacier melt to the overall precipitation induced runoff in the catchment we assume that the glaciers are in equilibrium with climate.

Table 1: Characteristics of gauge stations and the corresponding subcatchments. The stations are listed from east to west, with increasing stream order (see figure 1)

Station	1	2	3	4	5
Name	Brig	Visp	Sion	Branson	Porte du Scex
River	Rhone	Vispa	Rhone	Rhone	Rhone
Total catchment area (km^2)	913	778	3373	3752	5244
Glaciated area (%)	21.6	25.7	15.7	14.0	11.5
Altitude of gauge station (m)	667	659	484	457	377

2 Methods and Data

2.1 Study area

The canton of Valais is situated in southern Switzerland. It is a highly mountainous area reaching from an altitude of about 370 m above sea level (Lake Geneva) to over 4600 m (Dufourspitze). Except from minor differences its extent is most similar to the catchment area of the Rhone river upstream of Lake Geneva, which we define as our study area. The overall glaciated area of the catchment is about 11.5%, many major Swiss glaciers are fully or partially located inside of it (see figure 1). The catchment is divided into five subareas which we use for our analysis. The outflows of the subcatchments are equipped with discharge measuring stations (see table 1).

2.2 General approach

The method developed by Kaser et al. [2010] is based on the key assumption that the studied glaciers are in equilibrium with climate, which means that there is no mass change from one year to another. Thus the sum of monthly accumulation must equal the sum of monthly ablation in every year:

$$\sum_{1}^{12} M_m = \sum_{1}^{12} C_m$$

where M_m and C_m denote the ablation and accumulation in month m respectively.

The monthly accumulation on a glacier is taken to be equal to the total monthly precipitation over the glacier area. Using the accumulation and the above assumption we can calculate the monthly ablation of the glacier. We assume it to be proportional to the mean monthly temperature over the glacier if it is above 0 °C, and to be zero if the mean temperature is below 0 °C:

$$M_m = \frac{\Theta_m}{\sum_1^{12} \Theta_m} \sum_{1}^{12} C_m$$

where

$$\Theta_m = \begin{cases} T_m & \text{if } T_m > 0\,^{\circ}\mathrm{C} \\ 0\,^{\circ}\mathrm{C} & \text{if } T_m \leq 0\,^{\circ}\mathrm{C} \end{cases}$$

and T_m denotes the mean monthly temperature over the glacier[1].

2.3 Data and methods used

2.3.1 Present climatic conditions

The glacier extents are obtained from the GLIMS project [Taschner, 2004; Paul, 2009] (see figures 1 and 2). All glaciers with areas higher than 5 ha and located inside the study area are taken into account. Glaciers which are only partially contained in the study area are cropped at the catchment boundary. Every glacier is associated with the sub-catchment it is located in by an attribute.

We obtained the mean monthly precipitation data from the Hydrological Atlas of Switzerland [Haller, 2009, Tafel 2.7]. The data is spaced on a grid of 2 by 2 km, which is the result of a spatial interpolation taking into account topographical factors and based on rainfall measurements over the period of 1971 to 1990.

The monthly mean temperature data over the period of 1961 to 1990 was provided by MeteoSwiss. It has been measured at 91 stations all over Switzerland. We converted the data to a uniform altitude of 1000 m using a lapse rate of 5.2 K per 100 m[2]. Then we interpolated it in space on a grid of 500 by 500 m using a Krigging algorithm with a Gaussian variogram model and a maximal range of 50 km. Afterwards we converted the result to the actual altitude using a digital elevation model and the same lapse rate as above.

2.3.2 Climate change conditions

We used three different climate change scenarios obtained from the CH2011 [2011] project. All of them are based upon the SRES A1B emission scenario [IPCC, 2007]. The changes in temperature and precipitation are provided for 10 different GCM-RCM model chains. For the purpose of this study we used their mean values. We applied the delta change method [Bosshard et al., 2011] to the basedata (years from 1980 to 2009) which was provided by MeteoSwiss. We used 39 temperature and 88 precipitation measuring stations located in the study area to get the prospected temperature and precipitation for the three scenario periods (2021-2050, 2045-2074, 2070-2099). We will further refer to the scenarios by their central year (2035, 2060 and 2085).

