Chapter 65
Numerical Simulations for Multipurpose Reservoirs for Alpine Irrigation

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Abstract In most of the Swiss Alpine regions, the availability of water resources for irrigation is usually adequate, even in period of drought, as evidenced by the summers of 2003 and 2018. Indeed, important natural stocks are for the moment available in the form of snow and ice, but the situation is likely to change in the future considering global and regional climate change. The municipality of Val de Bagnes located in the canton of Valais, Switzerland, is a region where water is a very important economic factor used for hydropower, winter and summer tourism and agriculture. The study will make it possible to apprehend the needs and future availabilities for irrigation water, by 2050 and 2085, and to plan as soon as possible the modifications required to the water supply or distribution networks. This article focuses on the modeling and simulation of future scenarios of the water network. The results are based on the principle of deficit on the water demand compared to the available water in the adduction network. To illustrate the influence of the climate change on these deficits, simulations based on RCP scenarios have been run for years 2050 and 2085. The current network configuration seems to be suitable for the demand and the variability of the input until 2050. Nevertheless, for the 2085 forecasts, the existing network would not be able to match the demand. This study shows that a regional interdisciplinary approach between the technical, agricultural and social fields is necessary to manage water resources in the future even in Alpine regions where no extreme water stress is observed today.

Keywords Climate change scenarios · Alpine climate · Irrigation · Numerical simulations · Water network · Water storage

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65.1 Introduction

Since many years, Switzerland has enjoyed a very favorable hydrological situation. Switzerland alone holds 6% of Europe's freshwater, even though it represents only 0.5% of its territory [1]. Access to water has historically played a major role in the economic and social development of the Swiss Alpine valleys during the nineteenth century [2]. In this context of abundant water resources, the country was able to develop solid structures such as networks for drinking water, irrigation and hydroelectricity. In 2019, Switzerland generated more than 56% of its electricity from hydropower, making it one of the world leaders in this field. This implies that Switzerland is largely dependent on its water in many aspects. Despite its globally favorable hydrological situation, some recent years with low rainfall combined with prolonged droughts have led to large water deficits in parts of Switzerland especially during the summers of 2003, 2015 and 2018. Due to the climate change, in the future, Alpine regions will be more frequently in situations of water scarcity. As some studies have already highlighted, this will imply a reorganization of water management at all levels.

A major effect of climate change in the Swiss Alps will be the spatial and temporal changes in water availability. The National Centre for Climate Services (NCCS) estimates that by 2100, Switzerland will yearly not lack water, but the spatial and temporal distribution will vary significantly thus water will not always be available where and when it is needed [3]. In view of this issue, it is important that the municipalities act in the management of their water resources to anticipate the future potential scarcities, to prevent future conflicts of interest and to ensure sustainable water distribution to all users of a catchment. For example, in 2013, the case of the Seine River basin, in France was studied. The study highlighted the benefits in hydrological modeling to ensure the water management of a basin [4]. In another work, the research group of EDF (Électricité De France) studied the case of the Garonne catchment in south-west of France. Researchers has modelized the behavior of the whole catchment and simulate several climate scenarios to assess the quality of water distribution in the future [5]. This method has shown encouraging results in the use of numerical simulations. In 2016, EDF has also worked on a method helping to establish an appropriate governance of catchments to enable coordinated water use management. This method called the SHARE concept aims to bring sustainable solutions to manage multipurpose reservoirs. In this study, the authors have highlighted how important it is to engaging all stakeholders of a basin and that these stakeholders share the same vision, responsibilities, rights and risks and costs and benefits of a common project [6]. Similar work has been done in Switzerland, the National Research Program "Sustainable water management" (PNR 61) focused on the region of Crans-Montana in the Swiss Alps and studied impacts of climate change in the water availability. The goals of this study were to quantify the future supply and demand for water and to assess the social and economic issues linked to the implementation of water management decisions at the local level. The study has shown that by 2085 the region of Crans-Montana could yearly run out of 5.5 million m^3 of water during drought periods with a return period of 3 years. This situation could lead to significant conflicts of interests between the different users of water. The project also highlighted the importance of seasonal storage to manage water more efficiently [7].

In this context, the municipality of Val de Bagnes launched a research project led by its industrial services called Altis. The study aims at apprehending the future needs and availabilities for water, by 2050 and 2085, and to plan as soon as possible the modifications required to the water supply or distribution networks. This reflection must also be part of a global use of water on the valley by integrating a reflection on the use of already existing stocks (dams, reservoirs, networks) and on the competition between the different users of the water (drinking water, irrigation, tourism, hydropower) in a region where varies greatly according to the seasons. Several local partners are involved in the project. Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) has estimated future hydrological inputs of Val de Bagnes based on several RCP scenarios with their hydrological model PREVAH that use global and regional climate models [8]. Hydropower research group of University of Applied Sciences Western Switzerland (HES-SO) developed numerical models of the water adduction network and simulated the hydrological scenarios with the free software RS MINERVE [9] to identify the future water deficits and to help the Val de Bagnes to implement an appropriate water management strategy.

