https://doi.org/10.5194/egusphere-2022-1186
Preprint. Discussion started: 29 November 2022

Quantifying the hydrological disturbances induced by snow grooming and snowmaking in ski resorts: a case study in the French Alps.

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Abstract. The presence of a ski resort modifies the snow cover at the local scale, due to snow management practices on ski slopes, especially grooming and snowmaking, which affect the quantity and physical behavior of the snowpack. Snow management exerts two-fold disturbances to the local hydrological cycle, through (i) uptake of water used for snowmaking, either directly after uptake or following temporary storage and (ii) changes in water runoff due to added snow mass through snowmaking and/or delayed melting of the snowpack due to snow grooming. This induces a local pressure on water resources that can be substantial in places and fuels controversies regarding the environmental impact of ski resorts. However, no scientific study to date has quantified the quantitative and qualitative disruption of the local hydrological cycle downstream, concerning both the modification of the local seasonality of the flows (e.g. low water periods) and possible modifications of the volume of water returned. Here we describe results from a case study quantifying the various components of the water budget of a small catchment (several km^2), partly covered by a ski resort, in the Northern French Alps. Snow cover simulations, including the timing and amount of snowmelt, were performed using the Crocus snow cover model driven by the SAFRAN reanalysis and future climate scenarios, with and without accounting for grooming and snowmaking. Our study demonstrates a visible impact of snow grooming, through the quasi-suppression of winter snowmelt, leading to delayed snowmelt onset. Snowmaking leads to additional snowmelt amount, of the order of a few percent at the scale of the catchment, scaling with the fraction of the catchment covered by ski pistes, and the fraction of the ski pistes equipped with snowmaking. Under the situation of the case studied, there is no substantial further water loss due to snowmaking after the snow production itself, which induces about 10% of evaporative loss of water used for snowmaking, related to the snow production process. Snowmaking mainly leads to a moderate shift in snow cover formation and snowmelt processes, to a smaller degree than the influence of future climate change on mountain hydrology. This study provides quantitative estimates of the impact of grooming and snowmaking on the hydrological regime of mountain catchments interesected by ski resorts, which can inform further studies addressing water management and climate change adaptation in mountain regions harbouring ski tourism infrastructure.

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1 Introduction

Ski resorts are a prominent component of mountain economies in many regions of the world (Europe, North America, China, Japan, New Zealand and South-East Australia) (Steiger et al., 2019; Hock et al., 2019; Vanat, 2021). Snow management, in particular grooming and snowmaking, i.e. artificial production of snow on ski pistes before and during the ski season, have become routine activities for ski resorts operations (Steiger et al., 2019). Among the various environmental concerns related to the operations of ski resorts, the hydrological impacts of snowmaking is often mentioned as an argument against their development. In particular, the use of substantial amounts of water for snowmaking is pinpointed as an unsustainable pressure exerted on the mountain environment. It is however often argued by ski tourism supporters that water is only “borrowed” for snowmaking, and returned to mountain creeks and rivers at the time of snowmelt. Despite this contentious situation, very few scientific studies have addressed quantitatively the impact of snow management, in particular snowmaking, on the water cycle at the local or regional scale. This is however required, in order to contribute scientific information regarding the relationships between mountain water resources and ski resorts operations, at a time of intense debates regarding the transition of mountain tourism into a more sustainable pathway, taking into account climate change impacts and related adaptation options (Hock et al., 2019; Tschanz et al., 2022). Eisel et al. (1988, 1990) carried out pioneering studies on water losses due to snowmaking based on case studies in Colorado (United States of America), motivated primarily by water right issues. They separated water losses in two categories: "initial loss”, corresponding to “consumptive water loss that occurs during the actual snowmaking process due to evaporation and sublimation” and “watershed loss”, corresponding to “consumptive water loss that occurs from the time the man-made snow or ice particles have fallen on the snowpack through spring melt. This loss is due to sublimation and evapotranspiration.” Eisel et al. (1988) focused on the “initial loss”, which was later complemented by more recent studies carried out in Europe (Spandre et al., 2017; Grünewald and Wolfsperger, 2019). These losses, i.e. the fraction of the water mass used for snowmaking which is not recovered as snow on ski slopes, are estimated to range between 10 and 40%, depending on the meteorological conditions, with about 10% due to evaporation and sublimation processes. Additional loss amounts reflect that some of the machine-made snow falls besides the ski slopes, and is thus wasted from perspective of ski resort operations although it is not lost in terms of the total amount of water in the catchment. Eisel et al. (1990) investigated the watershed losses for several ski resorts, by means of a comparison between observed runoff, water consumption for snowmaking and meteorological conditions, and simulated runoff. They concluded that, for the situations analysed, the watershed loss ranged between 7 to 33 % of the water used for snowmaking, after the initial loss, leading to 13 to 37 % total consumptive loss. This indicates that, in this case, abstracting water for snow production leads to substantial net water loss for the catchments due to sublimation and evaporation of the snow cover on ski slopes. However, they clearly stated that “these results should not be extrapolated directly to other specific ski area sites because actual consumptive loss at these sites is dependent on atmospheric temperature during snowmaking, temperature, and precipitation during the winter and watershed conditions at the site.” We are not aware of whether these studies were corroborated by further studies, and whether they have been used operationally, in particular for water rights applications. In a more recent study, Wemple et al. (2007) reported on the fact that snowmaking corresponded to 3 to 4 % of the total annual precipitation in a ski resort in the NE USA. Even more recently, Gerbaux et al.

