Modelling runoff in a Swiss glacierized catchment - Part II: daily discharge and glacier evolution in the Findelen basin in a progressively warmer climate

Uhlmann-Schneiter, Bastienne; Jordan, Frédéric; Beniston, Martin

How to cite

UHLMANN-SCHNEITER, Bastienne, JORDAN, Frédéric, BENISTON, Martin. Modelling runoff in a Swiss glacierized catchment - Part II: daily discharge and glacier evolution in the Findelen basin in a progressively warmer climate. In: International journal of climatology, 2013, vol. 33, n° 5, p. 1301–1307. doi: 10.1002/joc.3516

This publication URL: https://archive-ouverte.unige.ch/unige:21645
Publication DOI: 10.1002/joc.3516

INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. (2012)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3516

Modelling runoff in a Swiss glacierized catchment – Part II: daily discharge and glacier evolution in the Findelen basin in a progressively warmer climate

Bastienne Uhlmann,[a]* Frédéric Jordan[b] and Martin Beniston[a]
[a] *Climatic Change and Climate Impacts, University of Geneva, Carouge, GE, Switzerland*
[b] *E-dric.ch, Le Mont-sur-Lausanne, Switzerland*

ABSTRACT: In the context of global warming, hydrological regimes in mountain areas are likely to be modified and will therefore result in significant impacts to the supply mechanisms for hydropower and other end-uses of water, both in the mountains themselves and in the lowland regions downstream. The main objective here is to attempt a fine and continuous analysis of the impacts of such changes on runoff and glaciers in a largely ice-covered catchment in the Swiss Alps: the Findelen watershed. The simulated daily discharge values have been obtained with a semi-distributed hydrological model called Routing System 3 (RS3.0). A stochastic weather generator has been used to generate a 110 year sequence of meteorological input data – described in a companion article – that have been further perturbed in order to simulate a progressively warmer climate by the end of the century. The amplitude of atmospheric change is suggested by regional climate model simulations, under the A2 greenhouse-gas emissions scenario. Results show at first an increase of discharge (19.4% in about 60 years) due to the rapid melt of the glacier, followed by a large decrease in runoff at the end of the period (−28% from the beginning to the end of the studied timeframe), primarily due to the depletion of the solid water reservoir. The glacier is indeed projected to lose 91% of its surface area. In parallel, a seasonal shift in flow patterns is also observed: the discharge values are high earlier in spring due to advanced snow and ice melt, while the rest of the curve flattens out. Copyright © 2012 Royal Meteorological Society

KEY WORDS climate change; discharge; glacier; hydrological modelling; Alps

Received 2 December 2011; Revised 2 April 2012; Accepted 1 May 2012

1. Introduction

Switzerland is often considered as the water tower of Europe, as 56% of the Swiss electricity generation comes from hydraulic power plants, mostly located in the Alps (Swiss Federal Office of Energy, 2009). As a large part of precipitation is stored in the higher parts of the mountains in the form of snow and ice; water resources in this environment is very sensitive to climate variability and change (Beniston, 2000). Moreover, the role of dams and reservoirs as a mean of flood control will also be affected by atmospheric modifications (Beniston, 2010). It is therefore of prime importance to analyse the potential impacts of global warming on hydrological regimes in the Alps, since shifts in the seasonality of runoff and changes in discharge amount will have numerous implications for water management.

The topic of shifts in water regimes has been explored at international level, for instance by Jha *et al.* (2006) for the Mississippi River basin, or Hagg *et al.* (2007) for central Asia. In the Alps, potential changes in runoff in a warmer climate have also been analysed (Westaway, 2000; Middelkoop *et al.*, 2001; Etchevers *et al.*, 2002; Jasper *et al.*, 2004). The evolution of discharge in highly glacierized watershed areas related to climate warming has also been addressed in a few studies (e.g. Braun *et al.*, 2000; Huss *et al.*, 2008; Kobierska *et al.*, 2011). However, these works generally use a doubling of atmospheric CO_2 or linear shift forcing in weather data records for particular time snapshots (typically a mean of the 2071–2100 period) as a reference change of climate. Nevertheless, the day-to-day and year-to-year fluctuations in terms of meteorological variables can considerably influence glacier-fed runoff. This article aims therefore at investigating the evolution of water discharge for a warming climate at a higher temporal resolution and with a continuous simulation through to the end of the century.

Among the widely exploited and thus exposed watersheds in the Swiss Alps, this study focuses on one of the numerous highly glacierized sub-basins which constitute the Grande Dixence hydroelectric complex; the site of Findelen serves as a case study area. It is a particularly suitable catchment for such an analysis since the large ice-covered fraction of the area makes it very sensitive to atmospheric warming; indeed, in this region, temperatures have increased by over 1.5 °C since 1900 (Beniston, 2003).