65.2 Study Case

The study case is the municipality of Bagnes. The municipality is in a typical alpine valley in the canton of Valais in Switzerland. The area is characterized by its multiple purposes of water and its large seasonal differences in water consumption. In the Val de Bagnes, a large part of the water is used by hydroelectricity, with the lake of Mauvoisin, one of the greatest hydroelectric reservoirs of Switzerland. The region is also known for its famous cheese and meat which represent important parts of its cultural heritage and economy. The livestock farming demand an intensive fodder farming thus an important amount of water for prairies irrigation during the months from April to October. Farmers use mainly sprinkler irrigation that is apparently the best method to water their steep prairies. At last, the Val de Bagnes is a popular winter tourist destination illustrate by the village of Verbier which has about 3000 permanent residents and over 35,000 residents during the winter season. Water demand is therefore strongly affected by the tourism for drinkable water and for the artificial snow at the beginning of winter.

Due to its favorable hydrography, the Val de Bagnes receives large quantities of water. The precipitations are abundant relative to the central Valais which received in 2019 less than 600 mm precipitations compared to 1000 mm precipitations for the region of Bagnes. The Val de Bagnes is a catchment of over 220 km^2 large and several glaciers are in the valley. The highest point of this catchment is the Grand Combin at an altitude of 4314 masl and the lowest point is the village of Le Châble at an altitude of 821 masl. The hydrological regime is influenced by glacier melt and snow melt, it means that the discharge regimes are much higher during the summer with high temperatures. The low water period takes place during the winter when the precipitations are in the form of snow and temperatures are low. The Dranse de Bagnes, the river that flows at the bottom of the Val de Bagnes has a month averaged flow regime ranging from 0.6 m^3/s in January to 5 m^3/s in June.

To bring water to the consumers, the Val de Bagnes has two different types of water networks: networks to assume the drinking water needs that takes water from the mountain sources and brings it to the consumers and networks to provides water for irrigation and artificial snow. The non-drinking water network consists of several sub-networks. The right bank is supplied with water by a 25 km long aqueduct running from the Lac de Louvie, a 400,000 m^3 reservoir, to the Pierre Avoi. Chambers are located all along the aqueduct to catch water from the upstream torrent, some of these can release the water in torrent to supply downstream consumers and others can directly supply the consumers by pipes. The left bank is mainly supplied by water intakes on torrents downstream the Mount Rogneux. The only storage of the left bank is the 15,000 m^3 reservoir of Moneyeu. The irrigation network is extended and complex, it consists of several sub-networks and it counts over 2500 irrigation canes. The water of the south-eastern part of Val de Bagnes is largely allocated to the FMM (Forces Motrices de Mauvoisin) who manage the Mauvoisin reservoir to produce hydroelectricity.

65.3 Method

The methodology used consists to model the behavior of the water networks to simulate the influence of different future climate and consumption scenarios. The adduction networks have been modelized with the free software RS MINERVE developed by the CREALP (Research center on alpine environment), the engineering office HydroCosmos SA, the EPFL (École polytechnique fédérale de Lausanne) and the Universitat Politècnica de València. This software is used to simulate 1-D complex hydrological and hydraulic networks according to a semi-distributed conceptual scheme. It allows also to use processes such as snowmelt, glacier melt, hydraulic control elements or hydropower production. The RS MINERVE program has been used in several projects and theses for studying basins in Switzerland, Spain, Peru, Brazil, France and Nepal [9].

Two distinct adduction RS MINERVE numerical models have been designed for each bank of the Val de Bagnes. Free surface areas such as the aqueduct have been modelized with a lag-time flow model with linear losses that is the simpler routing model where upstream and downstream flows are delayed by a fixed lag time. It has been calibrated by doing a wave on the aqueduct and measuring its propagation time. Calibration has been realized by using several performance indicators such as the Nash coefficient, the Pearson correlation coefficient and the relative volume bias [10]. Lag-time routing models have been added between each chambers of the free surface networks. Infrastructures such as reservoirs and spillways are implemented by assigning them a height-volume curve or a height-flow curve. To reproduce the behavior of certain parts of the networks, planner modules have been implemented on each chamber which allows to impose some conditions and priority rules on water intakes and consumers modules. A hydropower module has been implemented to simulate the hydroelectricity production of the future power plant of Versegères on the left bank. This module calculates the power based on the Darcy-Weisbach equation:

