Dams and Reservoirs under Changing Challenges – Schleiss & Boes (Eds)
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Optimized and adapted hydropower management considering glacier shrinkage scenarios in the Swiss Alps

S. Terrier, F. Jordan & A.J. Schleiss
Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Hydraulic Constructions (LCH), Lausanne, Switzerland

W. Haeberli, C. Huggel & M. Künzler
Geography Department, University of Zurich, Switzerland

ABSTRACT: Global warming is an alarming reality and likely leads to an increase of multiple pressures on socio-economic systems. However, in high-mountain regions it might also become an opportunity to adapt existing hydropower schemes and future projects to this new reality. In the Alps, the melting of glaciers first produces over the near future an increase of the average annual discharge depending on glacier and catchment characteristics, especially during the summer season. Nevertheless after a certain time, significant decrease of runoff related to glacier melting must be considered for hydropower management. Moreover, the melted glaciers free new alpine valley areas, which have a potential for the construction of new dams and reservoirs.

The opportunity to build new dams and hydropower plants downstream of retreating glaciers is studied systematically in Switzerland within the framework of the National Research Program on Sustainable Water Management (NRP61) under the project “New lakes in deglaciating high-mountain areas: climate-related development and challenges for sustainable use (NELAK)”. The developed methodology is based on several prediction models. Regional climate models provide spatially distributed rainfall and temperature scenarios for the next 50 years. The RS3.0 CLIMATE rainfall-runoff hydrological model computes the glacier evolution, the river discharge at the outlet of the catchment area as well as the hydropower production of the new lakes. Another model (GlabTop) is used to predict the future topography and geomorphology underneath the melting glaciers, in order to define the optimal locations of the future dams and reservoirs.

As a case study the Corbassière glacier near the Mauvoisin reservoir in Valais is presented. The opportunity of the construction of a new dam and a hydropower plant is studied, as well as its economic benefit and its impacts on the environment. The result of the case study provides a basis to assess the potential of investing in such projects to ensure the Swiss hydroelectricity production also in future.

1 INTRODUCTION

With the climate change, the mean temperature is rising globally and also in the Alps. One of the most visible consequences of this change is strong glacier shrinkage (UNEP 2007, Zemp et al. 2008).

Due to glacier retreat, each year, new glacier-free areas are revealing a topography carved by glaciers. In some locations, where a depression was present under the glacier, new lakes may be appearing with various sizes and depths. Sometimes they may form on unstable geology and be impounded by moraine dams, and thus representing a threat for the people living downstream (Clague & Evans 2000, Haeberli et al. 2001, 2010, Huggel et al. 2004). However, they might also be an opportunity for hydropower production.

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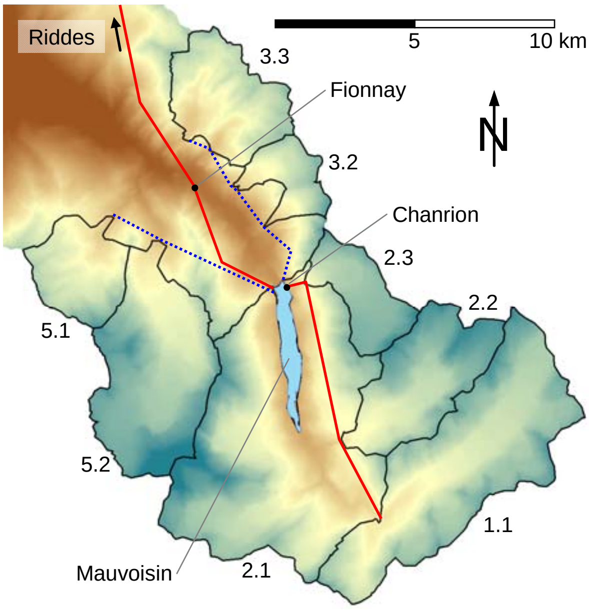
A second impact is a change in the hydrological regime of the Alpine rivers. As the glaciers are readjusting to the rising temperature, they may provide a higher discharge during the summer for a limited number of years and depending on glacier size, hypsography and catchment characteristics. However, this process is probably only temporary, as the glaciers either find a new equilibrium state or disappear. As a consequence the hydrological regime and the annual inflow volume will change, causing an important impact on the existing hydropower schemes.

In this contribution, the evolution of the glaciered catchment area of the *Forces Motrices de Mauvoisin* (FMM) hydropower scheme is studied. More precisely, an important depression currently lies under Corbassière Glacier and in the future could represent an opportunity to adapt the hydroelectric scheme to the changing situation.

2 DESCRIPTION OF THE UPPER BAGNES VALLEY BASIN

2.1 *Forces Motrices de Mauvoisin (FMM) hydropower scheme*

The FMM scheme lies in the upper Bagnes Valley in Valais, Switzerland. It is designed around the Mauvoisin reservoir (204 hm^3) which was created by the construction of the Mauvoisin arch dam (height of 250m) on the Dranse de Bagnes River (Fig. 1).