---

*Correspondence to: B. Uhlmann, Climatic Change and Climate Impacts, University of Geneva, Carouge, GE, Switzerland.
E-mail: Bastienne.Uhlmann@gmail.com

A conceptual hydrological model named Routing System 3.0 (RS3.0) is used to simulate water discharge. The calibration of the model and a detailed analysis of the simulated discharge of RS3.0 in a stable climate have been presented in a companion article (Uhlmann *et al.*, 2012). In order to undertake future projections of the various components of the water cycle, stochastic input data, created by a random weather generator, have been perturbed with the so-called 'delta disturbance method' (discussed further in this article) to simulate climate change. This methodology enables an uninterrupted estimation of runoff throughout the century, as mid-term and long-term values can also have considerable impacts on the hydraulic energy supply system. It also provides an investigation of the distribution of runoff in the course of the year, of flow amount and of changes in ice melt contribution to total runoff. As the hydrological model takes into account changes in glacier mass, the reduction of the ice thickness and surface areas are examined as well.

2. Data and methods

The Findelen basin is situated in the southern part of the Canton of Valais in the Swiss Alps (Figure 1). Its surface measures 21.18 km^2 of which 73% are glacierized. Observed values of discharge at the outlet have been obtained directly from Grande Dixence SA for the period from 1982 to 1991. Temperatures and precipitation needed as input data for the hydrological model are provided by four neighbouring stations (Sion, Viège, Evolène and Zermatt) of the automatic network of the Swiss weather service, MeteoSwiss. A digital elevation model of the area with a resolution of 25 m (DHM25) has been made available by the Swiss Federal Office of Topography. The Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at ETH-Zurich provided also flow velocities estimations as well as a DHM25 of the bedrock, enabling the extractions of values for ice thicknesses for the years 1981 and 1990.

A stochastic weather generator (described by Perroud and Goyette, 2009; Uhlmann *et al.*, 2012) has been used to produce 110 year stochastic input of hourly temperatures (T_{sto}) and precipitation (P_{sto}) for the four meteorological stations. Both series are representative of the conditions recorded during the baseline climate period 1961–1990. In order to simulate future climate conditions, the stochastic datasets have then been perturbed with the delta disturbance method (López-Moreno *et al.*, 2008; Perroud and Goyette, 2009; Uhlmann *et al.*, 2009) from the median of the baseline climate period (1976) to the median of a so-called greenhouse climate period 2071–2100 (2086). It follows the amplitude of climate change simulated by one of the regional climate models (RCM) used in the context of the EU 'PRUDENCE' project (Christensen, 2005), the Danish HIRHAM model. The only scenario used here is the A2 scenario (IPCC, 2007), which assumes high levels of greenhouse-gas emissions and thus a strong climatic response. The HIRHAM RCM has shown skill in reproducing contemporary climate in the Alpine domain (Beniston *et al.*, 2007). It should be emphasized here that this article is not aimed at looking at inter-model variability in terms of climate projections; hence, the use of just one RCM as the base for the scenario climate data is justified, since we are here establishing a methodology for a case study and not a range of predictions. The delta disturbance method consists in calculating the difference between the values of a meteorological variable in a greenhouse climate and the baseline climate simulated by the RCM. These deltas are computed for grid points closest to the research area for each month and for each decile (10th percentiles) of their respective probability density distributions. Therefore, 10 individual values of delta are produced per month; they are linearly added to the stochastic sets of input data starting from 1976 to 2086. The advantage of this method is that, it enables to reproduce small daily variations of atmospheric conditions in a warmer climate for a specific and complex topography and that it accounts not only for changes in the mean but also in the other different parts of the probability density function. It retains a high level of refinement which would not be possible with a commonly used procedure, namely uniform and constant shifts in temperature and percentage changes in precipitation. The temperature deltas are within the limits of global average annual warming (2.0–5.4 °C for this scenario) published by the IPCC (2007). The precipitation differences have also been compared with the results of the averaged projected precipitation change of the PRUDENCE project (2007), showing an increase in wintertime precipitation (seasonal mean of 31%), a decrease in summertime precipitation (seasonal mean of −22%) and a slight increase in yearly precipitation (6%). The method can be described as follows for each weather station:

$$\Psi_{\mathrm{in},i} = \Psi_{\mathrm{sto},i} + \lambda\Delta_i \qquad (1)$$

where $\Psi_{\mathrm{in},i} \in [T_{\mathrm{in}}, P_{\mathrm{in}}]$ is the hourly meteorological parameters, $\Psi_{\mathrm{sto},i} \in [T_{\mathrm{sto}}, P_{\mathrm{sto}}]$ is the 110 year stochastic data. λ, an empirical scaling parameter, is set to 0 in 1976 and increases linearly to 1 in 2086, in order to reproduce