$$Z_{net}{}^{n} = \left(Z_{water}{}^{n} - Z_{central}\right) - f \cdot \frac{8 \cdot L \cdot Q^{n2}}{g \cdot \pi^2 \cdot D^5} \tag{65.1}$$

$$Power^{n} = \eta^{n} \cdot 1000 \cdot Q^{n} \cdot g \cdot Z_{net}{}^{n} \tag{65.2}$$

where $Z_{net}{}^{n}$ is the net height at instant n [L], $Z_{water}{}^{n}$ is the water height in the reservoirs at instant n [L], $Z_{central}$ is the hydropower plant altitude, f is the friction factor [–], L is the length of the pipe [L], Q^n is the discharge at instant n [L^3/T], g is the gravity of 9.81 [L/T^2], D is the diameter of the pipe [L], $Power^n$ is the power at instant n, η^n is the performance of the turbine at instant n [–]. The friction factor is calculated with the equation of Colebrook-White:

$$\frac{1}{\sqrt{f}} = -2 \cdot \log_{10}\left(\frac{k/d}{3.7} + \frac{2.51}{Re \cdot \sqrt{f}}\right) \tag{65.3}$$

where k is the roughness [L] and Re is the Reynolds number [–]. Figure 65.2 shows an example of the modeling of an aqueduct chamber that illustrates the visual rendering of a RS MINERVE numerical model.

The entries of the numerical models such as water needs, and water inputs have been estimated by calculation. Values of the future hydrological inflows are given by the WSL hydrological model PREVAH for the nine subbasins of the Val de Bagnes (Fig. 65.1). Thirty-nine climate chains using different global (GCM) and regional (RCM) climate models, different spatial grid resolutions and different representative concentration pathways (RCP) have been simulated by the WSL from year 2010 to 2100 with a time step of one day. The variables available are potential evapotranspiration, icemelt, percolation into saturated zone, precipitation and discharge [11]. Three scenarios have been created by using these data based on a recent study of the WSL: a wet scenario with a RCP 4.5 with increased hydrological intakes (WET), a median scenario with a RCP 4.5 with low variations of the current hydrological regime but decreased hydrological intakes (MED) and a dry scenario with a RCP 8.5 with high variations of the current hydrological regime, decreased hydrological intakes and increased drought periods (DRY) [12]. For each scenario three temporal horizons have been considered: a current vision to 2020, and two future visions to 2050 and 2085. The data for these scenarios are the 10-year average of the WSL hydrological data. For example, for the 2050 horizon the hydrological data are averaged between 2045 and 2055. This method allows to obtain trends and to mitigate

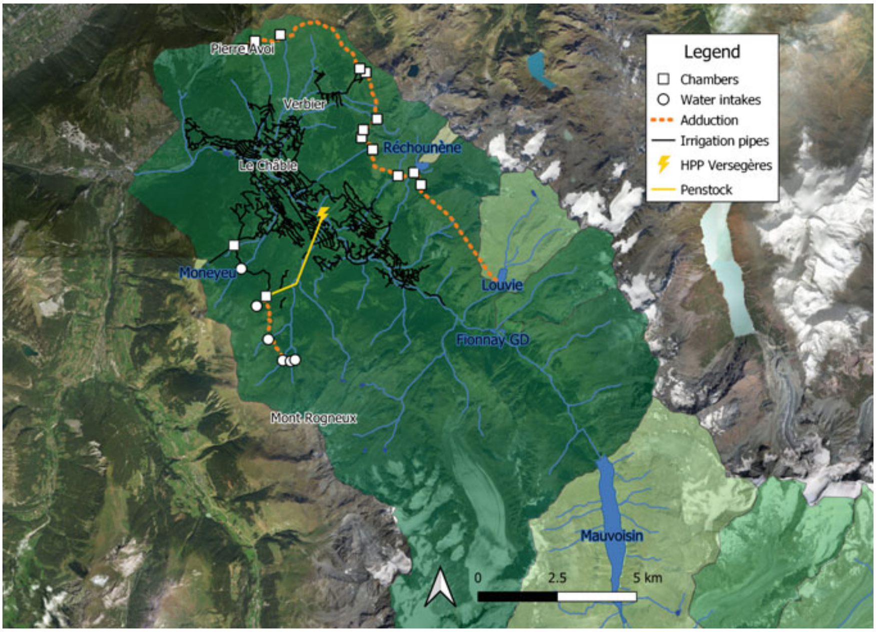

Fig. 65.1 View of the Val de Bagnes. The green colorized parts are the subcatchments of the valley. Orange lines are adduction free surface ducts and black lines are the irrigation network loaded pipes. Are also represented on this map the Versegères future power plant of 830 kW and its penstock in yellow and the Réchouène future hillside reservoir on the right bank

extreme values. The discharge of each water intakes has been calculated using the hydrological data relative to the surface of the upstream subcatchment.