We interpolated the monthly mean temperature on a coarse grid of 2000 by 2000 m using the same procedure as above to account for the effect of altitude. The monthly

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[1] Note that the procedure used to calculate ablation is slightly different from the one applied by Kaser et al. [2010]: they used one single glacier terminus height per bassin in order to calculate temperature and to distribute ablation over the year, whereas we calculated the mean temperature and monthly ablation for every glacier and took the sum in order to get the total monthly ablation for a catchment.

[2] The lapse rate has been obtained by linear regression of the mean yearly temperature versus the station altitude of all considered stations.

mean precipitation was interpolated over the same grid using a Krigging algorithm with a spherical variogram model and a range of 50 km, without taking into account neither altitude nor topographic effects.

We obtained the approximate glacier extents for the climate change scenarios by shrinking the total glacier surface by a given factor. We found the corresponding factor for each scenario using the results of Paul et al. [2007]. According to them, under the SRES A1 scenario we can expect a mean upwards shift of the ELA_0[3] of 250 m, 450 m and 600 m around the years 2035, 2060 and 2085 respectively. Knowing these values we determined the change in glacier area using the ELA - Area change relationship by Paul et al. [2007] and assuming that the ratio of the accumulation to the ablation area is 1.5 to 1. We obtained changes in total glacier area of -65%, -83% and -94% for the three scenarios. These area changes we applied to the glacier areas by removing successively (in steps of 100 m) all parts of the glaciers in the study area lying below a certain altitude, until the desired area change was reached. The result of this procedure is shown in table 2 and figure 2.

Table 2: Total glacier surface and glaciated catchment area of each subcatchment under present and climate change conditions derived from the GLIMS database and our calculations.

	Subcatchment	Brig	Visp	Sion	Branson	Porte du Scex
Present	Glacier surface (km^2)	196	202	529	536	628
	Glaciated area (%)	21.6	25.7	15.7	14.0	11.5
Scenario 2035	Glacier surface (km^2)	57	98	193	193	217
	Glaciated area (%)	6.3	12.5	5.7	5.0	4.0
Scenario 2060	Glacier surface (km^2)	18	39	66	66	73
	Glaciated area (%)	1.9	5.0	2.0	1.7	1.3
Scenario 2085	Glacier surface (km^2)	4	18	24	24	26
	Glaciated area (%)	0.4	2.3	0.7	0.6	0.5

2.4 Detailed procedure

For each scenario, in order to get the mean values of precipitation, temperature and altitude over each glacier surface, we transferred the temperature and precipitation data to a 100 by 100 m point grid. We then took the mean values of all points situated inside the boundaries of each glaciers. Thus each glacier is associated with a mean temperature and a mean precipitation value for every month and also a mean altitude value.

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[3] Steady state equilibrium line altitude, mean altitude for which accumulation equals ablation on a glacier.

