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Introduction

1 Among the départements of the French Alps, Isère (around Grenoble) occupies the third place for the winter sports offer with 12% of the ski lift infrastructure and fourth place in terms of accommodation capacity (7.6% of tourist beds) and attendance (11.4% of Alpine skier days). Investments in ski resorts, in terms of ski lifts, development, slope profiling and snowmaking are not negligible in operators' overall costs and are amortized over many years. It is thus appropriate to assess their relevance with regard to current and future operating practices and conditions, in the context of a changing climate. In view of the increasing use of snowmaking (Steiger *et al.*, 2017) and its almost universal use in the day-to-day operation of ski resorts (Steiger and Mayer, 2008), it is

essential that snow management is taken into account in any analysis or forecasting study of the operating conditions in these areas (Hock *et al.*, 2019). The impact of climate change on snowmaking is twofold, through increased need and decreased favourable production conditions. Indeed, snowmaking is itself sensitive to climate change, both in terms of favourable weather conditions for production (cold spells) and in terms of the water resources available for production (Spandre, 2016, Steiger *et al.* 2017). Up to recently, the main studies have addressed the issue of the vulnerability of winter sports resorts to climate change without explicitly taking these factors into account (Abegg *et al.*, 2007, 2020). The public debate on the issue of ski resort development in the context of past and future climate change can only be conducted appropriately if snow management is taken into account, since climate projections concerning the depletion of natural snow are not sufficient to provide the elements necessary to assess the stakes and make relevant decisions.

2 Among all the public support schemes for French mountain resorts since their construction, the choice to subsidise snowmaking facilities by the AuRA and Sud-PACA regions of the French Alps in 2016, followed by dedicated schemes at the scale of départements, has contributed to renewing the debate on these development choices. It is in this context that the Department of Isère, through Isère-Tourisme (currently Isère Attractivité), commissioned a scientific study on the reliability of snowmaking, supplemented by studies on the associated water needs and economic implications. This article is based on the first two parts of this study (which took place in 2017 and 2018), and summarizes an analysis of the natural and managed snow conditions of the 24 stations in the Isère département, in current and future climates, and the water requirements associated with snow production. The first step consisted in assessing the snow conditions of the Isère ski resorts over the past period and in drawing up an inventory of existing and/or planned snowmaking equipment. This made it possible to simulate the future snow cover of the resorts and the associated snowmaking needs in the context of climate change. A second phase aimed at using the simulated data from the stations to feed dedicated hydrological models, in order to assess the availability of the resource in relation to needs and, more generally, to understand the multiplicity of pressures on water resources for each of the resorts. The linking of these methods constitutes an original integrated approach, which is essential for a better understanding of snow production and its consequences in a climate change perspective (Hock *et al.*, 2019).

Material and methods

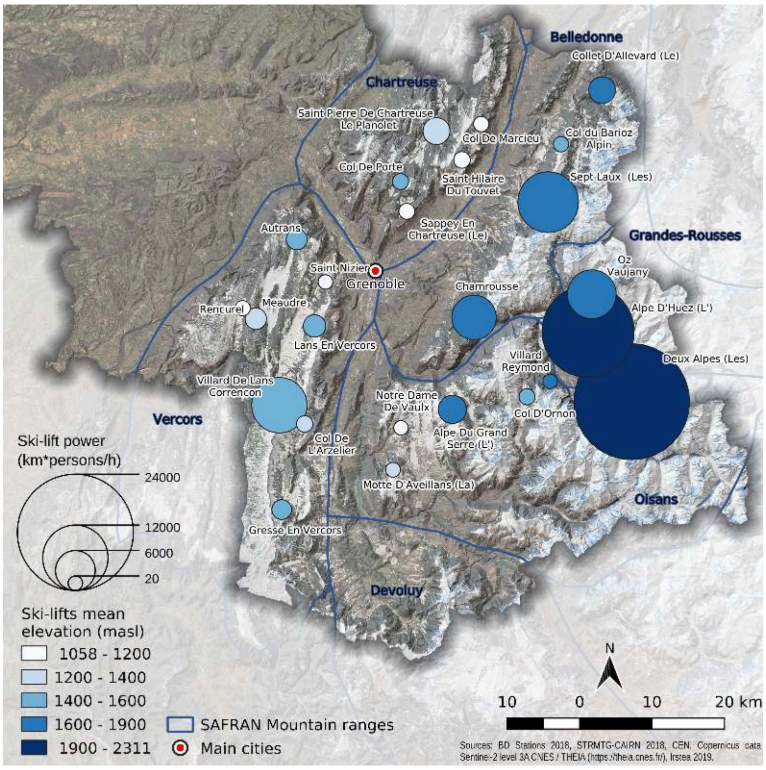
3 In addition to a detailed knowledge of the ski resorts of the Isère département and their snowmaking practices, the following tools have been developed or used in order to to carry out this study:

- explicit modelling of the snowpack in order to calculate the snow reliability and the related water requirements ;
- modelling the water resource and other water uses in the basin to characterise the balance between water requirements and supplies;
- downscaling and adjustment of regional climate change scenarios to generate time series of meteorological conditions in future climate at an hourly time step, usable for each ski resort.