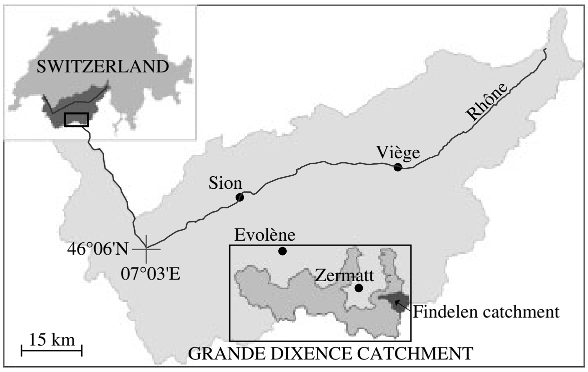

Figure 1. Study site in the southern part of the Canton of Valais in the Swiss Alps.

the evolution of the climate from the current to the future period. Δ_i is the monthly differences between the simulated future and baseline HIRHAM values. It has to be noted that the precipitation deltas have been applied only to the hours where precipitation occurred in the stochastic data set, assuming a stationary behaviour in number of wet days.

The numerical hydrological model used in this study, RS3.0, has been made available by the engineering firm E-dric.ch (www.e-dric.ch). It is based on object-oriented programming and consists of snow, glacier, infiltration and runoff submodels (Hernández *et al*., 2007; Jordan, 2007). It is an extension of the GSM−SOCONT Model (Schaefli *et al*., 2005). The watershed is separated into sub-basins, which are in turn divided into glacial and non-glacial elevation bands that can be parameterized individually. RS3.0 has proved to be successful in modelling water discharge (Schaefli, 2005; Schaefli *et al*., 2005; Jordan *et al*., 2008; Uhlmann *et al*., 2012). It has been calibrated using observed data for the hydrological years 1982−1983 and 1985−1986 and then validated over the years 1987−1992. The ice velocity of the glacier and the ice degree-day factor are the only calibration parameters in the model that have been adapted empirically and linearly every 20 years to the end of the century in order to fit the evolution of the glacier morphology and the projected increase of debris cover as precisely as possible. Model and calibration are more rigorously described in the companion article (Uhlmann *et al*., 2012).

3. Results and discussion

Simulations with RS3.0 have been undertaken with perturbed input data from 1976 to 2086, using a daily time step. The aim is to give a comprehensive view throughout the 21st century of 110 years of variations in discharge, changes in seasonality and flow duration as well as modifications in glacier contribution to total runoff, in ice surface area and thickness.

Figure 2 illustrates the 110 years of runoff through to the end of the century with daily discharge values in grey and averaged yearly discharge values in black. The graph can be divided into three main phases, corresponding to the visual changes in trend of the average smoothed yearly discharge. During phase one, which lasts more than 55 years, runoff first exhibits a rather stationary trend for a few years where λ remains weak. It highlights the attempt of the glacier – which is the main driver for runoff in this catchment – to reach an equilibrium with an almost steady state climate (Benn and Lehmkuhl, 2000) by modulating changes of ice thickness and maintaining fairly constant its water discharge. The slight climate forcing during this first years, however, enhances sufficiently melting processes to prevent a reduction of runoff, a process that would in fact occur if climate were to remain unchanged as shown by Uhlmann *et al.* (2012). From about the hydrological year 1980−1981 and for more than 50 years onwards, the average yearly runoff shows a more pronounced increasing trend. The mean annual discharge of decade 6 rises by 19.4% compared with the mean annual discharge of decade 1. During this time, discharge values are dominated by the glacier melt which is responding to progressively higher temperatures, thereby resulting in much more water at the outlet. The slight projected increase in precipitation by the RCM also contributes to this additional amount of water. In this phase, variations in the daily weather largely govern variations in runoff. As a consequence, it induces climate internal variability and discharge displays large fluctuations from one day to another. In phase two, runoff declines vary regularly (−14% between decades 6 and 10). This decrease can be attributed to the fact that the size of the glacier is unable to act as the primary