No	Name	Surface [km^2]	Glaciated
1.1	Otemma	35.2	47.5%
2.1	Mont Durand	52.5	21.2%
2.2	Brenay	16.3	52.8%
2.3	Giétro	8.2	66.9%
	Dranse	112.2	37.4%
3.2	Louvie	5.5	1.9%
3.3	Crêt	13.6	2.7%
	Right collector	19.1	2.4%
5.1	Sery	10.0	13.6%
5.2	Corbassière	25.1	71.6%
	Left collector	35.1	55.1%
	Total	166.4	37.1%

Figure 1. Catchment areas and FMM hydroelectric scheme.

The natural catchment area of the reservoir is 112 km^2. Additional water is transferred from intakes on the left and right bank of the Bagnes valley, increasing the contributive area by respectively 35 and 19 km^2. The elevation of the catchment area ranges from 1976 m a.s.l. (Mauvoisin dam crest level) to 4315 m a.s.l. 37.1 % of the total catchment area of 166 km^2 is covered by glaciers. Therefore the hydrologic regime is glacial.

The average annual inflow in the Mauvoisin reservoir reached 280 hm^3 in the recent years. 76 % of this inflow is produced by the natural catchment area. The remaining part is brought by the left and right side tunnels with a proportion of 18 % and 6 % respectively. As 90 % of the inflow occurs in the summer months and the peak electricity demand is in winter, the 204 hm^3 capacity of the Mauvoisin reservoir is used as a seasonal storage.

The total head between the Mauvoisin reservoir and the tailrace in the Rhone River varies between 1498 and 1361 m, and is divided into two different stages. The two corresponding power plants are Fionnay (138 MW) and Riddes (225 MW). A smaller run-of-river power plant (Chanrion 28 MW) was built upstream of the Mauvoisin reservoir to produce energy with a part of the natural inflows coming from the right side water transfer tunnel.

2.2 *Corbassière Glacier*

The Corbassière Glacier is the 5th longest glacier in Switzerland with a length of 9.8 km and an area of 17.4 km^2. It is located on the west side of Mauvoisin reservoir and is part of the left bank tunnel.

An analysis of the topography currently covered by glaciers shows that an important depression is present under the tongue of the Corbassière Glacier. The methodology to assess the glacier bed topography is based on a model estimating the glacier thickness using an inverse ice flow law together with a shallow ice approximation (Haeberli & Hoelzle 1995; Linsbauer et al. 2009). Since the basic parameter that influences ice thickness is surface slope, the method explores the variability of glacier thickness for glacier parts with variable surface inclination in a spatially explicit way. Subtracting the ice thickness grid from the input DEM yields a DEM without glaciers. We consider the overdeepenings (depressions) in the modeled glacier beds as potential sites for new glacier lakes. We furthermore use a simplified model of future glacier retreat (Paul et al. 2007) to roughly classify the potential lakes by their mean depth and their time period of appearance. The likelihood of actual lake formation is probably high but currently remains difficult to assess safely due to a number of uncertainties with respect to future drainage patterns.

Based on this method, we assess that a lake of 0.64 km^2 might appear at 2500 m a.s.l. Having a depth of 200 m, the estimated new lake volume is 51.6 hm^3, which is about 25 % of the Mauvoisin reservoir. This potential depression is currently located 2 km upstream of the tongue's end and underneath about 120 m of ice.

2.3 *Potential future hydroelectric projects*

In the 1990's, the "Mauvoisin II" project was developed. The idea was to build a new underground power house of 550 MW in parallel of the existing two stages system directly from the Mauvoisin reservoir to Riddes. With this new plant, the total FMM installed capacity could have been increased from 390 to 940 MW and the energy production could be concentrated on a few peak hours per day. For the time being, this project was not followed up for economical reasons, but could be reactivated in future.

With the creation of a new lake at Corbassière due to glacier retreat, a new pumped-storage scheme of 500 MW could be installed between this lake and the Mauvoisin reservoir (Figs 2-3). As these two lakes have a significant volume of 204 hm^3 and 51.6 hm^3 respectively, this high capacity power house can be used to regulate the electricity grid at hours of peak demand. The energy produced by renewable sources such as a wind power during low demand could be pumped in order to transfer it to peak energy. Based on the topographic assessment, the new reservoir Corbassière would need the construction of an earth fill dam (eventually concrete faced rockfill dam) of about 40 m height.

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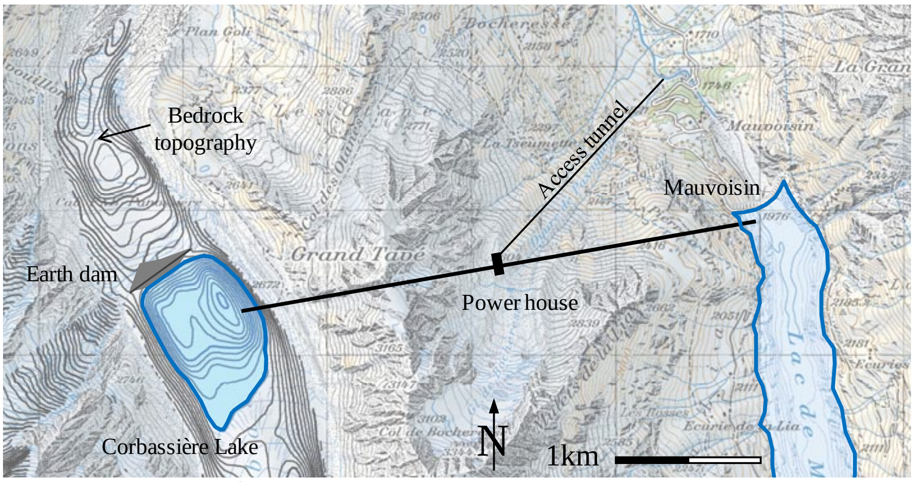

Figure 2. Plan view of the new lake Corbassière and pumped-storage scheme.