Ski resorts in the Isère département

4 The 24 ski resorts of Isère (figure 1) total 2015 ha and 1030 km of slopes. They are distributed in five mountain ranges (with in terms of lift infrastructures 21% in Belledonne, 5% in Chartreuse, 28% in Grandes Rousses, 29% in Oisans and 18% in Vercors) and present a great diversity of size and elevation (http://www.observatoire-stations.fr/carto.php). According to the Domaines Skiables de France classification (François *et al.*, 2014), 2 are considered as very large (XL), 4 as large (L), 3 as medium-sized (M) and 15 as small (S) ski resorts. This distribution is quite similar to the distribution on the scale of the French Alps, both in number and in ski lift infrastructures: the small domains are the most numerous (more than half of resorts) but represent only a small part of the infrastructures (less than 10%).

Figure 1 – Location of ski resorts in Isère



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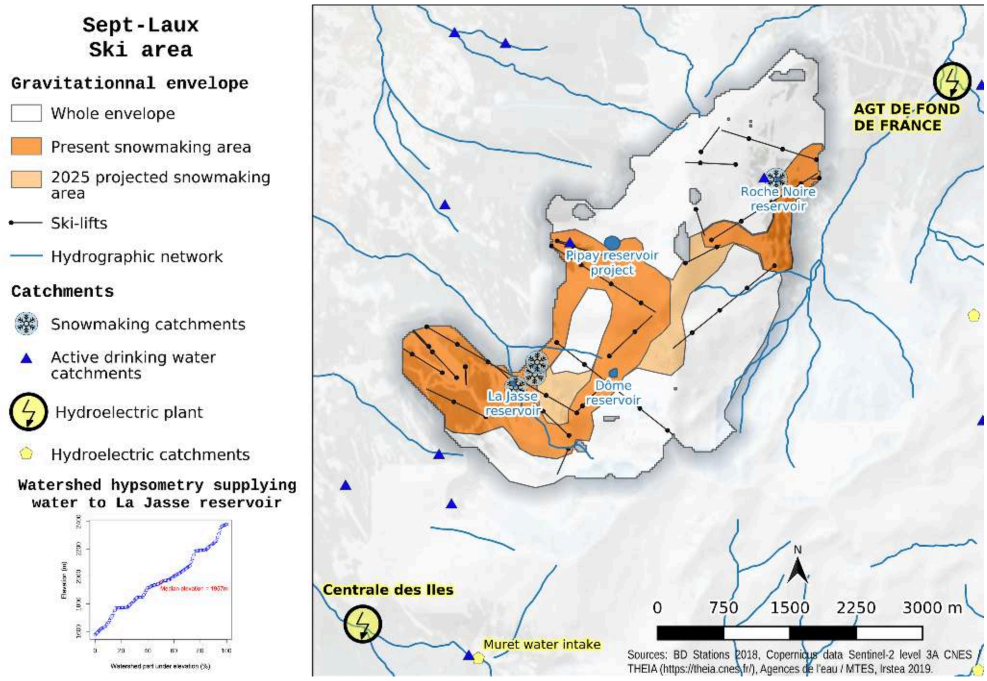
5 As of 2017, 14 of the 24 Isère ski resorts were equipped with snowmaking equipment, 12 of which were planning to increase their production capacity. Four areas not yet equipped with snowmaking equipment also planned to do so by 2025 (time horizon corresponding to projects currently under study). The total area equipped with artificial snow in Isère doubled between 2001 and 2016 (from 271 ha to 536 ha, or about 27 per cent of the total runway area) and is expected to increase significantly by 2025 to 854 ha, or more than 42 per cent of the total ski slopes surface area, if all the projects to equip the resorts identified in the study are implemented.

6 In order to model the snow cover of the ski resorts, the BD Stations database (INRAE) was used to provide structural data on the ski resorts (data on ski lifts, geographical

location, quantitative information). This database, coupled with a digital elevation model, makes it possible to determine gravitational envelopes (François *et al.*, 2014, 2016, see Figure 2), composed of all the pixels accessible by gravity from the top of the ski lifts and which give access by gravity to the bottom of a ski lift within the resort in question. These gravitational envelopes were computed in a systematic way for all the resorts and were adjusted with the managers of all ski resorts in order to refine them (thereby leading to more adequate and meaningful results, Abegg *et al.*, 2020) while keeping the principle of an overall envelope of which only a part is effectively covered by the slopes (about 10%, with variations). The areas potentially covered by artificial snow at the time of the study (2017) and those which are concerned by future projects were defined with the operators. These exchanges also made it possible to collect additional data (water consumption and supply, facility management and attendance) necessary to provide context to our approach and thus compare the values resulting from the simulations with measurements.

Figure 2 - Example of a map of the ski resort (gravitational domain and artificially snow-covered areas - current or planned) and associated watersheds, locating the other uses of the water resource



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Snow cover modelling

7 Snow conditions in each of the ski resorts were simulated using the SURFEX/ISBA-Crocus model (Brun *et al.*, 1992; Vionnet *et al.*, 2012) with recent developments referred to as Crocus-Resort allowing explicit consideration of snowmaking and grooming (Spandre *et al.*, 2016, 2019). In French mountain areas, Crocus is generally driven by meteorological data provided by the SAFRAN system (Durand *et al.*, 1993). SAFRAN has already been used in a large number of studies in the French Alps (Martin *et al.*, 1994; Gerbaux *et al.*, 2005; Durand *et al.*, 2009a; 2009b; Lafaysse *et al.*, 2011; François *et al.*, 2014). SAFRAN operates on a scale known as “massifs” within which meteorological

conditions are assumed to be homogeneous and depend only on the elevation and characteristics of the pixel considered (slope, orientation). Meteorological data is provided in elevation steps of 300 m and at hourly resolution. SAFRAN assimilates data from large-scale numerical weather models and surface observations (automatic stations, manual observations) since 1958 to 2016 in the case of this study (Durand *et al.*, 2009b).