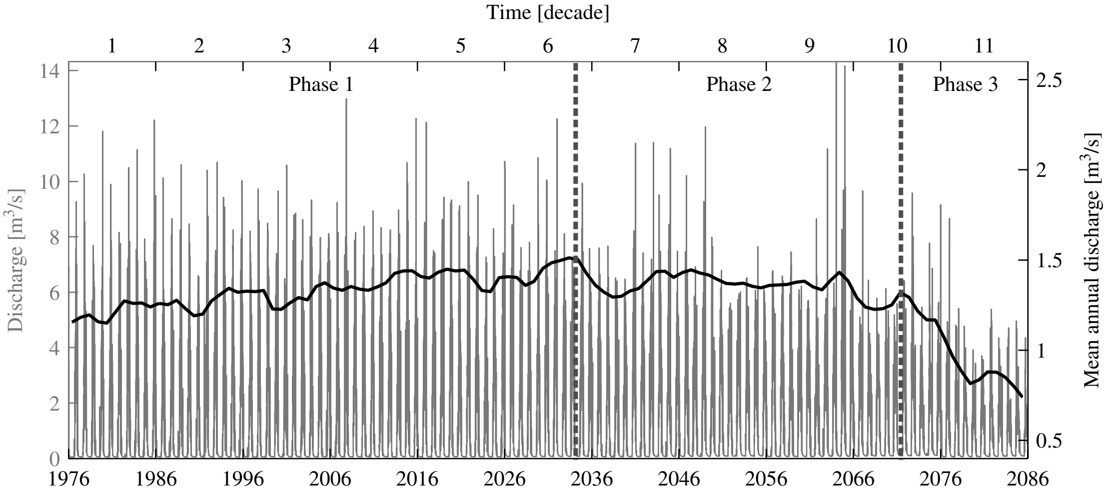

Figure 2. Discharge evolution for the period 1976−2086 in a progressively warmer climate: in grey, daily discharge; in black, smoothed averaged yearly discharge. The graph has been divided into three phases: phase 1, increased discharge period; phase 2, decreased discharge period; phase 3, greenhouse climate period.

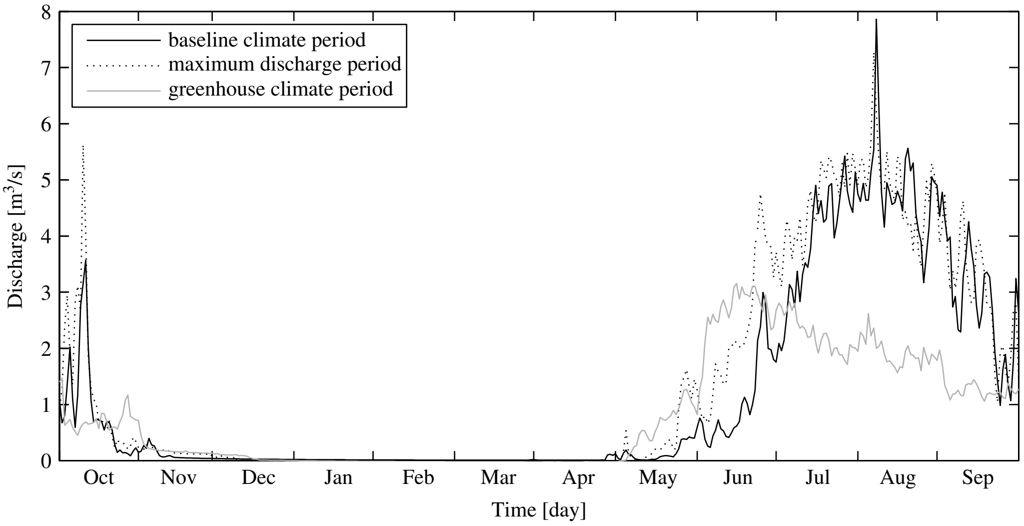

Figure 3. Daily discharge averaged on a decade representative of the baseline climate period (decade 1), the maximum discharge period (decade 6) and the greenhouse climate period (decade 11).

control on water flows anymore. During phase three, the decrease in runoff is dramatic (−30% between decades 10 and 11), showing the almost total withdrawal of the glacier's influence. From decades 1 to 11, runoff at the outlet of the catchment has finally decreased by 28%. The next potential phase would probably show an attempt of the system to reach a new equilibrium at a lower level of discharge. The precipitation regime is gradually driving the amount of discharge, exceeding the influence of the glacier on runoff.

In Figure 3, a hydrological year of daily discharge averaged on a decade illustrates shifts in seasonality representative for the baseline climate period (decade 1), the maximum discharge period (decade 6) and the greenhouse climate period (decade 11). For the baseline climate period, no runoff is modelled in winter, while the peak flows occur in summer. For the maximum discharge period, the flow of water is higher throughout almost the entire year, with the same amplitude of day-to-day variation compared with the first period (standard-deviation of 1.8 and 1.9, respectively). During spring, runoff is 1–2 m^3 s^{-1} larger, indicating that the snow is melting earlier and more rapidly. The melt of the glacier from the end of May to the end of July induces generally larger values of discharge compared with the baseline climate period. In addition, the low-water flows occur later in the season. During the greenhouse climate period, the discharge is still high from the end of May to the end of June due primarily to the snow melt, while the rest of the curve has flattened out because of the reduced input of ice melt. The average yearly discharge represents about 60% of that of the maximum period. The day-to-day variation in runoff has been largely reduced as well (standard deviation of 0.9), reinforcing the idea that water available in the catchment has become scarce, therefore attenuating the possible contrasts from one day to another. In addition, low-water flows more rarely reach the null value during winter contrary to what they do under current conditions, which denotes that ice and snow melt longer throughout the year in the warmer climate. This also contributes to the levelling off of runoff, since the range of possible daily values is reduced. The annual cycle of runoff in this watershed is therefore transformed from an ice melt dominated regime to a more snow melt and pluvial one.