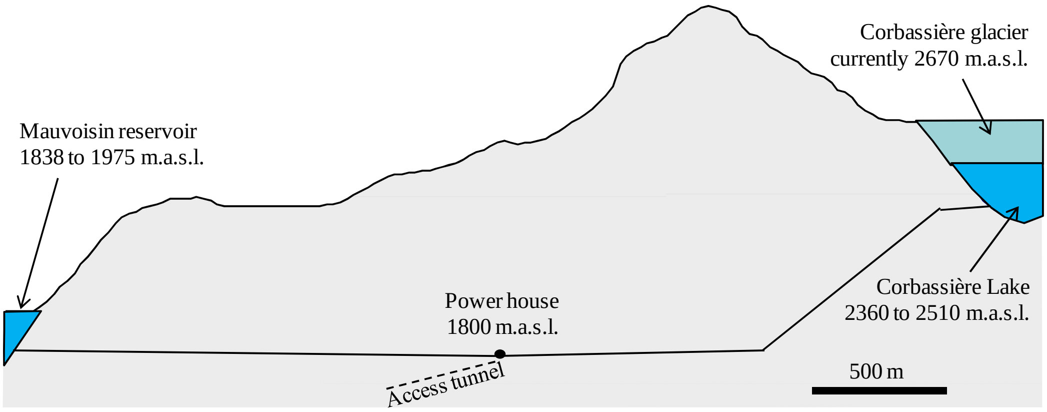

Figure 3. Longitudinal profile of the pumped-storage scheme project Corbassière.

3 MODELLING

3.1 *RS3.0 Software*

3.1.1 *Rainfall-runoff*

The rainfall-runoff model used in the RS3.0 hydrological software (Keller 2009, Garcia et al. 2007) is based on GSM-SOCONT (Glacier-Snow Melt Soil CONTribution). This semi-distributed conceptual model is able to consider numerous hydrological processes determining the river flows (Schäfli et al. 2005, Jordan 2007). The basins are subdivided into 300 m elevation bands in order to take into account the influence of the temperature evolution with altitude. When necessary, the elevation bands include a glacier melt model in addition to the soil infiltration model.

The considered hydrological processes in the GSM-SOCONT model are the spatial interpolation of the precipitation and temperature, the evapo-transpiration, the snow melt, the glacier melt, the soil infiltration, the surface runoff and the river routing, as well as the hydraulic transfers and storage functions due to the hydropower plants and natural lakes.

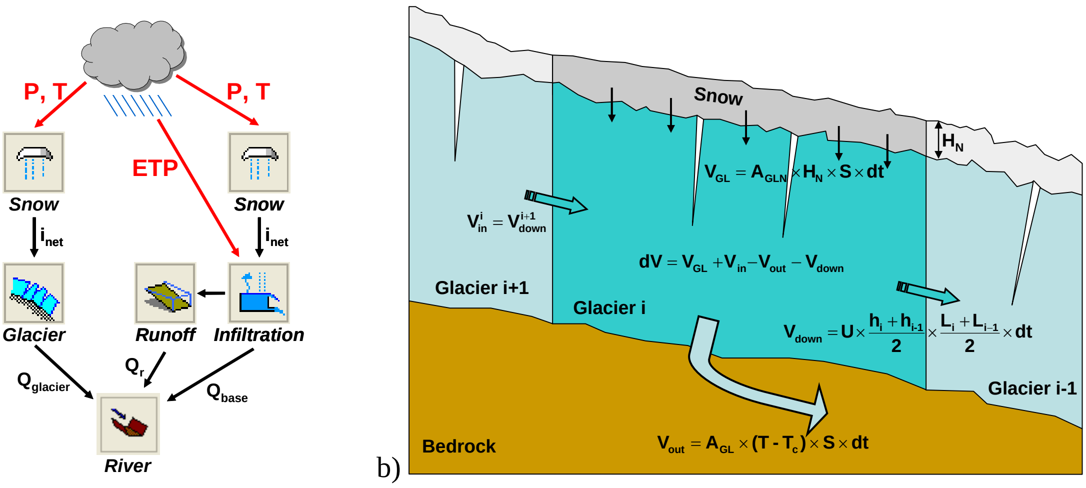

Figure 4. RS3.0 software : a) Structure of the hydrological model, example of a basin with one glacier (left) and one non-glacier (right) elevation zone ; b) Functioning and equations of the glacier model.

3.1.2 *Glacier*

The purpose of the glacier melt model is to simulate the glacier evolution and the discharge at its outlet over a long period. The focus is more on the precision of the discharge than on the glacier evolution (surface and height modifications during time).