The consumption data were estimated by using hydrological data and measurement data. The drinking water need has been calculated by using 10 years measurement data of the Val de Bagnes and a population growth factor for Switzerland:

$$Q_{DW}{}^{n} = Q^{n}_{meas} \cdot \frac{N \cdot V_{ref}}{\overline{V_{meas}}} \cdot R_0{}^{n} \tag{65.4}$$

where $Q_{DW}{}^{n}$ is the discharge estimated for drinking water at instant n [L^3/T], $Q_{meas}{}^{n}$ is the discharge of drinking water measured at instant n [L^3/T], N is the number of inhabitants [–], V_{ref} is the reference daily volume per inhabitant for drinking water in Switzerland of 400 l [L^3], V_{meas} is the average daily volume per inhabitant measured in the Val de Bagnes [L^3] and $R_0{}^{n}$ is the population growth factor at instant n [–]. The needs for irrigation are calculated with hydrological data based on a FAO equation, which characterizes the water needs of a crop [13]:

$$Q_{IR}{}^{n} = (ETP \cdot K_c - P_e - D_c)^{n} \cdot S_{ag} \tag{65.5}$$

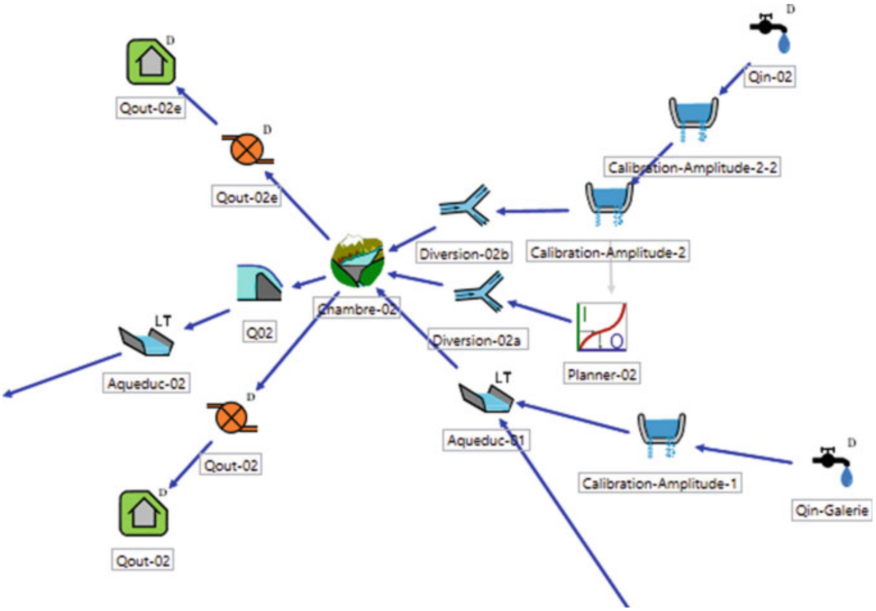

Fig. 65.2 Example of the numerical model of an aqueduct chamber. The chambers are modelized as reservoirs ("Chambre-02"), "Aqueduc-01" et "Aqueduc-02" are the lag-time routing model. The spillway "Q02" permit to set a specific H-Q curve to the chamber output. The source "Qin-02" is the water intake of the chamber, "Calibration-Amplitude" modules set a linear factor on the input discharge and the "Diversion" modules permit to set a maximum flow threshold on the intake. The "Planner" module makes possible to program if intake will catch water upstream or not with several conditions. At last, this chamber has two consumers (green modules) that takes water through the orange "turbine modules"

where $Q_{IR}{}^{n}$ is the discharge estimated for irrigation water at instant n [L^3/T], ETP is the evapotranspiration simulated by WSL [L^3/T], K_c is the crop factor of 1.15 [–], P_e is the effective rainfall (precipitation simulated by WSL with a factor of 0.7) [L^3/T], D_c is the change in soil moisture which was neglected [L^3/T] and S_{ag} is the agricultural surface to be irrigated [L^2]. The water needs for artificial snow have been estimated with measurement data. No factor considering time has been added because of the extreme uncertainly in the use of artificial snow and for the almost unsignificant part it represents in water uses. Simulations were run with a time step of 10 s due to the small size of the chamber volume. The data are daily, and the program interpolates linearly each point. The recording time step is 1 day. Figure 65.3 summarizes the inputs and outputs that are connected to the numerical model.