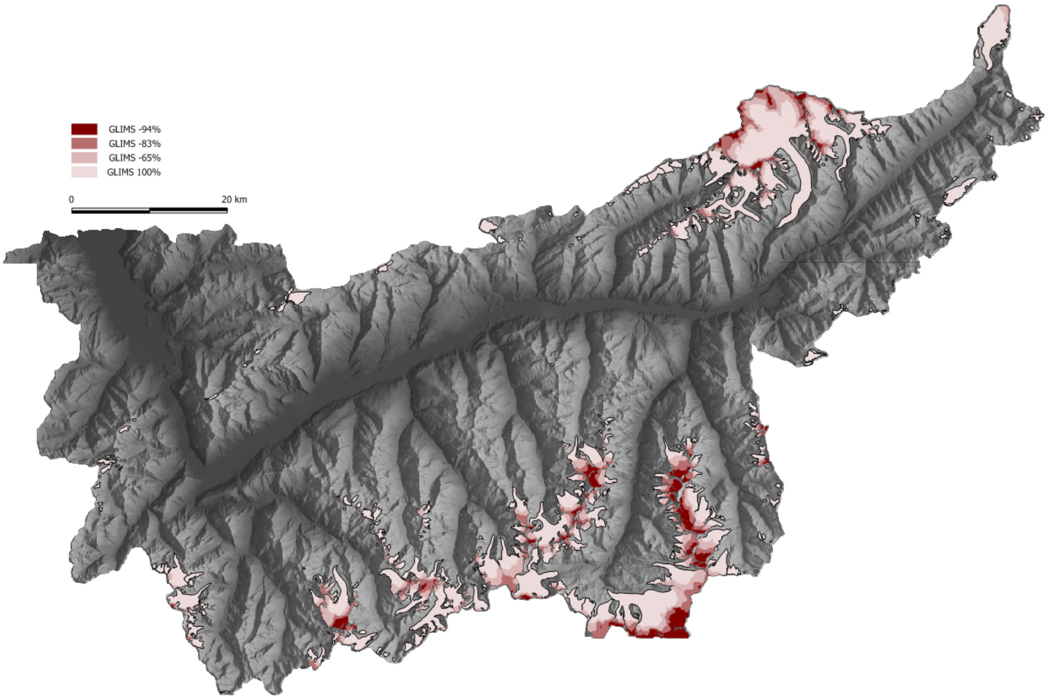


Figure 2: Glacier extents in the study area under present (light red) and future scenarios (darker shades of red) derived from the GLIMS database and our calculations.

We then applied the procedure described in chapter 2.2 to get the monthly accumulation and ablation over the glacier surfaces. Finally took the sum of the monthly accumulation and ablation data of all glaciers situated in the same subcatchment according to figure 1. The resulting data was then used to calculate the contribution of all glaciers in a subcatchment by summing up all ablation values for each month and subtracting the accumulation values from it. In order to compare the results we divided them by the subcatchment area. To be able to compare the amount of glacier runoff to the total water input in a catchment we took the mean values of precipitation over every subcatchment (see figure 4b).

3 Results

3.1 Situation under current climatic conditions

Figures 3a and 4 show the results we obtained using the current glacier extensions, the precipitation mean values from 1971 to 1990 and the mean temperature data from 1961 to 1990.

3.1.1 Accumulation and Ablation

Figure 3a illustrates the total ablation and accumulation over all glaciers of the study area. It is similar to Kaser et al. [2010] (Fig. 1. left column fourth graph). The total amount of precipitation is slightly higher in our case, which must be due to the different data we used for our study. The ablation period is shorter by two months and correspondingly the peak ablation is much higher. This can be explained by the different procedures to calculate ablation from temperature (see footnote 1 on page 4).

3.1.2 Glacier influence

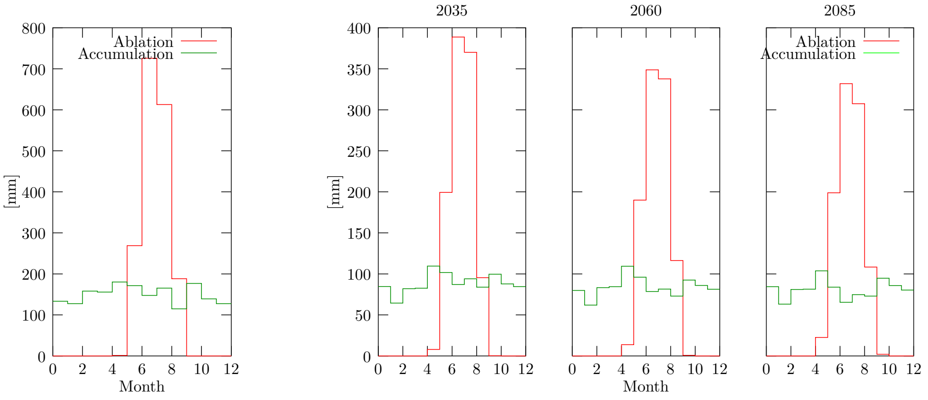
In figure 4a we reported the change in water input due to glacier storage for every subcatchment. As expected, the change is highest for the first two bassins due to their high glaciated areas. As we go downstream the glaciers loose a part of their influence.