Concerning the discharge amount, the differences between the periods are also pronounced. The flow duration curves which show the percentage of time that a given flow rate is equalled or exceeded are represented in Figure 4 for the same periods as those illustrated in Figure 3. Flows during the maximum discharge period are generally higher by about 1 m^3 s^{-1} for 5–50% of the time, consequently showing a large increase in runoff for high and mid-range flows compared with the baseline climate period. However, the parts of the curves corresponding to extreme high values (the first 5% of the time) are very similar. This indicates that the additional ice melt of the maximum discharge period does not necessarily imply more exceptional discharge values but increases the frequency of mid-range values. The curves of the low-range flows are very close as well. Again, the curve corresponding to the greenhouse climate period is a much smoother one, with maximum values representing generally half of the baseline climate ones. In contrast, mid-range and low flows exhibit somewhat higher values. This can be explained by an enhanced potential for ice and snow melt in a warming climate as well as an increase in precipitation. By comparing the curves for the baseline climate and for the greenhouse climate, it is clear that high flows follow opposite trends to low flows: strong discharge will occur less frequently, while the period of null-water flows will be shortened as there will be more fall and winter runoff.

The repercussions of climate change on ice melt contribution to total runoff can be further investigated through RS3.0. In Figure 5(a), the ice melt runoff for a mean

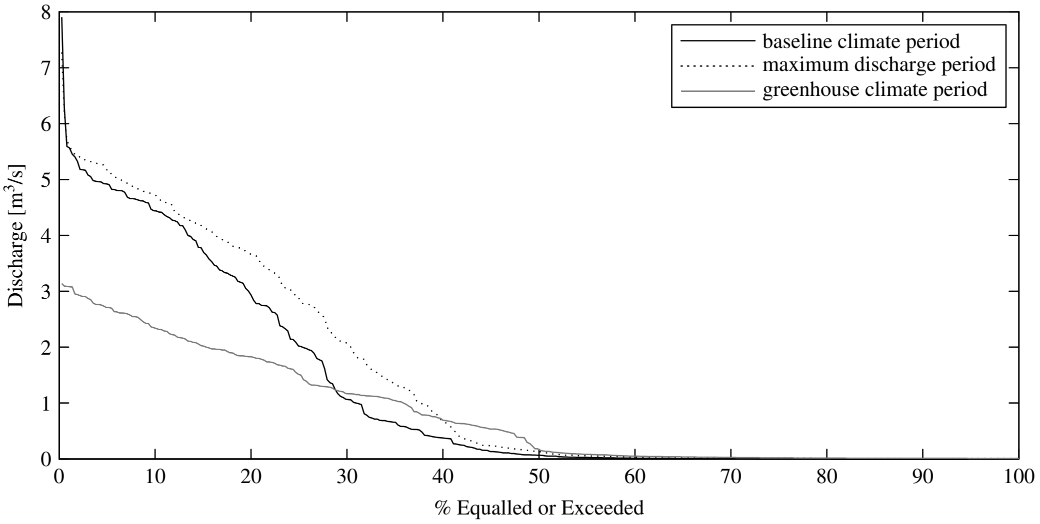

Figure 4. Flow duration curves averaged on a decade representative of the baseline climate period (decade 1), the maximum discharge period (decade 6) and the greenhouse climate period (decade 11).

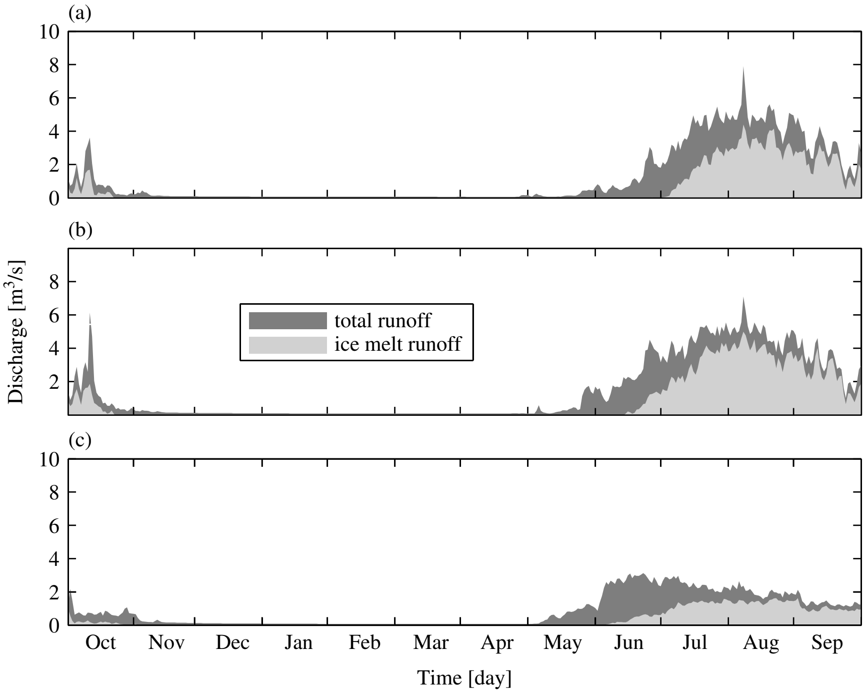

Figure 5. Evolution of the contribution of ice melt runoff (light grey) to total runoff (dark grey) during one hydrological year. Runoff is averaged on a decade representative of the baseline climate period (decade 1, graph a), the maximum discharge period (decade 6, graph b) and the greenhouse climate period (decade 11, graph c).