In each glacier elevation band, the glacier is modeled as a simplified rectangular cuboid with a surface S and a thickness h (Fig. 4b). The melt V_{out} depends on a melt parameter A_{GL}, on the temperature and on the surface. If a snow height H_N is present above the glacier, it gradually transforms into ice (V_{GL}) depending on a controlling parameter A_{GLN}. The ice flow between the elevation bands V_{down} is taken into account with a flowing speed U and the glacier width L. After each time step, the volume balance dV is either added or subtracted to the ice volume.

When the volume changes, part of it is transformed to glacier height, the other contribution to the glacier area. The parameters A_{GL} and A_{GLN} are calibrated for an observed reference period (see section 3.2).

3.1.3 *Energy production algorithm*

An energy production algorithm is used to simulate the hydropower plants. To perform an optimization of the income, it takes into account the hourly electricity prices and reservoir target curve to simulate the seasonal level variations. At each time step, depending on these parameters and the reservoir filling percentage, the algorithm chooses if the power plant is turbining or not (Jordan & al., 2010).

3.2 *Calibration*

The model was calibrated in order to reproduce the measured discharges as close as possible. For the period from October 2002 to October 2004, Figure 5 compares the observed and simulated discharge in the left bank collector which is mainly fed by the Corbassière sub-basin.

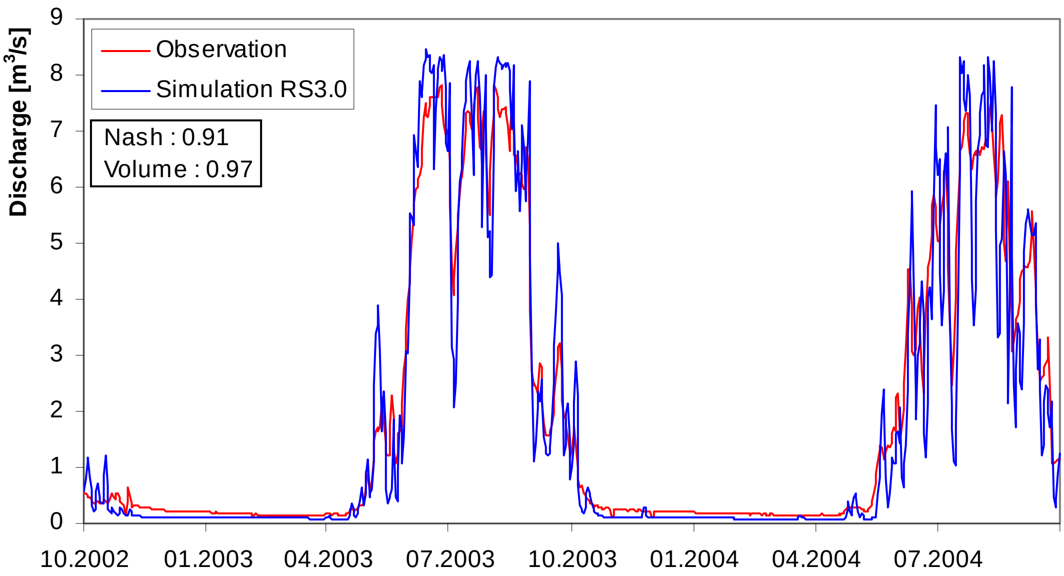

Figure 5. Observed and simulated outflows in the left bank water transfer tunnel.

3.3 *Climate scenarios*

Different climate models and scenarios were considered. They are all based on temperature and precipitation measurements made at different weather stations in the vicinity of the study area during the period from 01.10.1981 to 30.09.2009.

The first scenario is considered as a reference (also named 0°) and represents the climate of the past 30 years, reproduced during the next 100 years. The data from 1981 to 2009 are simply repeated each 28 years until 2100.

The second and third scenarios are modifications of the first one, with a linear temperature increase and no precipitation change. The scenario +4° adds 4 °C linearly until 2100 and the -2° scenario subtracts -2 °C until 2010.

The last scenario, called ETHZ, modifies the temperature and the precipitations. This scenario is based on a model from the recently completed EU-ENSEMBLE project and was provided by the Center for Climate Systems Modeling (C2SM) at the ETH Zurich. The results are derived from the Regional Climate Model (RCM) CLM, driven by the General Circulation Model (GCM) HadCM3Q0. The model and the respective method assess the relative difference between the future climate and a reference observation period, and add the difference to the reference period (Bosshard et al. 2010). The difference is a value to add to the reference for the temperatures and a coefficient to multiply for the precipitations. The differences are given for every weather station and for two periods: 2021-2050 and 2070-2099. Between these periods, a linear interpolation is applied. Compared to the +4° scenario, the temperature rises faster, especially in the summer months.

3.4 *Electricity prices*

The energy production algorithm needs a future price curve to compute the expected incomes. For the pump-storage scheme, this information is important as it is used to determine the benefits and the operation time.

The spot market prices from 01.01.2004 to 31.12.2008 are used as a reference and repeated every 5 years. Of course they do not represent fully the reality, but can be used to optimize the power production of the scheme. Moreover, an important part of the electricity production is sold at higher prices by mid-term and long-term contracts which guarantee beside energy also firm power during a certain time. In the economical analysis this is considered by a multiplication factor of the spot market price proportional to the guaranteed firm power.