Some hypotheses had to be made in the modeling of the networks for several reasons: due to lack of current measurement, the exact amount of water consumed by agriculture is not known. The irrigation needs estimated by calculation cannot therefore be confirmed. It is also important to remember that the estimated needs

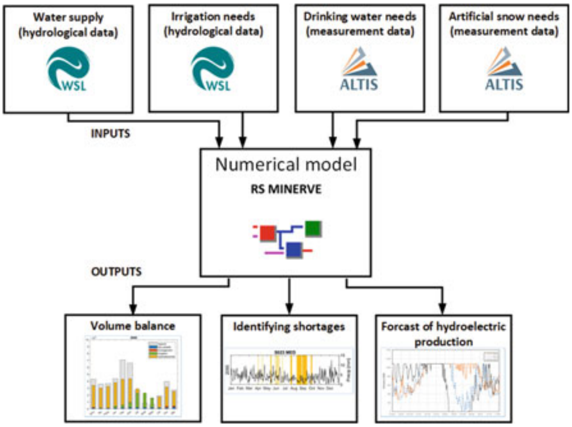

Fig. 65.3 Diagram of inputs and outputs of the numerical model RS MINERVE

for irrigation are assessed by considering a continuity of the current agricultural production and methods of the Val de Bagnes, namely, sprinkling water on forage crops. Agriculture could evolve over time to become more water efficient. At last, the current operating strategy for the aqueduct is not fully evaluated. Because of the difficulty in predicting its behavior, it was decided to prioritize the capture of the torrents upstream of the chambers over the drawing of water from the aqueduct, in the image of what is currently being done.

65.4 Results

65.4.1 *Current Infrastructures*

Simulations of the adduction networks numerical models have been done for nine scenarios (WET 2020, WET 2050, WET 2085, MED 2020, MED 2050, MED 2085, DRY 2020, DRY 2050, DRY 2085). Results of the numerical simulations are presented in two parts, one part for each bank. On the right bank, for the wet scenario, there is a slight decrease of the hydrological inputs by 2050 and an increase by 2085. Due to a slight rise in temperatures, the volumes used for irrigation are expected to increase. The use of Louvie reservoir is not expected to change by 2085 with the low water period in winter lowering the reservoir level and the snowmelt beginning in May that filling the reservoir. For the median scenario, there is a small decrease of the hydrological inputs by 2085. The volumes used for irrigation are expected to increase by 2085 especially in August when the needs are expected to exceed the water inputs. The share of irrigation over the other uses should increase from 53% in 2020 to 64% by 2085 (not including hydroelectricity) in the case of a median scenario. The use of Louvie reservoir is expected to change with two periods of lower reservoir level. For the dry scenario, hydrological regimes are expected to change drastically by 2085. With higher temperatures, the winter precipitations are expected to be in the form of rainfall and thus the hydrological inputs will increase during the winter. In the summer, the hydrological inputs are expected to decrease while irrigation needs will increase. During this period, the level of the Louvie reservoir is expected to drop and the demand will not be met, resulting in a significant shortage for agriculture (Fig. 65.4).

According to the numerical simulations, significant shortages are expected by 2050 on the right bank, mainly due to the increasing irrigation needs. For the dry scenario, during the end of the summer, shortages of more than four times the volume of Louvie reservoir are expected, thus a volume of 1,600,000 m^3. The median scenario also provides shortage periods. By 2085, during the summer, shortages of one time the volume of the Louvie reservoir are expected (Fig. 65.5).

On the left bank, the hydrological regimes will be the same as the right bank. The share of water drinking over the other uses is smaller than the right bank because of the small population living there. Irrigation needs are also expected to increase gradually by 2085, especially with median and dry scenarios. The share of irrigation should increase from 46% in 2020 to 65% by 2085 (not including hydroelectricity) in the case of a median scenario. With an extreme low water period during the end