Figure 4b shows the influence of the glaciers on the specific water input per month. The curves representing the situation without the glacier influence are simple mean precipitation values over the five subcatchments. The seasonal storage due to the snow cover of the subcatchments is not taken into account.

The influence of the glaciers on runoff is very important in the summer months, especially in the first catchments with a high glaciated surface. It looses importance approaching Lake Geneva, but the difference is still marked.

3.1.3 Comparison with discharge data

In figure 4c we compare the specific water input taking into account glacier storage to the specific discharge obtained from official data at the subcatchment outflows provided by the Swiss Federal Office for Environment. Note that our data does not take into account



(a) (b)

Figure 3: Total of ablation and accumulation over all glaciers of the study area per month for current (a) and climate change (b) conditions. Note the difference in scale. This figure is similar to Kaser et al. [2010], Fig. 1. left column fourth graph.

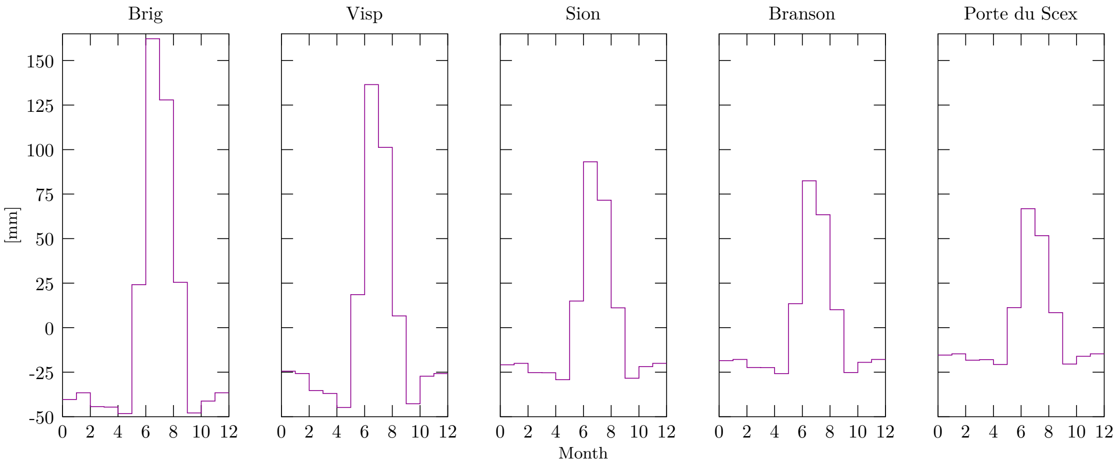
the seasonal delay due to snow cover, evapotranspiration nor the transition time between the input into the bassin and the outflow, which can be of several days.

The higher peaks of specific discharge and the lower values in the cold season we can see in the discharge data can be explained by the influence of seasonal snow cover over the catchment area. The important difference in total input compared to total discharge in the Visp subcatchment is due to deviations of water for hydroelectric power production from the Vispa river to the neighbouring watershed (Val de Dix). A similar explanation might account for the difference observed for the last subcatchment at Porte du Scex. Near to the estuary where the Rhone river flows into Lake Geneva, several parallel channels exist. Their discharge is not taken into account. In addition, evapotranspiration plays a significant role in the summer months due to the warm and dry climate in the Rhone valley.