4 RESULTS AND DISCUSSION

4.1 *Corbassière Glacier*

Figure 6 shows the evolution of the thickness of the Corbassière Glacier's lower elevation band for the different climate scenarios. The lowest elevation band will disappear during the next 40 years, regardless of the climate scenario.

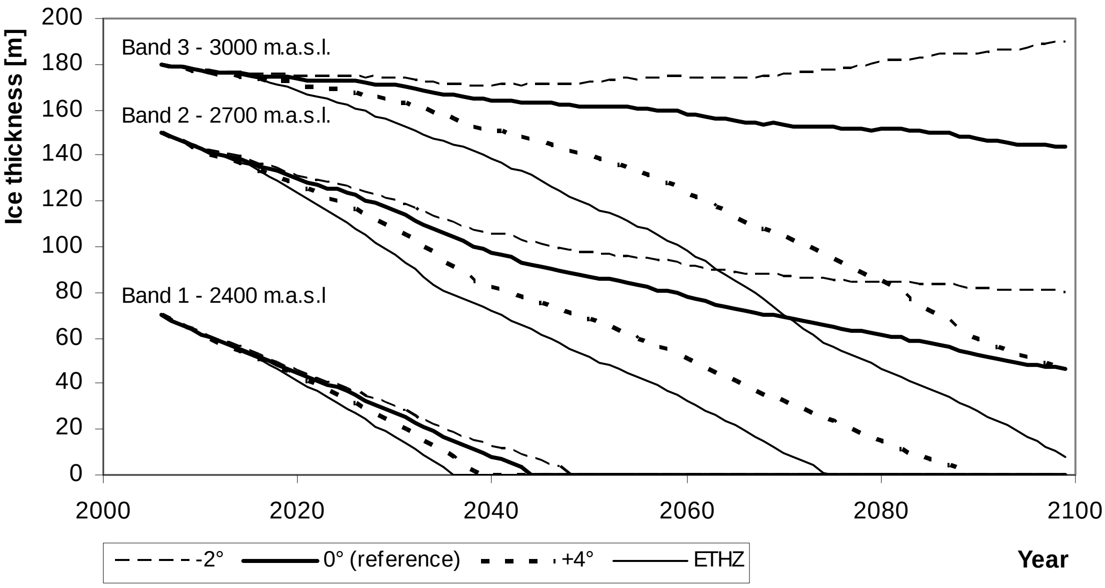

Figure 6. Ice thickness of the 3 lower bands of Corbassière Glacier simulated for the 4 climate scenarios.

The second band, which covers the new Corbassière Lake, is also decreasing. But there are important differences between the climate scenarios. For the scenario ETHZ and the scenario +4°, the second band is disappearing in 2075 and 2089 respectively. Although the mean temperature is about the same in 2100 with these two scenarios, the ETHZ scenario has a mean temperature that rises more rapidly than the linear increase in the +4° scenario. This explains why the glacier band is melting sooner in this case. In the reference scenario, the band is losing 70 % of its thickness, and probably disappears around 2150. With the cooling scenario -2°, the glacier band is loosing 50 % of its thickness, but is almost stabilized in 2100.

Finally, the climate scenarios have a major impact on the third band. In the scenarios ETHZ and +4°, this glacier band is disappearing between 2100 and 2130. In the reference scenario, the thickness is slowly decreasing during the whole 21st century. And in the -2° scenario, the glacier is growing in the second half of the century.

For the power production analysis, the date of 2075 is considered as the emergence of the new Corbassière Lake. Important uncertainties are related to this estimation, as the model was primarily developed to simulate the inflows and not to simulate the glacier evolution in detail.

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4.2 *Inflows*

Figure 7 shows the annual inflow into Mauvoisin reservoir. A 5 years average was used to smooth the high annual variability (showed with dashed line for the measured values) and therefore having a better vision of the trends.

For the measured values, an increase of the inflow occurred since 2000 which can be explained by an increased temperature. The summer of 2003 was the hottest ever recorded in Switzerland, and the annual inflow into Mauvoisin was 339 hm^3.

For the reference scenario, the annual inflow volume remains constant at about 270 hm^3/year until 2030. After this date, it decreases slowly until reaching 210 hm^3/year at the end of the century. For the -2° scenario, the annual volume decreases from the beginning and is reaching 185 hm^3/year in 2100.

For the +4° scenario, the inflow does not vary much until 2035 and then decreases to 220 hm^3/year in 2100. For the other rising temperature scenario of ETHZ, the inflow keeps rising and reaches often the 2003 peak annual inflow. After reaching a peak around 2020, the inflow decreases faster than the other scenarios, and reaches 195 hm^3/year at the end of the century. This annual volume in 2100 for the ETHZ scenario is lower than the volume for the reference and for the +4° scenarios.