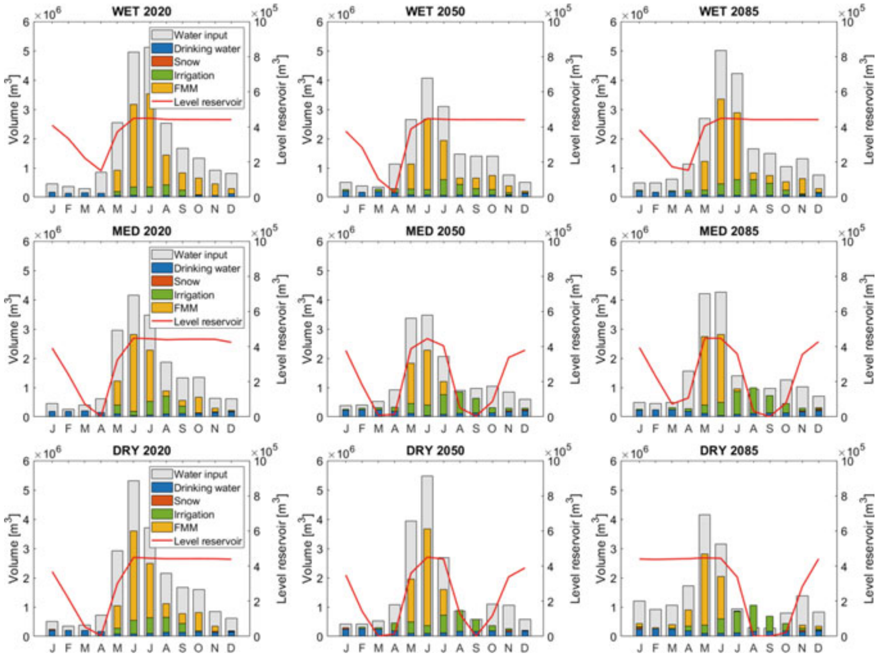

Fig. 65.4 Monthly volume balance of the right bank of the Val de Bagnes for each scenario. The gray bars represent the available water input, the colored bars inside represent the different water purposes. The yellow bars represent the volume spilled to the FMM (Forces Motrices de Mauvoisin) to produce hydroelectricity. The red line represents the evolution of the level of the Louvie reservoir

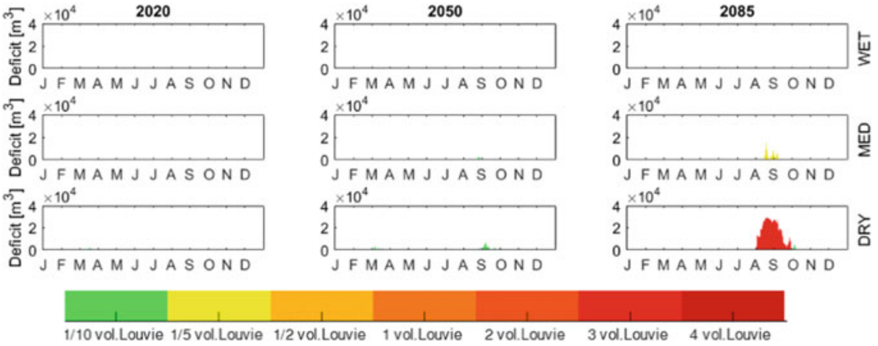

Fig. 65.5 Shortage periods predicted by the numerical simulations for the right bank. The colors show the importance of the shortage relative to the volume of the Louvie reservoir

of the summer by 2085, the irrigation needs are expected to exceed the water input leading to large scarcity of approximately 400,000 m^3 in the case of a dry scenario. Hydroelectricity production regimes are also expected to change with generation peaks in winter by 2085 (Fig. 65.6).

Numerical simulations on the left bank have also been able to estimate the production of the future Versegères power plant using the Eqs. (65.1), (65.2) and (65.3). Simulations shows that the annual production are expected to decrease by 2050. By 2085, production could even increase in the case of a wet scenario. For median and dry scenarios that imply more water during the winter, the production is expected to shift with a productive period during winter and spring. Annual production between 5.3 GWh and 6.7 GWh according to the scenarios, represents the electrical consumption of 1300 to 1600 households. With large amounts of water on the left bank, the implementation of this hydroelectric plant in the next few years seems to be a good way to reuse the water overflow (Fig. 65.7).

65.4.2 Modified Infrastructures

To face these potential shortage periods, storage solutions could be implemented. On the right bank, the implementation of a hillside reservoir in the Combe of la Chaux, the Réchouène reservoir, could be considered (see Fig. 65.1). This reservoir of about 60,000 m^3 would allow to avoid deficit periods by 2085 in the case of a median scenario and by 2050 in the case of a dry scenario. Figure 65.8 shows the estimated shortage periods on the right bank with the implementation of the Réchouène reservoir. On the left bank, the expansion of the reservoir of Moneyeu could give the necessary storage to face the future deficits in any case until 2050.