8 Based on these previous studies, Crocus-Resort allows to simulate the evolution of the snowpack, at hourly intervals, including grooming and snow production as practiced by the operators (when and where). In the simulations, the production is possible, from 6pm to 8am the next morning, if the wet bulb temperature is below -2°C and if the wind speed is below 4.2 m/s. For the French resorts, the average rate of snowmaking equipment (from 2.5 to 3.1 snowmaking units per hectare of piste) leads in Crocus to a maximum daily production of 60 kg/m^2 of snow on the equipped surfaces. The snowmaking production scheme was determined based on previous studies on professional practices (Spandre *et al.*, 2015, 2016; Spandre, 2016), which have been confirmed by our discussions with ski area managers in the Isère département. The winter season is divided into three phases:

1. From 1 November to 15 December, an underlayer of 30 cm of snowmaking (total amount of 150 $kg\ m^{-2}$) is produced, if meteorological conditions allow, regardless of the snow cover during this period.
2. From 15 December to the end of February, snow is produced, if meteorological conditions allow, to maintain a total snow depth on the ski slopes of at least 60 cm.
3. After 1 March, no more snow is produced.

9 The snow conditions for the period 1958-2016 can thus be calculated at every point in the ski resort. For each resort, and for each winter, we can calculate the snow reliability of ski resorts, and the corresponding water volume used for snowmaking.

10 The snow reliability of the ski resorts is an index, defined as the proportion of the ski resort that has a quantity of snow of at least 100 $kg\ m^{-2}$ (equivalent to 20 cm of snow with a density of 500 $kg\ m^{-3}$) taking into account natural snow, the addition of artificial snow and the grooming of the whole. It therefore takes into account the spatial representation of the ski resort and the internal variability of snow conditions in the ski resort. This daily snow reliability index is calculated for each day between November 1 and May 15. The average of this index is calculated (each year) for the Christmas holiday period (December 20 - January 5) and for the winter school holiday period (February 5 – March 5) by taking the average of the daily indices for each period. The annual reliability index for a ski resort is defined as the combination of the Christmas holiday index (10% weighting) and the winter school holiday index (90% weighting). This index has been named “combined holidays”. These indicators were calculated for natural snowpack, groomed natural snow and groomed natural snow conditions with the current or future snowmaking fractional coverage values.

11 The volume of water required for the production of artificial snow is calculated from the model-simulated production for the entire ski resort. The exact slope surface area is taken into account to allow comparison with the measured water volumes, provided by ski resorts for this study.

Estimation of water resources

12 The estimation of water resources was calculated at the level of water intakes supplying each snowmaking facility and more generally for all catchment areas affected hydrologically by snowmaking installations. Hydrological phenomena are very complex, all the more so in the mountains where snow and glacier components can play a predominant role compared to a lowlands hydrology. High elevation areas are generally very poor in monitoring and instrumentation of water resources: there are only a few places where it is possible to directly monitor this resource. Elsewhere, it is necessary to extrapolate it from more distant information or to reconstruct it by taking into account the hydrological phenomena that govern it.

13 Hydrological modelling was thus chosen to achieve two goals:

- To be able to provide an estimate of available flows in the form of a time series, at existing or planned water intakes for snowmaking,
- To be able to assess the impact of climate change on the resource.

14 It is therefore not simply a question of modelling a water flow at a hydrometric station, but of being able to implement a model that is robust for watershed transpositions or with regard to the use of meteorological driving data under changed climate conditions, that are different from what is currently observable.

15 Due to the significant snow-related component of the hydrology in these mountain areas, the hydrological model used must account for snow processes sufficiently well. We have chosen the GR4J model (developed at INRAE), which allows us to simulate flows in daily time steps based on precipitation and evapotranspiration series and which can be coupled to the Cemaneige snow module (Valéry 2010). Cemaneige allows to simulate the evolution of the snow cover on a catchment area and to estimate its melting, by discretizing the catchment area into elevation bands. For each watershed studied, this hypsometry curve was calculated from its surface area (determined according to topography and geology for aquifer formations) and a digital elevation model.

16 This hydrological model is fed from the same SAFRAN meteorological data used to model snow conditions in ski resorts, both under current climate and for projections under future climate. SAFRAN data (available in elevation steps of 300 m) are chosen to be closest to the median elevation of the basin. They are then recalculated by the hydrological model over each elevation band using an elevation gradient for temperature and precipitation, and split between rain or snow depending on the temperature over the elevation band considered.

17 For each watershed studied, the model was calibrated on a relevant hydrometric station and then transposed to the location where the resource is to be estimated. Models were calibrated to maximize their potential for replicability, even if it meant sacrificing a little on the quality of the calibration. In fact, rather than representing exactly what exists, it is mainly the evolution between current and future hydrological regimes that is of interests for this study. Thus, for the GR4J model, we have eliminated the capacity for water exchange between basins. For Cemaneige, we also imposed limits on the degree-day model coefficient Kf (between 2 and 6 mm $°C^{-1}$ day^{-1}, Valéry *et al.*, 2014), so that the model does not over-react to future temperature increases. The optimization criterion retained is the maximization of the Kling-Gupta Efficiency KGE2

(Gupta *et al.*, 2009), applied to the square root of the flows in order to favour a good representation of low flows.