hydrological year of the baseline climate period corresponds to 27% of total runoff. The highest proportion of ice melt flows takes place in the fall season. During the maximum discharge period (Figure 5(b)), the yearly contribution of ice melt water increases up to 46% in average and the largest percentages of ice flows are observed not only in fall but also by mid-summer. For example in August, the contribution of ice melt discharge is 10% higher during this period than it is during the baseline climate period. Concerning the greenhouse climate period (Figure 5(c)), the starting point of the ice melt flow is also located at the beginning of June but the glacial contribution to total runoff (35%) is not the predominant one anymore. An earlier onset by 27 d in June of glacial runoff is projected for the greenhouse climate period as well.

Figure 6 highlights the fact that glaciers are among the most sensitive and visible expressions of climate change. It shows the evolution of the glacier surface, as well as the six successive glacial elevation bands of the largest part of Findelen Glacier, classified by ascending order of altitude. In terms of the total glacier surface area, a continuous glacier retreat can be observed throughout the century. From the beginning to the end of the simulation,

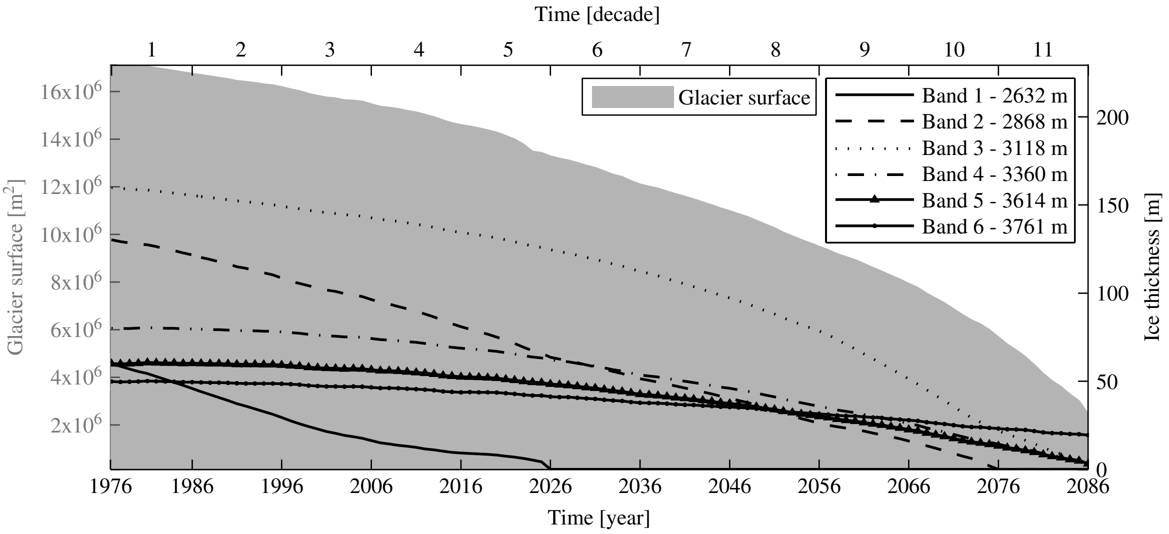

Figure 6. Evolution of total glacier surface and evolution of ice thickness from 1976 to 2086 for six chosen glacial bands corresponding to the main part of the Findelen Glacier, classified by ascending order of altitude. The mean elevation of each band is given in the legend.

the glacier has lost 91% of its surface. The decrease of the ice area accelerates during the last two decades, when the warming climate begins to take a serious grip on processes while at the same time the amount of ice still remains significant.

Among the six chosen elevation bands of the watershed presented in Figure 6, the first one shows a very rapid decline. Its modest thickness and its relatively low altitude make it more vulnerable to a warmer climate. Again, a tailing off of the decrease in ice thickness is observed when the band has almost disappeared, indicating that the lack of ice volume decelerates the glacier flux. Bands 2, 3 and 4 follow the same decreasing trend but the tailing off is less obvious, probably because they are much larger and the glacier velocity can be maintained despite the reduction of thickness. Bands 5 and 6 are the only ones that show a slight ice expansion or stable level of ice thickness during the first decades. Because of their high altitude, and the fact that the accumulation of precipitation is expected to increase in an atmospheric environment where temperatures will remain below the freezing point even in a warmer climate, the ice thickness can actually increase or remain constant. Rapidly, however, the increasing trend are reversed; because the lower bands are narrowing rapidly, the entire glacier dynamics will be altered, even at high elevations where a warmer climate does not normally have any direct impact on ice melt processes.