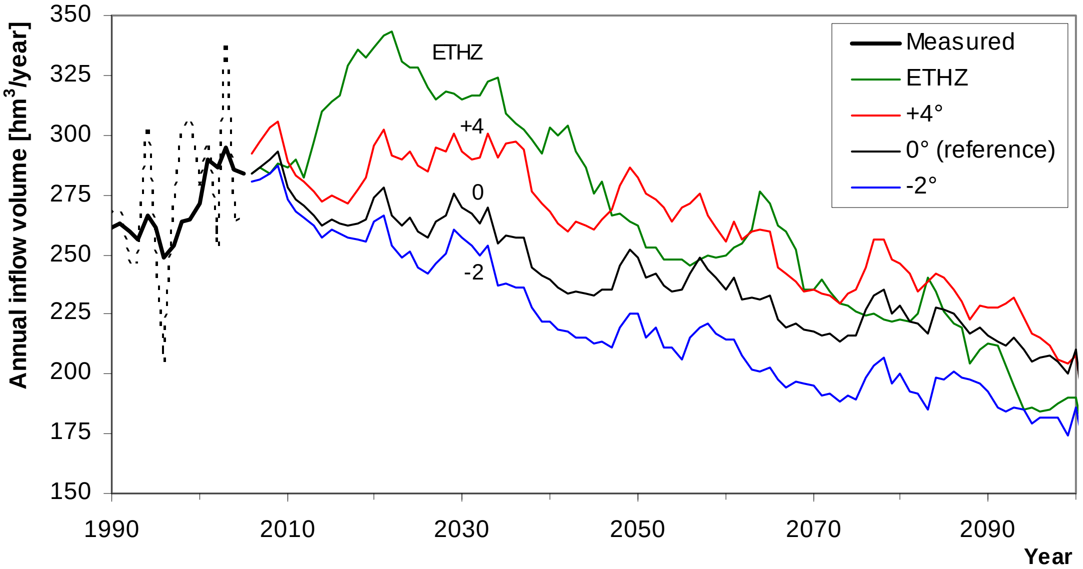

Figure 7. Annual inflow volume (5-years average) in the Mauvoisin reservoir.

It is important to note that whatever the scenario is, there will be a decrease in the annual inflow volume in the second part of the century compared to past years. This is partly related to the response time of a large glacier like Corbassière to current climate (i.e. it is in a state of imbalance with current climate). To better understand the driving processes we analyze here the origin of the inflow.

Figure 8 shows the inflow predicted by the ETHZ scenario. As it can be expected, an important part is coming from non-glacial flow (snow melt, runoff, and groundwater base flow). Currently, a volume of about 12 % of the annual precipitation is coming from a sustainable glacial melt (renewed). This means that the ice volume melted in the lower part of the glacier is in the same year formed by snow fall in the upper part of the glacier. The third type of flow is also coming from glacial melt, but it is not renewed as it comes from the readjustment of the glaciers. The proportion of this inflow is very important in the first 50 years with an average of 48 % of the precipitation volume. In the second part of the century, as the glaciers increasingly lose their mass, this inflow will decrease down to 13 % in 2100 and when the glaciers will be in equilibrium, this inflow will not exist anymore. Currently the glacier melt coming from the existing mass is about a third of the total inflow.

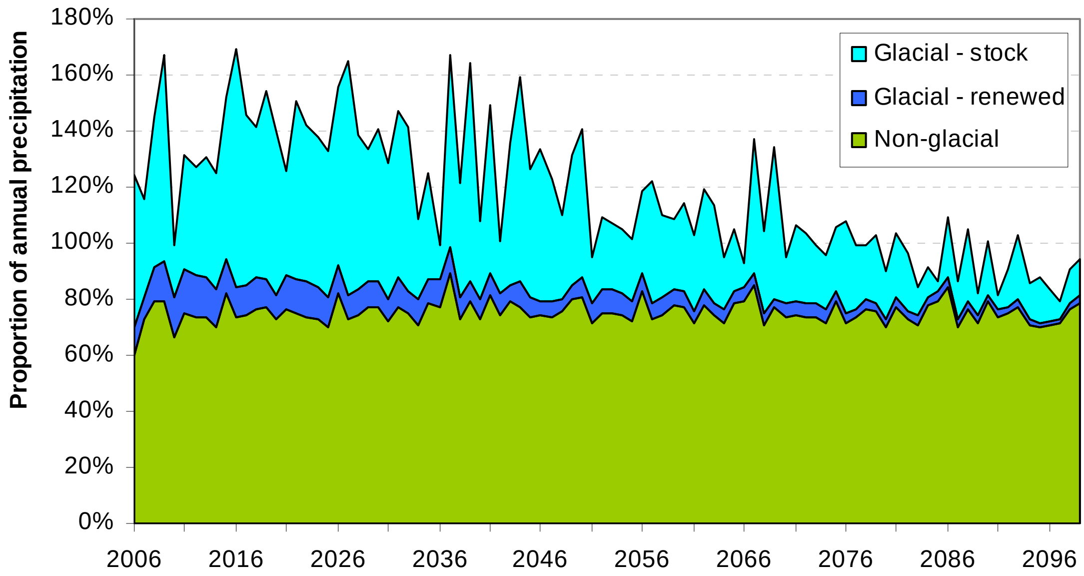

Figure 8. Origin of the inflow into Mauvoisin reservoir (ETHZ scenario).