18 Each ski resort thus required a specific study to determine the water withdrawal points (for snowmaking, but also for other uses) and the associated catchment areas. Daily time-stepped flow records were then calculated over the meteorological observation period (1958-2016) and the climate projection period (1950-2100). This resource estimate can then be compared to the water demand, both for snowmaking facilities and for other uses: environment, drinking water, hydroelectricity.

Climate change scenarios

19 The RCP4.5 and RCP8.5 climate change scenarios used in the recent reports of the Intergovernmental Panel on Climate Change (IPCC) have been used in this work (IPCC, 2014, Hoegh-Guldber *et al.*, 2018; Hock *et al.*, 2019). These two scenarios cover a relevant range of changes in global greenhouse gas concentrations for the 21st century (O'Neill *et al.*, 2014). The RCP 4.5 scenario assumes climate policies leading to the global stabilization of greenhouse gas emissions in the middle of the 21st century, while the RCP 8.5 scenario assumes continued growth in greenhouse gas emissions (IPCC, 2014). Climate change, which a global phenomenon, will not have the same impacts or the same amplitudes in all parts of the world. It is therefore necessary to downscale the simulations carried out on a global scale in order to model future meteorological conditions as close as possible to what can be expected in the Isère mountains.

20 In order to feed the Crocus-Resort model and the hydrological models, the hourly meteorological time series over the period 1950-2100 were calculated using the ADAMONT method developed by Verfaillie *et al.* (2017), using the SAFRAN reanalysis as an observation base for the period 1960-1990. In order to cover the uncertainties associated with possible climate changes in the coming decades, thirteen distinct climate scenarios were used, each composed of global model driving a regional model (see Verfaillie *et al.*, 2018 and Spandre *et al.*, 2019, for the list of models used).

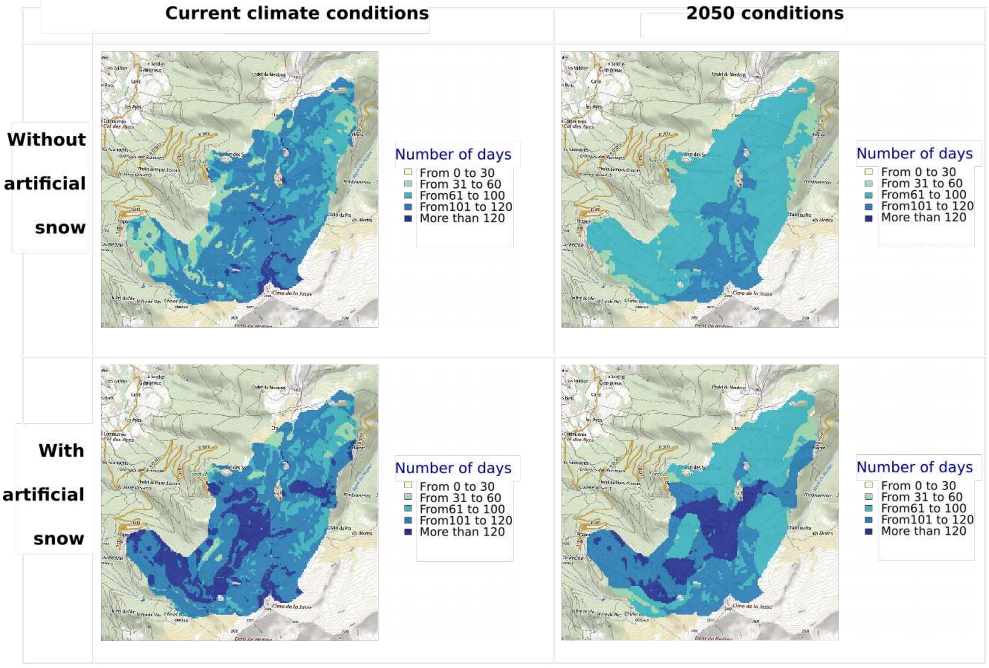
21 The climate changes expected over the next thirty years depend more on the history than on the prospects for GHG emissions and are fairly independent of the climate scenario envisaged for 2050 (Hock *et al.*, 2019). However, the two scenarios diverge more over the period 2050-2100.

Results

Snow reliability

22 Our approach makes it possible to map on the ski resorts, the height of snow or the duration of snow cover, for different configurations (natural snow, groomed snow or use of snowmaking; Figure 3).

Figure 3 - Snow cover duration with a minimum of 20 cm of groomed snow on the ground under current climate conditions and by 2050 with and without artificial snow on the Sept-Laux ski area