For the end of the century, these findings are consistent with previous studies in various Swiss glacierized basins (e.g. Horton *et al.*, 2006; Schaefli *et al.*, 2007; Huss *et al.*, 2008; Kobierska *et al.*, 2011) reporting shifts in seasonality, decrease in glacier contribution and in total runoff. In this perspective, the present analysis can be seen as representative for high mountain catchment areas with similar characteristics. Such methodological approach has, however, the advantage of enabling a precise and continuous quantification of glacier-fed runoff in a warming climate that could be applied in other ice-covered regions.

5. Conclusions

A numerical hydrological model has been used with a long time series of temperature and precipitation input data to simulate continuously the potential future discharge of a highly glacierized catchment in the Swiss Alps in a progressively warmer climate. The obtained results show first an increase in runoff with a maximum level of discharge during the years 2026–2036, followed by a large decrease in discharge where changes in climate are much more significant. From the first decade of the studied timeframe to the last one, discharge at the outlet generally decreases by 28%, whereas the contribution of ice melt to total runoff is not the predominant one anymore. The changes in the melt timing and amount of the Findelen Glacier remain the dominant factor that governs flow amount: it first amplifies the discharge and generates shifts in seasonality. Then the fact that the glacier loses 91% of its surface by the end of the century leads the annual cycle of runoff to a nivo-pluvial dominated regime.

It should be noted here, that the SRES A2 scenario used for this study leads to one of the greatest responses in climate projected by the IPCC. One should therefore keep in mind that the runoff trends simulated here depict an extreme outcome of climate change. Moreover, as mentioned earlier in this article, only the results of the HIRHAM RCM have been used. A comparison with other scenarios and other models would provide a range of possible outcomes not necessarily as ‘pessimistic’ as the one described here. However, the methodology described in this article remains simple to implement and the findings give a comprehensive insight of the evolution of discharge throughout the century. A future step would be to open up the present methodology to the entire watershed of the Grande Dixence and to investigate the economic and energy-relevant impacts of climate change on this catchment area.

Changes in discharge amount will have important indirect impacts on the Grande Dixence catchment area as a whole. The consequences will be first positive for hydroelectric potential, as more water will be made available for energy production. Shifts in seasonality and peak discharge may imply, however, rethinking the management and operation of the hydropower infrastructure. Furthermore, the additional melt and rain water in the environment may also require reviews to flood control procedures. However, at the end of the analysed timeframe, the flattening and decrease of the discharge curve will have negative repercussions for this exploited watershed, since water will become scarcer, despite a projected slight increase in precipitation. Water shortages could even become problematic, especially during hot and dry summers, as the glacier melt water will no longer be able to sustain discharge. As a result, hydropower utilities will need to consider a contrasted future composed of challenging economic issues where adaptation measures will be inevitable.

Acknowledgements

This work would not have been possible without the help of Grande Dixence SA and Javier Garcia Hernandez from the EPFL for providing meteorological and runoff data, of Daniel Farinotti and Martin Funk for glacier data and of E-dric.ch Sàrl for making the hydrological model available. Part of this work is of relevance to the EU-FP7 'ACQWA' project under contract number 212250 with the European Commission.

References

Beniston M. 2000. *Environmental Change in Mountains and Uplands*. Arnold/Hodder and Stoughton, Chapman and Hall Publishers, Oxford University Press: London, UK, New York, USA, 192.

Beniston M. 2003. Climatic change in mountain regions: a review of possible impacts. *Climatic Change* **59**: 5–31.

Beniston M. 2010. Impacts of climatic change on water and associated economic activities in the Swiss Alps. *Journal of Hydrology*. DOI: 10.1016/j.jhydrol.2010.06.046 (in press).

Beniston M, Stephenson DB, Christensen OB, Ferro CAT, Frei C, Goyette S, Halsnaes K, Holt T, Jylhä K, Koffi B, Palutikoff J, Schöll R, Semmler T, Woth K. 2007. Future extreme events in European climate; an exploration of regional climate model projections. *Climatic Change* **81**: 71–95.

Benn DI, Lehmkuhl F. 2000. Mass balance and equilibrium-line altitudes of glaciers in high-mountain environments. *Quaternary International* **65–66**: 15–29.

Braun LN, Weber M, Schulz M. 2000. Consequences of climate change for runoff from Alpine regions. *Annals of Glaciology* **31**: 19–25.

Christensen JH. 2005. *Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects (PRUDENCE)*. Final Report. Jens Hesselbjerg Christensen: Copenhagen, 269.

Etchevers P, Golaz C, Habets F, Noihan J. 2002. Impact of a climate change on the Rhone river catchment hydrology. *Journal of Geophysical Research* **107**(D16): 6-1–6-18.