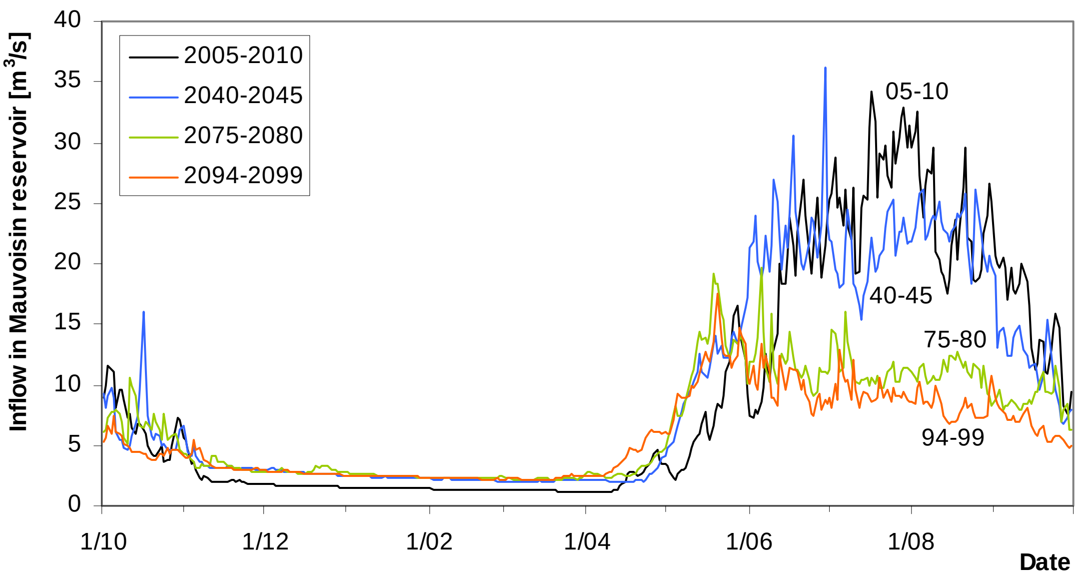

Figure 9. Inflow regime (5-year average) into Mauvoisin reservoir (ETHZ scenario).

The evaporation (not represented on the graph as it is not entering the Mauvoisin reservoir) doubles from about 12 % in 2010 to 25 % in 2095. When neglecting the inter-annual mass differences, the evaporation, the non-glacial and sustainable glacial flow are equal to the precipitation.

As the glacier melt volume will change during the 21st century, the inflow regime will also change, especially in the summer months. Figure 9 shows the hydrological regime for the ETHZ scenario for 4 different periods (average of 5 years). The regime of 2005-2010 is mainly glacial, with a high discharge between June and September. After 35 years, the snow melt will start earlier in spring and the peak discharge of the glacier melt during July will be reduced as the glacier has already lost a significant part of its surface. In 2075-2080 and 2094-2099, the regime is significantly changed, with highly reduced glacier melt, thus decreasing also the annual inflow.

4.3 *Energy production and economical analysis*

The energy production is studied for 3 periods with the ETHZ scenario: 2005-2010 to have a reference situation, 2075-2080 when the Corbassière pump-storage scheme could go into operation and 2094-2099 to have the lowest inflows in the 21st century. Over these 3 periods, different states of the schemes are analyzed: the actual scheme (FMM) alone, with Mauvoisin II project, with Corbassière pump-storage project and a combination of the two projects. The results are shown in Table 1.

Table 1. Summary of energetical and economical results for the different schemes at 3 periods.

Period		**2005-2010**		**2075-2080**				**2094-2099**				
Mauvoisin II		-	**yes**	-	**yes**	-	**yes**	-	**yes**	-	**yes**	
Corbasière P-S		-	-	-	-	**yes**	**yes**	-	-	**yes**	**yes**	
Power	Run-of-the-river	28	28	28	28	28	28	28	28	28	28	MW
	Storage	363	913	363	913	863	1'413	363	913	863	1'413	MW
Production	Corbassière					1'126	1'091			1'040	1'024	GWh/year
	(winter)					51%	50%			51%	50%	-
	Mauvoisin	1'001	1'021	755	768	762	771	617	624	619	626	GWh/year
	(winter)	65%	57%	71%	70%	70%	71%	68%	67%	68%	68%	-
Pump energy	Corbassière	0	0	0	0	-1'399	-1'352	0	0	-1'372	-1'348	GWh/year
Expenditures	Energy purchase	0	0	0	0	44	42	0	0	44	42	mil. EUR/year
	Annual installment	29	60	29	60	56	88	29	60	56	88	mil. EUR/year
	Operation costs	14	26	14	26	24	36	14	26	24	36	mil. EUR/year
Production costs	Corbassière					72	73			78	78	EUR/MWh
	Mauvoisin	43	84	57	112	57	112	70	138	70	137	EUR/MWh
Income	Energy sale EEX 0%	71	86	58	71	140	152	50	62	128	139	mil. EUR/year
Benefits		27.3	0.2	14.7	-15.3	15.6	-13.7	7.2	-24.3	3.3	-26.7	mil. EUR/year
Income	Guaranteed power	84	127	72	115	224	300	66	109	219	302	mil. EUR/year
EEX multiplication factor		19%	47%	25%	63%	60%	98%	30%	76%	72%	118%	-
Benefits		40.4	40.7	29.2	29.2	99.2	134.5	22.5	22.7	95.1	136.4	mil. EUR/year

During the 21st century, the inflows will probably decrease from 290 hm^3/year in 2005-2010 to 216 in 2075-2080 and to 178 in 2094-2099. As a consequence, in 2074 and 2094 the Mauvoisin reservoir cannot be filled anymore according to the actual annual curve. The reservoir can be used to regulate the inter-annual inflow changes. In the model, the minimum operation level at the end of winter was raised from 1840 m a.s.l. in 2005 to 1880 in 2075 and to 1900 in 2099.