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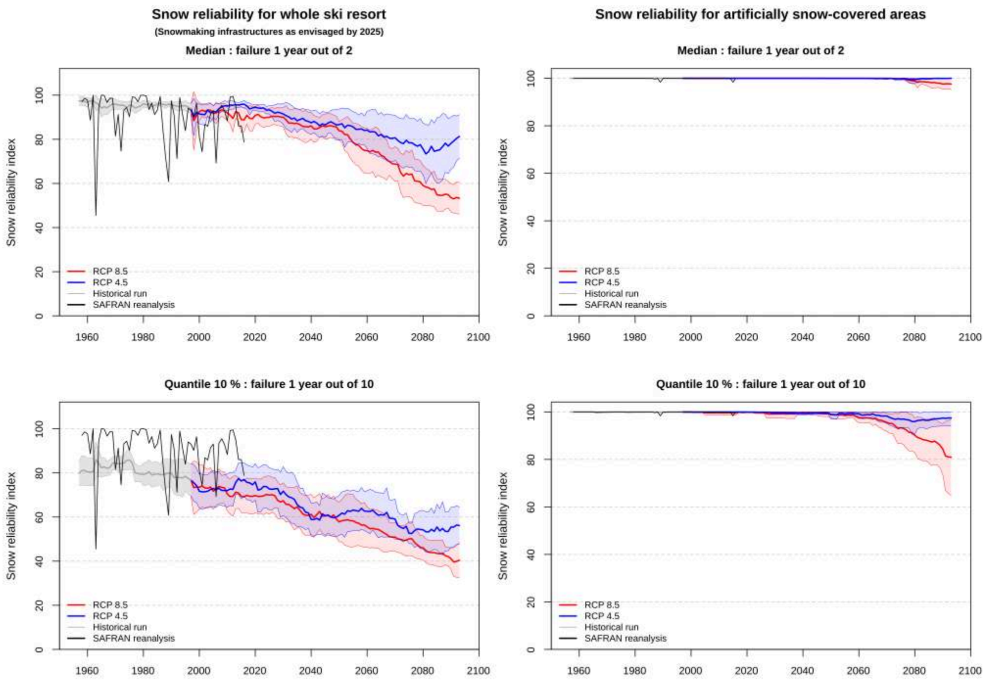
The situation with artificial snow takes into account the planned evolution of the snowmaking infrastructures between the current period and 2050.

23 These mappings make it possible to highlight the more or less snow-covered areas of the ski resort, or those that are more or less sensitive to the effects of climate change, as well as the contribution of snowmaking to increase the snow cover duration on ski slopes, and the good resistance of this artificial snow to higher temperatures. Figure 4 shows how the snow reliability can be computed and represented for each ski resort.

Figure 4 - Evolution of the snow reliability index (smoothed over 15 years) for the Sept-Laux ski resort



On the left, for the entire ski resort with the current rate of snowmaking equipment, on the right, assuming that the entire area is covered with snowmaking. The blue curve illustrates the RCP4.5 climate scenario, the red curve the 8.5 scenario. The envelopes around the curves represent the variability of the 13 climate model pairs used (standard deviation). The graph reads as follows: by 2050, with the current rate of snowmaking, there is a 1-in-2 chance of having at least 88% of the domain covered by snow during the target periods for calculating the index (Christmas and February school holidays), or 9 chances out of 10 of having at least 60% of the domain covered by snow during these periods. The right-hand side shows that in the case where the ski resort is fully equipped with snowmaking, the model indicates that snow is virtually guaranteed during these periods until approximately 2060, then climate change becomes too marked to fully ensure snow reliability, with divergences that become more marked at the end of the 21st century.

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24 Climate projections indicate that the different Isère massifs are projected to experience comparable impacts at equal elevations. The major discrimination between the massifs is therefore probably more in the elevation of the resorts (Figure 1) than in the snow and meteorological conditions.

Table 1 – Snow reliability index under past and future climate conditions

	Without artificial snow			With artificial snow		
	Worst season out of 10	Median	Best season out of 10	Worst season out of 10	Median	Best season out of 10
Recent period (2001 - 2016)	49	75	93	57	79	94

Future period (around 2050)	29	60	86	58	75	90

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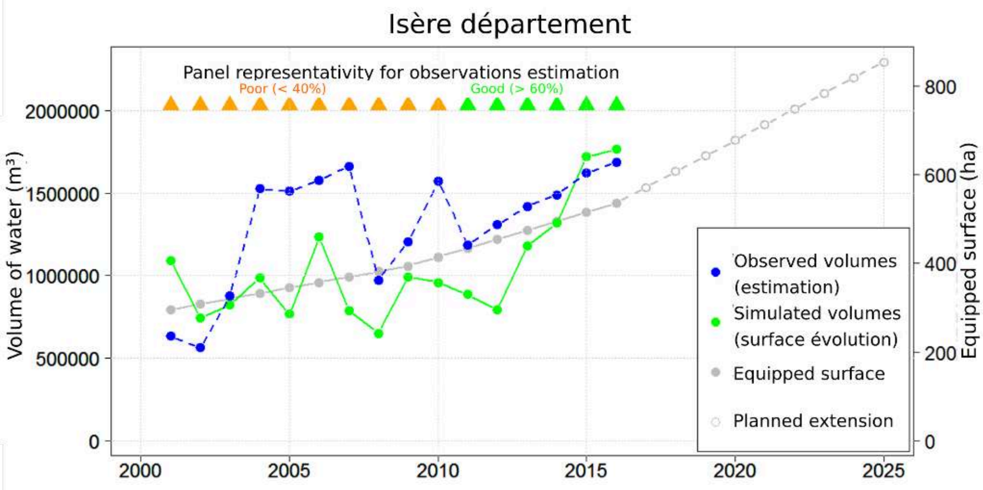
25 Table 1 presents the Isère-wide aggregated reliability index of the ten-year low snow season, the ten-year high snow season, and the median for the recent period (2001-2016) and the future period (around 2050). In the recent past, snowmaking has significantly improved the reliability of the snow deficit seasons (49% to 57%) while it had little impact on the reliability of the good snow seasons (93% to 94%). At the scale of all ski resorts in Isère, the median snow reliability was 75% without artificial snow and 79% with it.