The current storage solutions are not sufficient to cover the expected shortage of a dry scenario by 2085. In addition to the two existing reservoirs of Réchouène and the one of Moneyeu, other water supply connections could be considered in

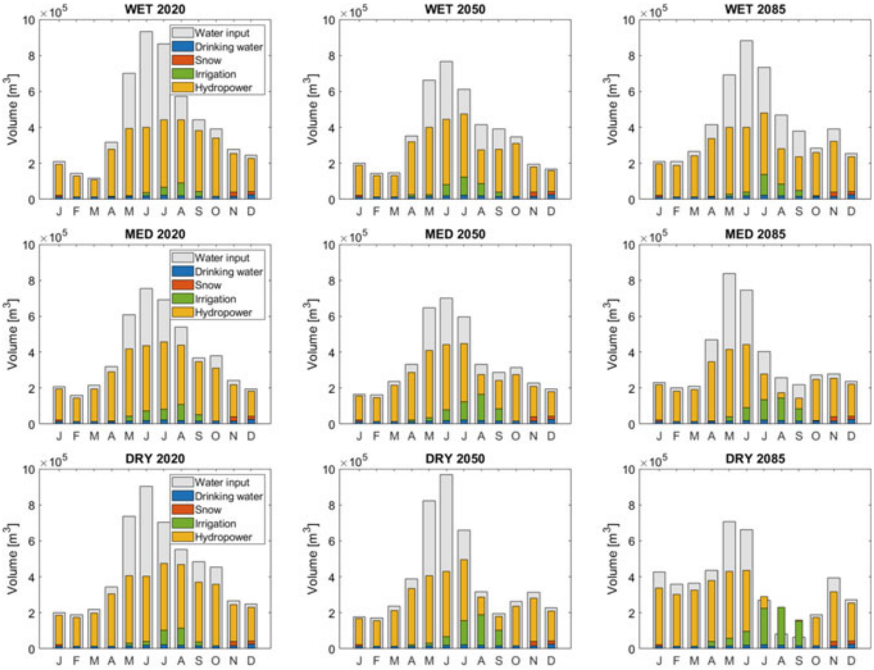

Fig. 65.6 Monthly volume balance of the left bank of the Val de Bagnes for each scenario. The gray bars represent the available water input, the colored bars inside represent the different water purposes. The yellow bar represents the potential volume used by the future Versegères hydroelectric plant

long, even medium term. It is estimated that by 2050 three quarter of the glaciers all around the word will have disappeared [14]. Switzerland and the Val de Bagnes will also be affected by this occurrence of glacier retreat. In addition to the problems that this raises, such as the impact on tourism for example, the retreat of glaciers could be an opportunity for some regions to increase their water storage capacity by implementing new reservoirs at these locations still requiring the construction of dams. On the right bank, the glacier du Parrain and the glacier de la Chaux will form lakes which could represent about 2 million m^3 each. On the left bank, the glacier du Petit Combin will form another lake that could represents about 1 million m^3. These additional reservoirs could then fill the deficits estimated by the simulations but could also be used for hydroelectric production or pumped storage [15]. These last solutions would obviously require further studies (Fig. 65.9).

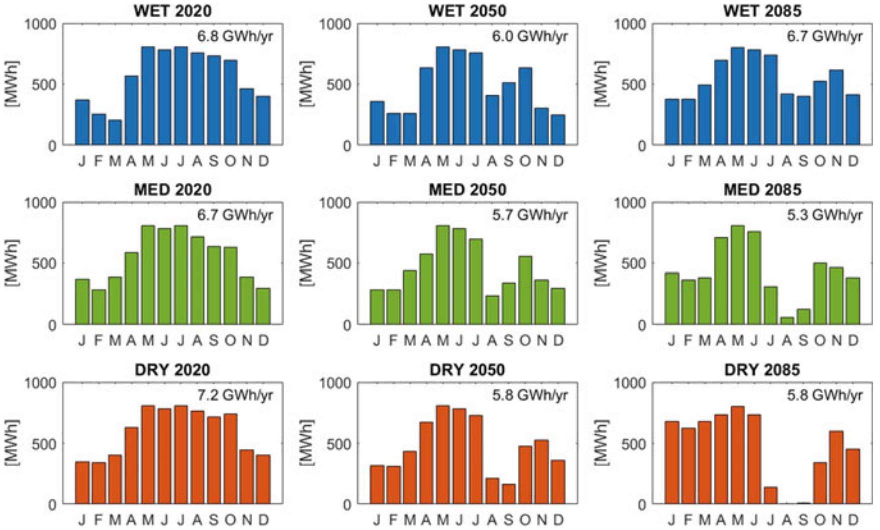

Fig. 65.7 Estimated monthly hydroelectricity production of the Versegères future hydropower plant by scenarios