Table 2 summarizes the results for the different scenarios. With the Mauvoisin II capacity extension of 550 MW, there is only a small increase in production due to increased plant efficiency. About two third of the production from the Mauvoisin reservoir is generated in winter time. This proportion, given by the production algorithm, could be increased but at the cost of losing high price hours in summer.

The construction cost of Mauvoisin II was estimated to 650 mil. CHF in 1994 which is equivalent of 495 mil. EUR today (with an exchange rate of 1.3 EUR/CHF). For the Corbassière pumped-storage scheme, a preliminary cost analysis resulted in a construction cost of 450 mil. EUR. The annual installment considered is 5.48 % of the construction cost (5 % loan for 50 years) and the annual operation costs assumed with 2 % of the investment.

The annual benefits are estimated with the EEX energy prices. As mentioned before, the income might be higher because of price of the guaranteed power. With these EEX spot market prices only, the Corbassière pumped-storage scheme is economical, but the Mauvoisin II extension not yet. Nevertheless if this guaranteed power can be sold at a 47 % higher price than the short-term spot market in 2005, or 63 % in 2075 and 76 % in 2094, the Mauvoisin II capacity extension would be economical compared to today’s scheme. In the case of Corbassière pumped-storage scheme it would be economical already if the energy would be sold on the spot market only.

A more accurate economical value is the cost of the produced energy (Fig. 10). The inflow reduction in the 21st century has a clear impact on the production cost: the expenditures are the same, but less energy is produced which leads to an increased cost. Nevertheless at the same time, the yearly operation hours are also reduced. Thus the production could be more concentrated on the peak hours, leading to a higher average sell price. For Corbassière P-S, the production cost of the water in the Mauvoisin reservoir is the same as the FMM scheme alone. The production cost of the lake Corbassière pumped-storage is between 70 and 75 EUR/MWh for 2300 h/year.

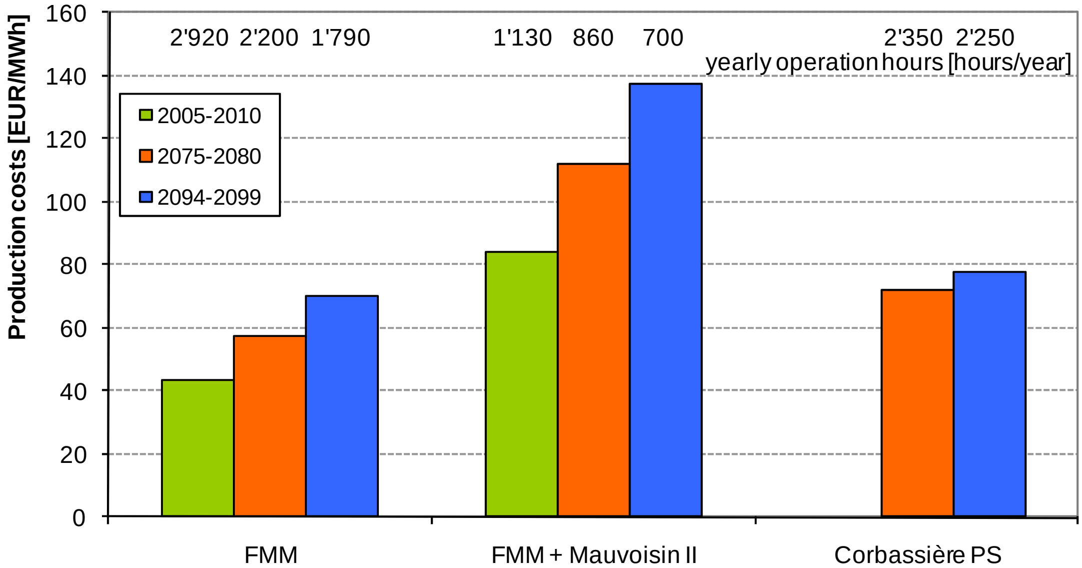

Figure 10. Production costs and yearly operation hours of the different schemes.

5 CONCLUSIONS

At strongly glacierized catchments such as Corbassière, glaciers retreat is producing an increase of runoff for the next few years, resulting in larger inflows to reservoirs in alpine basins. By the end of the 21st century, the inflows will probably return to a balanced situation (the precipitations minus the evaporation). However, the hydrological regime will be significantly modified as the melt of the remaining glaciers will be very small. With retreating glaciers and this decreasing inflow, new lakes will appear at locations currently covered by glaciers. In addition to potential new hazards of such lakes, they may also represent an opportunity to extend the existing hydropower schemes. In the case of the Corbassière glacier, an economically interesting pumped-storage scheme could be built between the new lake Corbassière and the existing Mauvoisin reservoir. Our study shows that with the significant volume of the lower Mauvoisin reservoir of 204 hm^3 and the new upper Corbassière reservoir 51.6 hm^3, this pump-storage power scheme could play an important role in the regulation and safety of the European electricity grid.

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