26 By the middle of the 21st century, the reliability of snow cover in deficit seasons is projected to decrease from 49% to 29% without artificial snow and the median from 75% to 60%. With the expected changes in snowmaking equipment by 2025, the reliability of snow deficit seasons is projected to stabilize (57% and 58%), while the decline in median reliability (from 79% to 75%) and in seasons with higher snow conditions (from 94% to 90%) is projected to be limited by the addition of artificial snow. It is interesting to note that the median reliability of snow cover in 2050 with snowmaking would be equivalent to the recent past without snowmaking (75%). An important lesson from this study is that in the coming decades, according to the climate projections used, it will generally remain possible to continue to produce artificial snow (cold spells will diminish, but there will still be enough of them in the current production pattern).

Evolution of water demand

27 Over the period 2001-2016, the simulated water demand for artificial snow is very consistent with the water consumption data provided by ski resorts, increasing from 600,000 m^3 in the early 2000s to 1.6 Mm^3 in 2016 (Figure 5). Over the last 30 years, the increase in the ski resorts equipped with artificial snow has been the main driver for the growth in water consumption. As this demand can be different each year, we have generally chosen to use 90% for the sizing of the installations, i.e. a volume of water that can meet the snowmaking requirements 9 years out of 10, as 100% safety is often out of reach due to some very dry or too hot seasons such as 2006-2007 (for some massifs, going from 90% to 100% of the water demand means doubling the volume of water to be available).

Figure 5 - Estimation of the volumes of water used for the production of artificial snow in the Isère département over the period 2001-2016 and simulations by our method



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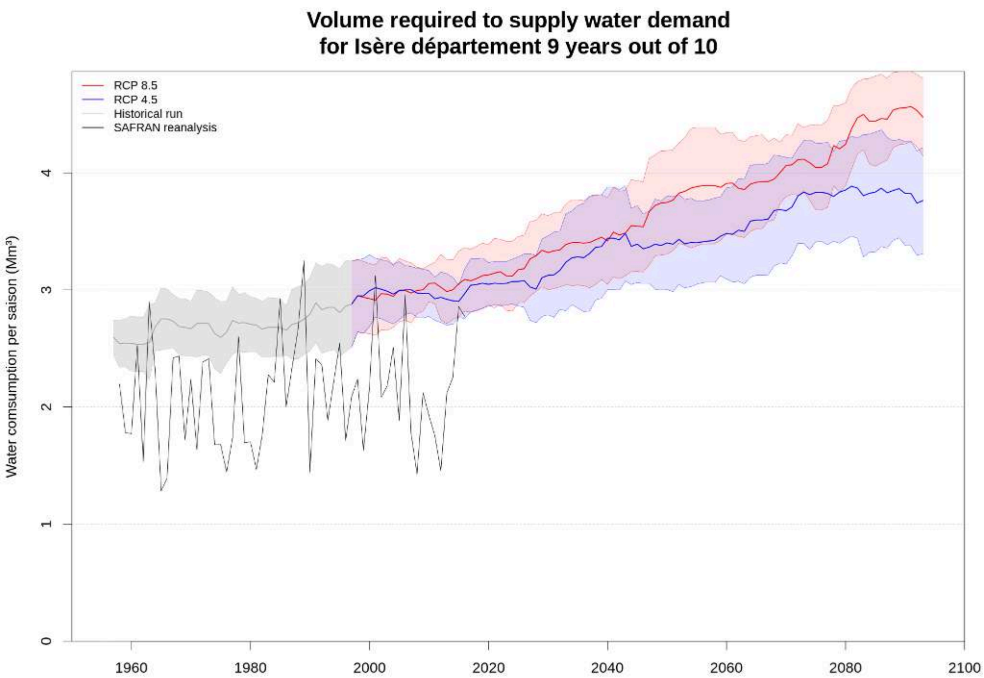
28 By 2050, water requirements are projected to increase by about 15% compared to the period 2001-2016, to supply snowmaking on average 9 out of 10 years (using snowmaking infrastructures as envisaged by 2025), i.e. between 3.5 Mm^3/year and 3.8 Mm^3/year depending on the climate scenarios (Figure 6).

Figure 6 - Future evolution of aggregated water demand at the scale of the Isère département for snowmaking, on the basis of a fixed equipment rate equal to what is planned by 2025



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29 It should be remembered that these graphs serve above all to illustrate the sole share of climate change in the evolution of water demand, disregarding the evolution of ski resorts snowmaking fractional coverage (set here at 854 ha, i.e. 42% of the

Department's current skiable areas, corresponding to the plans by 2025). They thus do not prejudge new areas that could be covered with snowmaking infrastructure in the future (projects not known to date), which would mechanically increase the demand for water. At constant snowmaking fractional coverage, the increases in individual ski resorts water demand induced by climate change are fairly homogeneous per massif (≈ 15% in Belledonne, ≈ 10% in Oisans and Grandes Rousses, ≈ 22% in Vercors, ≈ 20% in Chartreuse).

30 The impact of climate change on water demand remains moderate, while the natural snowpack will be strongly affected by the warming projected by all climate models in the coming decades (Verfaillie *et al.*, 2018). This is partly explained by snowmaking practices since most of the production takes place at the beginning of the season in order to form an underlayer, regardless of the natural snow cover conditions for the rest of the season.