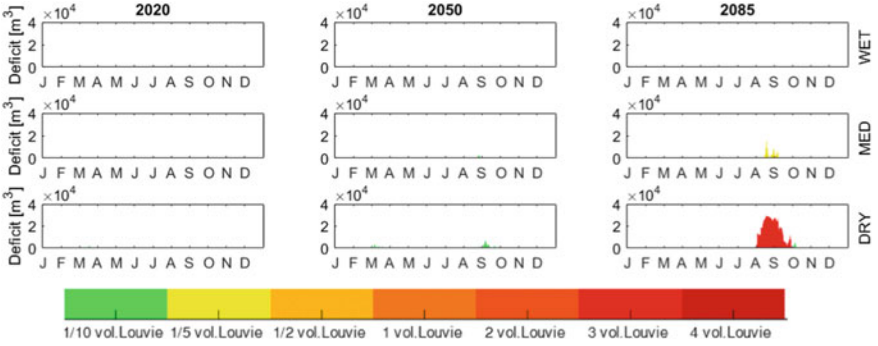

Fig. 65.8 Shortage periods predicted by the numerical simulations for the right bank with the addition of the Réchouène reservoir. The colors show the importance of the shortage relative to the volume of the Louvie reservoir

65.5 Conclusion

Adduction numerical models allow to simulate the behavior of water networks of the Val de Bagnes for different scenarios for 2050 and 2085 according to the demand for water by the multiple users. These simulations have the advantage of having a lower cost than field tests and especially of being able to test critical scenarios. From the results obtained for the different scenarios, it is possible to determine the performance of the networks in terms of transport capacity, storage volume or demand

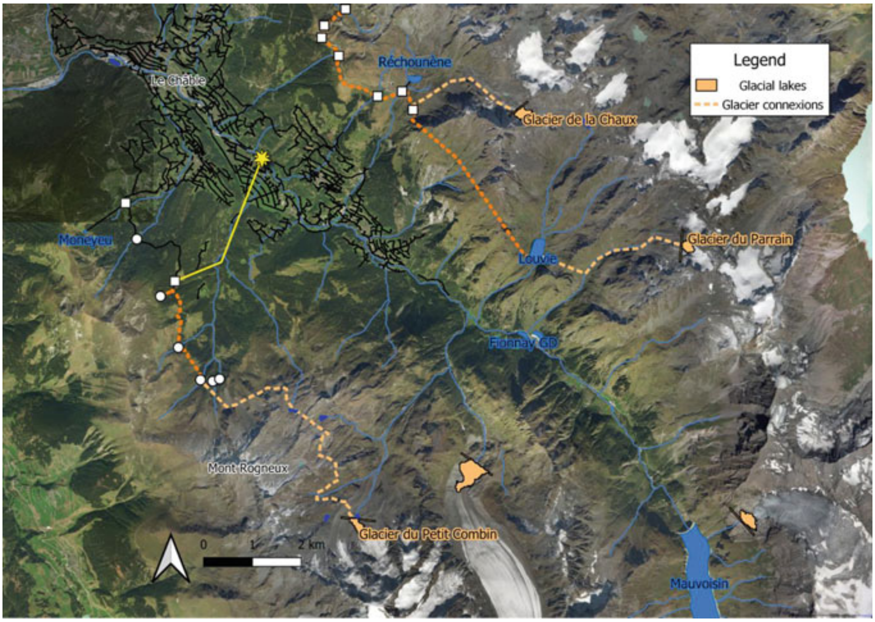

Fig. 65.9 Possible connections with future glacial lakes of the Val de Bagnes. The route of the connections between the glaciers and the water supply networks is supposed to be a free surface flow, which explains their sinuous route. The connection between the Chaux glacier and the Ruinettes is 2.5 km long, the connection between the Parrain glacier is 3.3 km long and the connection between the Petit Combin glacier and the water intakes under the Mont Rogneux is 6.9 km long

satisfaction. The models also offer the possibility to test network modifications in order to know their impact and thus to allow a relevant planning of network maintenance and development. Nevertheless, numerical models depend on available data to their design. Therefore, the validity of these models is limited by the quantity, quality and reliability of these data.

More specifically, the RS MINERVE numerical model of the water supply network highlights the impact of the change in the hydrological regimes resulting from climate change, with a shift in the risk of shortages towards the months of August to October. This risk is particularly linked to the increase in water demand for irrigation. To mitigate these risks, the impact of an increase in storage capacities shows the need to at least double these capacities in order to significantly reduce the duration of shortage periods. Even if the retreat of the glaciers by 2050 could offer an opportunity to increase the storage volume, it must be kept in mind that the implementation of new dams is not necessarily the most sustainable solution. On the other hand, this model has allowed to estimate that the annual hydroelectric production of the future Versegères power plant should, for dry and median scenarios, see its production decrease by about 20%.

Switzerland, and more particularly the mountain regions, are therefore faced with a major challenge: to ensure water supply for a future that is relatively contrasted by the effects of climate change. Solutions exist; a large part of the water used today is wasted, so it will be necessary to make efforts in the efficiency of water use. Water storage is obviously a sustainable solution to ensure a seamless supply. With this study, the potential of numerical simulations to make the right decisions on water management strategies, to correctly size possible reservoirs to be built and to anticipate future periods of water stress has been highlighted.

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