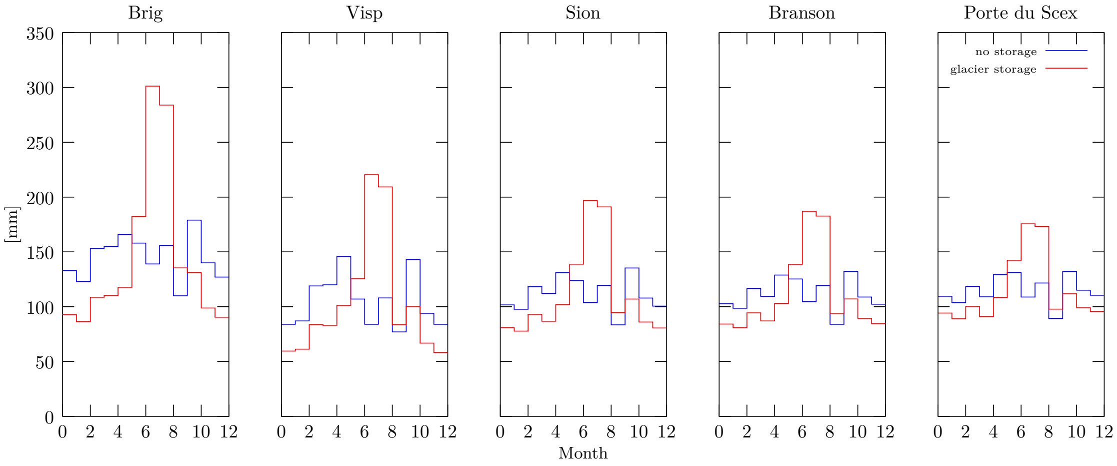
3.2 Situation under climate change conditions

Figure 3b shows the overall accumulation and ablation over the total glacier area for the three climate change scenarios. Note the difference in scale compared to figure 3a. We can state that the accumulation decreases only little between the three scenarios. The resulting decrease in ablation in the summer months is much more marked.

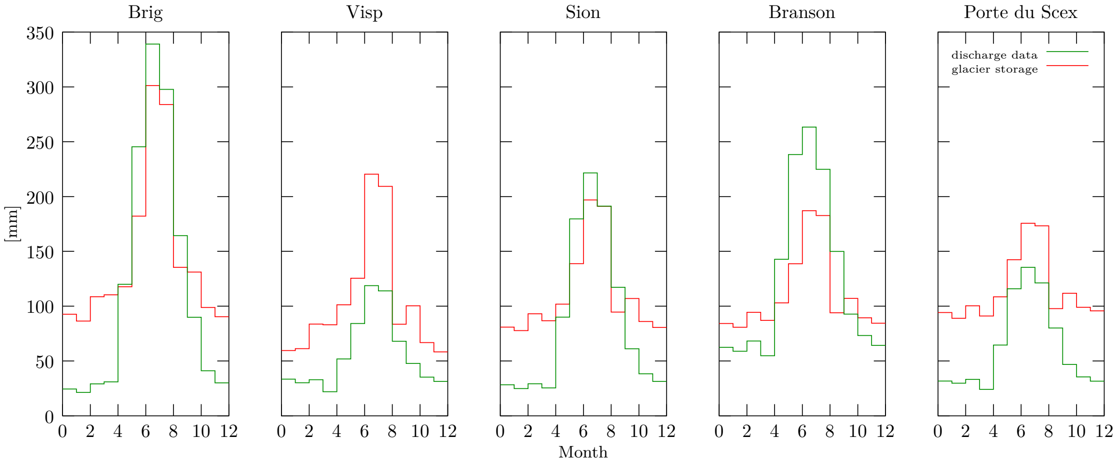
In figure 5a we reported the change in specific monthly water input caused by glacier storage for each subcatchment and the three scenarios. The amount of water stored decreases with advancing climate change and becomes negligible for the 2085 scenario. As we can see in figure 5b, seasonal fluctuations of precipitation are already as important as the influence of glacier storage for the 2035 scenario in all subcatchments, and become predominant in the two later scenarios. Also note the increase in precipitation for all catchments between the 2060 and the 2085 scenarios.



(a) Change in monthly water input due to glacier storage for the five subcatchments.