Evolution of water resources, and balance between water supply and demand

31 For each of the ski resorts, we cross-referenced observations or projections of available water resources with requirements for snowmaking, other uses in the vicinity (drinking water, hydroelectricity) and the needs of the environment (reserved stream flows).

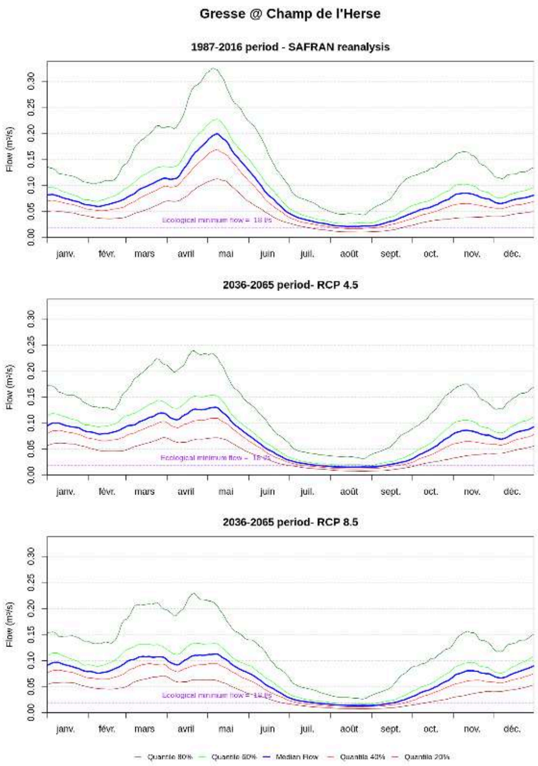
32 Of the 24 ski resorts in Isère, there are currently few actual conflicts of use identified, except for one resort where hydroelectricity is fairly developed downstream (a larger withdrawal in winter could be a loss of income for the hydropower sector). In recent years, the ski resorts have developed projects to avoid withdrawals when the resource is not available (winter low water levels) or when it is to be shared between several uses. Snowmaking infrastructure projects in recent years or those planned for the next few years (by 2025, as assessed in this study) are often governed by the desire to have greater instantaneous production capacity (especially at the beginning of the season when production slots are critical because there are few production slots compared to the need for production) and to reduce dependence on winter refills, unless the winter resource appears abundant compared to needs (Lans-en-Vercors, Saint-Hilaire-du-Touvet, Alpe-du-Grand-Serre). Several strategies have been or are being implemented:

- Creation of new or larger reservoirs if the situation allows (Deux-Alpes, Villard-de-Lans);
- Fetching water “far” from resources (e.g., large hydropower dams) that appear “inexhaustible” in relation to needs (Oz-Vaujany, Alpe d'Huez);
- In the Vercors massif, where the surface resource is scarce and where drinking water is supplied by the drinking water supply network from deep or more distant resources, it is more the capacity of the network that is limiting than the availability of the resource (Villard-de-Lans, Méaudre, Autrans).

33 Based on field surveys and estimates of the volumes needed for production, it can also be seen that the volumes of artificial snow produced generally correspond to the need for snow reliability, according to current production and management methods (production sites and control of installations, grooming). In general, the volumes produced increase snow reliability, even if losses are not always technically controllable at the level of the snow gun.

34 For the future (up to 2050 for these results, with trends becoming even stronger by the end of the twenty-first century), the following overall trends can be observed in the hydrological regimes simulated using the available climate projections, which are of course different according to the massifs and elevations, but also according to hydrological and hydrogeological functioning. The peak of spring snowmelt is projected to be less pronounced and to occur slightly earlier in the season. The winter low-water levels are projected to be less marked, or even no longer visible for the lowest elevation rivers (catchment area below 1500m): more rain instead of snow, greater melting of the snow cover due to the increase in temperature. Water resources in winter are projected to increase by 30 to 100% depending on the basin. Summer low water levels are projected to be more marked, due to greater evapotranspiration and less support from snowmelt at the end of spring/summer. The annual volume of water runoff is projected to be hardly modified by climate change, i.e. water resources remain similar if we consider the year as a whole.

Figure 7 - Example of the evolution of the hydrological regime of the Gresse River at the water intake supplying the network for snowmaking for the Gresse-en-Vercors ski resort



The curves for the different quantiles represent, for each day of the year, the flow that one can expect to have at least, with the corresponding probability.

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35 Climate projections regarding spring melt and summer runoff indicate sufficient amounts in the future to fill the hillside reservoirs before the winter season, as these runoff volumes far exceed the storage capacity. On the other hand, at constant reservoir capacity (which for all areas is less than the volume of water generally used over a season), the increase in demand is projected to involve more winter refilling than in the current climate. The additional winter water resource available in liquid form (30 to 100% depending on the basin) is projected to be greater than the increase in

demand induced by climate change (at constant snowmaking fractional coverage). These additional winter fills should thus generally be possible, but for some ski resorts, this additional resource would not necessarily always be available. At high elevation (Deux Alpes, Oz-Vaujany), the reserved flows are projected to not be satisfied more than they are at present: despite the warming, temperatures are projected to remain too low for the snowpack to melt sufficiently in the middle of winter. These resorts are in the process of turning to other resources or are planning to increase their storage capacity to cover all their needs. In some ski resorts, the current withdrawal administrative authorizations limit the quantity or prohibit withdrawals during the winter period, without reference to the flow rate (Alpe d'Huez, Sept-Laux). Overall, by 2050, and on the basis of the areas equipped with snowmaking infrastructure by 2025, our analysis indicates that the adequacy of water supply and demand is in general projected to not deteriorate compared with the current situation.