Hagg W, Braun LN, Kuhn M, Nesgaard TI. 2007. Modelling of hydrological response to climate change in glacierized Central Asian catchments. *Journal of Hydrology* **332**: 40–53.

Hernández JG, Jordan F, Dubois J, Boillat J-L. 2007. In *Routing System II – Flow Modelling in Hydraulic Systems*, Communication 32, Schleiss A (ed). Laboratory of Hydraulic Constructions, EPFL: Lausanne, Switzerland, 70.

Horton P, Schaefli B, Mezghani A, Hingray B, Musy A. 2006. Assessment of climate-change impacts on alpine discharge regimes with climate model uncertainty. *Hydrological Processes* **20**: 2091–2109.

Huss M, Farinotti D, Bauder A, Funk M. 2008. Modelling runoff from highly glacierized alpine drainage basins in a changing climate. *Hydrological Processes* **22**: 3888–3902.

IPCC. 2007. *Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, UK, 946.

Jasper K, Calanca P, Gyalistras D, Fuhrer J. 2004. Differential impacts of climate change on the hydrology of two alpine river basins. *Climate Research* **26**: 113–129.

Jha M, Arnold JG, Gassman PW, Giorgi F, Gu RR. 2006. Climate change sensitivity assessment on upper Mississippi River basin streamflows using SWAT. *Journal of the American Water Resources Association* **42**(4): 997–1015.

Jordan F. 2007. *Modèle de Prévision et de Gestion des Crues – Optimisation des Opérations des Aménagements Hydroélectriques à Accumulation Pour la Réduction des Débits de Crue*, PhD thesis, School of Architecture, Civil and Environmental Engineering – Civil Engineering Section, EPFL, Lausanne, Switzerland, 270.

Jordan F, Hernández JG, Dubois J, Boillat J-L. 2008. In *MINERVE: Modélisation des Intempéries de Nature Extrême du Rhône Valaisan et de Leurs Effets*, Communication 38, Schleiss A (ed). Laboratory of Hydraulic Constructions, EPFL: Lausanne, Switzerland, 112.

Kobierska F, Jonas T, Magnusson J, Zappa M, Bavay M, Bosshard T, Paul F, Bernasconi SM. 2011. Climate change effects on snow melt and discharge of a partly glacierized watershed in Central Switzerland (SoilTrec Critical Zone Observatory). *Applied Geochemistry* **26**: 60–62.

López-Moreno JI, Goyette S, Beniston M, Alvera B. 2008. Sensitivity of the snow energy balance to climatic changes: prediction of snowpack in the Pyrenees in the 21st century. *Climate Research* **36**: 203–217.

Middelkoop H, Daamen K, Gellens D, Grabs W, Kwadijk JCJ, Lang H, Parmet BWAH, Schädler B, Schulla J, Wilke K. 2001. Impact of climate change on hydrological regimes and water resources management in the Rhine basin. *Climatic Change* **49**: 105–128.

Perroud M, Goyette S. 2009. Impacts of a warmer climate on Lake Geneva water temperature profiles. *Boreal Environment Research* **15**: 255–278.

PRUDENCE. 2007. Special Issue dedicated to the EU-FP5 "PRUDENCE" project. *Climatic Change* **81**: 1–322.

Schaefli B. 2005. *Quantification of Modelling Uncertainties in Climate Change Impact Studies on Water Resources: Application to a Glacierfed Hydropower Production System in the Swiss Alps*, PhD thesis, Laboratory of Hydrology and Land Improvement, EPFL, Lausanne, Switzerland, 219.

Schaefli B, Hingray B, Musy A. 2007. Climate change and hydropower production in the Swiss Alps: quantification of potential impacts and related modelling uncertainties. *Hydrology and Earth System Sciences* **11**(3): 1191–1205.

Schaefli B, Hingray B, Niggli M, Musy A. 2005. A conceptual glacio-hydrological model for high mountainous catchments. *Hydrology and Earth System Sciences* **9**: 95–109.

Swiss Federal Office of Energy. 2009. *Energy Consumption in Switzerland 2009*. Extract from the Swiss Energy Statistics 2009. SFOE: Bern, Switzerland, 72.

Uhlmann B, Goyette S, Beniston M. 2009. Sensitivity analysis of snow patterns in Swiss ski resorts to shifts in temperature, precipitation and humidity under condition of climate change. *International Journal of Climatology* **29**: 1048–1055, DOI: 10.1002/joc.1786.

Uhlmann B, Jordan F, Beniston M. 2012. Modelling runoff in a Swiss glacierized catchment – Part I: methodology and application in the Findelen basin under a long-lasting stable climate. *International Journal of Climatology* DOI: 10.1002/joc.3501.

Westaway R. 2000. Modelling the potential effects of climate change on the Grande Dixence hydro-electricity scheme, Switzerland. *Water and Environment Journal* **14**: 179–185.