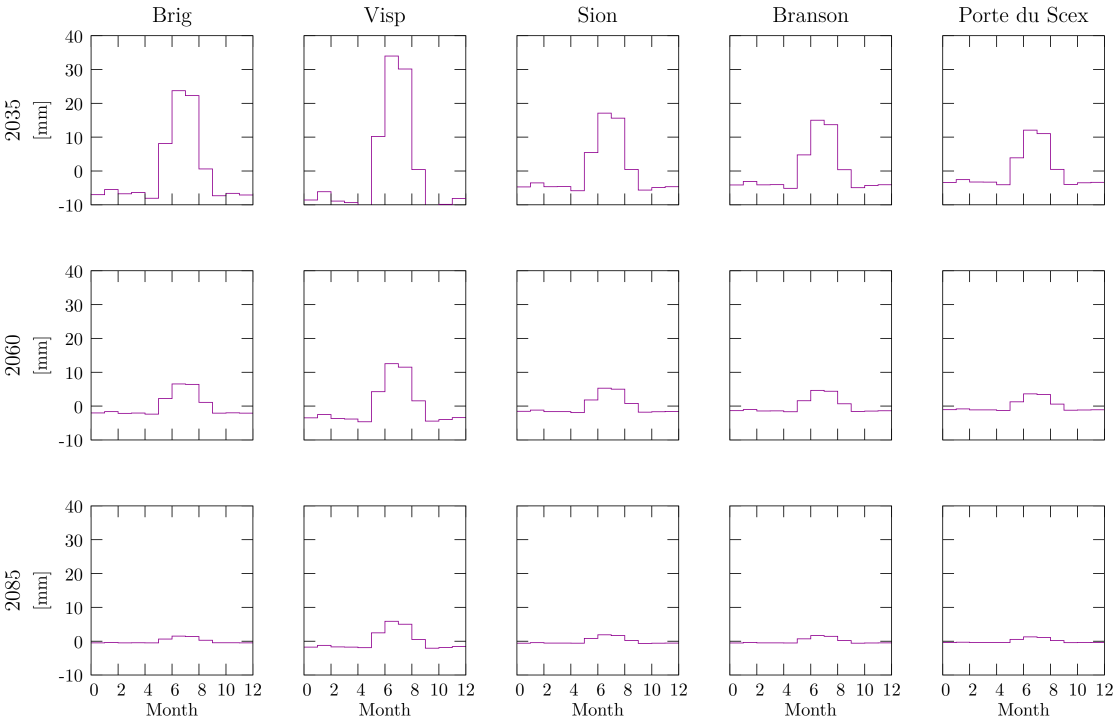


(b) Calculated water input per month to the subcatchments without (blue) and with (red) the effect of glacier storage. Seasonal snow cover of the catchment area is not taken into account.