Discussion and conclusions

36 This work lays the foundations for an integrated approach to modelling the issues related to the water cycle in ski resorts and their operating conditions, taking into account as fully as possible the tools and methods for projecting the impact of climate change in the mountains.

37 All ski resort managers in Isère have access to information relevant to analyse the future evolution of the snow cover, in terms of the reliability of natural snow cover, the efficiency of snowmaking and the relationship with the availability of water resources. Our study does not set a threshold below which the viability of a ski resort is at risk: depending on the operating mode, clients and location of the resorts, the snow reliability levels required for their operation are variable, and it is up to managers and communities alike to specifically analyse the relevance of development choices with regard to the issues and characteristics specific to each resort.

38 Beyond the management of ski resorts, this study also aims to feed the public debate on the issue of snowmaking and the management of water resources in the context of a changing climate. These subjects are often hot topics in the public debate and often rely on little or old evidence. For example, the extrapolation of future snow cover in ski resorts has often been made with reference to a natural snowpack, without taking into account grooming and snowmaking (Hoegh-Guldberg, 2018). Also, the debate on the use of water resources for snowmaking still often refers to periods when withdrawals were made directly from watercourses without buffer reservoirs or respect of reserved flows and therefore had strong impacts on natural environments.

39 This study thus brings objective elements to these debates, on the one hand, by going down to very local scales (within ski resorts), and on the other hand, by the methodology used, developed specifically to answer these questions around snowmaking. The analysis shows that the snow cover of areas covered by artificial snow is greatly improved compared to snow cover in areas managed solely by grooming, or without snow management. It shows that, for the Isère resorts, the availability of water resources does not seem to be the most critical point for the implementation of artificial snow in the 21st century.

40 This methodology would be quite easily reproducible on other ski resorts: the models are developed, the climate or hydrological data exist. If in broad outline one could expect similar results on the evolution in the coming decades of the water demand for snowmaking and the joint evolution of water resources in the environment, it should not be forgotten that the balance between supply and demand for water resources can only be the result of a local study, integrating the modes of water supply to snowmaking facilities (environment and elevation of the withdrawal) and stock management (availability of storage reservoirs, snow production pattern during the season). The "rather good" balance between supply and demand observed in Isère cannot therefore be automatically transposed to other regions or other ski resorts.

41 A number of questions, which go far beyond the scope of this study, remain unanswered, particularly in the field of the economy and governance of winter sports resorts. In the field of water, these include the following:

42 - Taking into account the water quality aspect when water transfers are increasingly important and more and more distant: what is the quality of the water discharged at the basin heads when it is sometimes brought up from areas located quite downstream, thus potentially more exposed to anthropogenic pollution?

- Taking energy consumption into account in water transfers from the point of withdrawal to the inlet of snowmaking facilities.
- The question of the evolution of regulations in the context of a changing climate: to what extent should the water abstraction authorization orders evolve or be revised if the seasonal distribution of the water resource changes?
- In terms of hydrology, beyond the issue of abstraction, this study does not deal in detail with the disturbance induced on runoff by snowmaking and snow management within the catchment areas supporting the ski resorts. This highly controversial question of the time lag in the "return to the environment" of water used for the production of artificial snow remains open and could be the subject of subsequent studies to refine this knowledge, for example by using the Crocus model concomitantly both for estimating snow cover on the slopes and the associated water requirement, but also to estimate the fate of snow melt water on and around the slopes. One could thus be interested in the fine-scale disruption of the water cycle at the scale of all or part of a ski resort (from the scale of a portion of a ski slope to that of the watershed upstream of the ski area), by questioning the reference period in a context of changing climate: a managed snow cover, including snowmaking, certainly melt later than the natural snow cover it reinforces, but does it finally melt later than the natural snow cover of a few decades ago (with or without grooming)? A direct coupling of Crocus instead of Cemaneige with the hydrological model could allow more precision on these fine-scale studies.

43 The central challenge of this approach would thus be to achieve an integrated simulation of the hydrology of the catchment areas of ski resorts by explicitly taking into account the dynamics and specificities of snow management.

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ABSTRACTS

This study presents the evolution of the snow reliability in the 24 alpine ski resorts of the Isère département (Northern French Alps, around Grenoble) over the last decades and its projection into the 21st century, taking into account grooming and snowmaking. The water demand for snowmaking is calculated and can be compared with hydrological simulations of water resource availability, under current and future climate conditions. Over the recent period, snowmaking has significantly improved the snow conditions in seasons with a natural snow deficit. For the middle of the 21st century, climate projections indicate that the expected evolution of snowmaking infrastructure by 2025 should make it possible to stabilize the snow reliability in seasons characterized by a deficit of natural snowfall. At a constant equipment rate, the evolution of water demand due to climate change is of the order of +15% on average in Isère between the recent period and the middle of the 21st century. The study shows that the pressure on water resources appears to not be the most critical point for the implementation of snowmaking, at the scale of the catchment basins in which the Isère ski resorts are located.

INDEX

Keywords: snowmaking, water resources, climate change, snow reliability, ski tourism

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