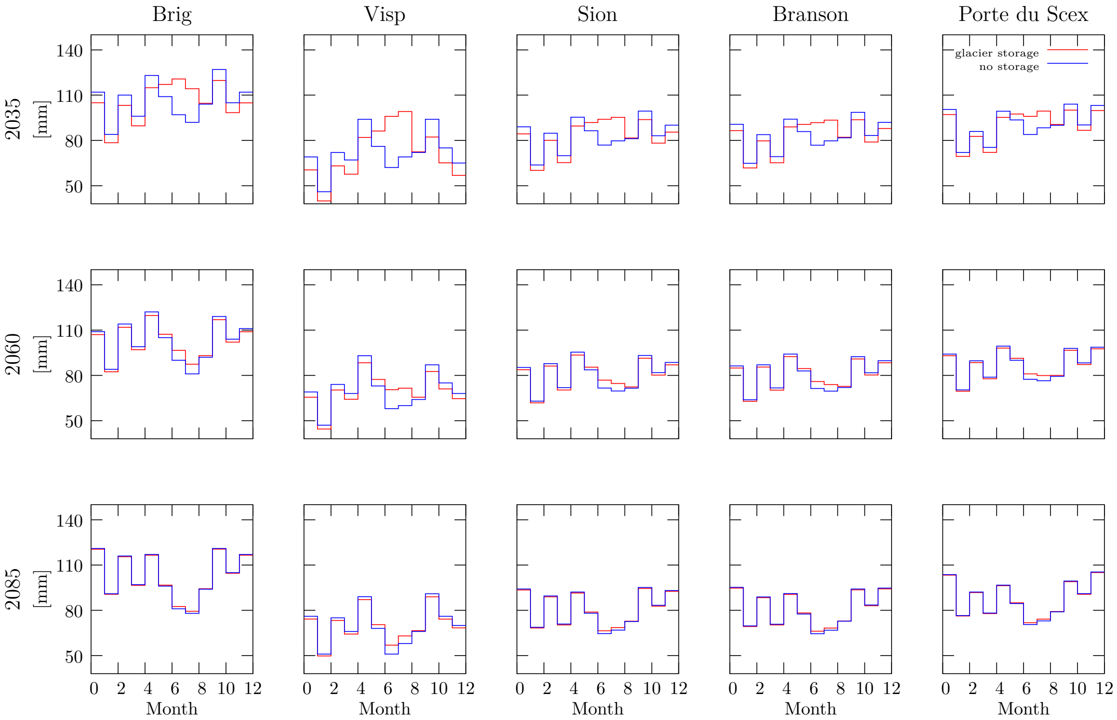


(c) Comparison of the specific water input with glacier storage (red) to the specific discharge calculated from official data (green).

Figure 4: Results obtained using the past climate conditions scenario and the current glacier extents.



(a) Change in monthly water input due to glacier storage for the three climate change scenarios and the five subcatchments.



(b) Calculated water input per month to the subcatchments without (blue) and with (red) the effect of glacier storage for the three climate change scenarios. Seasonal snow cover of the catchment area is not taken into account.

Figure 5: Results obtained for the three climate change scenarios (2035, 2060 and 2085).

4 Discussion

The results of this study are a first-order estimate. Thus they should give a general idea about the current and future contribution of glacier melt to the total runoff. However, the approach used has several sources of uncertainties.

As the approach assumes the glaciers to be in equilibrium with climate, the results do not take into account melt water from glacier volume loss due to global warming. This would lead to higher runoff values in periods when the mean annual glacier volume is decreasing.

Further, glacier mass loss due to sublimation from the glaciers as well as due to infiltration into groundwater are not taken into account.

The glacier data used are taken from the GLIMS database, which is near to complete in the study area. However, for practical reasons, only glaciers bigger than 5 ha are taken into account. The small glaciers which have been omitted represent only about 0.6 % of the total glaciated surface.

It is important to state that the results we present in chapter 3.2 are obtained from different temperature and precipitation data than the results in chapter 3.1. This means that their intercomparison difficult and needs to be done with care. In addition, there are much more uncertainties in the results for the climate change scenarios, in particular the expected glacier extents, which are obtained using very general approximations.

5 Conclusion

We have presented a general approach which allowed us to estimate the current and future contribution of seasonally delayed glacier runoff to the total water availability in the catchment of the Rhone river upstream of Lake Geneva. This seasonal delay is due to accumulation on to the ice surface during winter and ablation in summer months. The results state that currently the glacier runoff (in addition to direct water input) reaches up to 150 mm during the summer months in the highest lying subcatchments of the Rhone river. The further downstream we go, the lower this value becomes. Right upstream of Lake Geneva it is still around 75 mm.

Under the SRES A1B [IPCC, 2007] scenario, considerable decreases in the glacier contribution to runoff can be expected. Around the year 2035 the glacier runoff will still be around 20 to 30 mm in the highest lying catchments during summer and around 10 mm just upstream of Lake Geneva. This values further decrease for the 2060 and 2085 scenarios, where the glacier contributions become almost negligible compared to the direct input by precipitation.

With more accurate models of future glacier extents in the alps becoming available [Paul et al., 2007], one of the main uncertainties of this study could be alleviated and more accurate estimations of the future glacier contribution to runoff could be done. Data on population or on hydroelectric production could be taken into account in order to show the influence on society and economy of the decreasing contribution of glaciers to total runoff.

Acknowledgements

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