(2020) compared water demand for snowmaking with water resources availability in several ski resorts in the Northern French Alps, but did not address the downstream disruption of the water cycle induced by snow grooming and snowmaking and potential water losses. Leroy (2015) developed an integrated modelling approach for the quantitative comparison of the amount of water uptake for various uses (hydropower, agriculture, domestic use, snowmaking) in a pilot ski resort in the northern French Alps, but also did not address downstream impacts on river flows.

The present study explores the impact of snow management on the hydrological cycle and downstream water availability, in particular seasonal patterns, at the local scale, and implements this approach as a case study in the Northern French Alps (La Plagne ski resort). We describe simulations results, and corresponding observations when available, for a study domain encompassing the entire ski resort area, a single point at 1800 m elevation, and two interconnected catchments for which detailed hydrological and snow management information are combined.

Complementing the framework introduced by Eisel et al. (1988), we address not only the effect of snowmaking but also of snow grooming on water runoff downstream the ski slopes, and also investigate the hydrological impact of water uptake used for snowmaking. In addition to hydrological observations gathered from various sources and covering several aspects of water management and water resources in the surrounding environment, this study makes extensive use of snow cover modelling, with and without snow management (Spandre et al., 2016b; Hanzer et al., 2020; Ebner et al., 2021), which enables us to directly estimate the disturbance induced by snow management, under current and future climate conditions, for this location.

2 Materials and methods

2.1 Snow cover modelling

In this study, the simulation of the natural and managed snowpack is performed by the Crocus snow cover model, equipped with the ability to simulate natural snow processes, grooming and snowmaking (Spandre et al., 2016b, 2019). The model accounts for all the processes governing the internal evolution of the snowpack and its interfaces, including the surface mass balance: absorption and reflection of solar radiation, as a function of the surface albedo of the snow calculated by the model, absorption of atmospheric infrared radiation, emission of infrared thermal energy as a function of the surface temperature of the snow, latent and sensible heat fluxes at the surface of the snowpack, as a function of wind speed, surface temperature of the snow, and atmospheric conditions (temperature, relative humidity etc.) (Vionnet et al., 2012). The implementation of snowmaking in the model (described in detail in Spandre et al., 2016b) is consistent with typical practices in ski resorts operations (Spandre et al., 2016a), although local deviations can be observed (Abegg et al., 2020). We here use typical values rather than refining in detail the model configuration, so that the modelling system can more easily be transferred to other contexts. In the model, snow production is only possible for wind speed values below 4.2 $\mathrm{m\,s^{-1}}$ and for wet bulb temperature values below -2°C for the fan snowguns and -6°C for the lances snowguns. The density of the snow produced is 600 $\mathrm{kg\,m^{-3}}$. In early season, before the start of the main winter holiday period, production can take place between 1/11 and 15/12, only if the wet bulb and wind speed conditions are met, until a maximum of 150 $\mathrm{kg\,m^{-2}}$ of water is converted into artificial snow, i.e. 25 cm of artificial snow at 600 $\mathrm{kg\,m^{-3}}$, taking into account 40% initial water loss (combining evaporative losses and the fact that not all of the machine made snow falls on the ski slopes). Between 15/12 and 31/03 the production can take place (again, if the wet bulb temperature and wind speed conditions allow) as soon as the snow depth falls below 60 cm. There is no more production after 31/3. The model calculates the water demand corresponding to snow production, without imposing limits to the availability of water used for snowmaking.

For areas besides the ski slopes, only natural snow cover processes are considered, and we ignore, in the calculations relevant to the natural snow cover, the fact that some of the machine made snow falls on the areas surrounding the ski slopes (although, as introduced above, it is subtracted from the amount of snow falling on the ski slopes). When results are aggregated over areas combining ski slopes and their surrounding, this approach therefore overestimates the impact of snowmaking on the hydrological balance of the catchment covered by the ski pistes, because a fraction of water used for snowmaking is assumed to be lost due to snow production, although in practice some of it is added to the snow cover surrounding the ski pistes.

The snowpack interacts with the underlying soil, represented by the SURFEX/ISBA land surface model (Masson et al., 2013). Thermally, the underlying soil is coupled to the snowpack through a thermal diffusion scheme. This makes it possible to represent the insulating effect of the snow, according to its physical properties, and the thermal interaction between the snow, the ground and the atmosphere. From the hydrological point of view, several water fluxes are calculated by the model, and available at daily time step in the simulation results produced for this study. This study focuses on quantifying the impact of snow management on water availability in the watershed. The main water flux analysed and used is therefore the amount of water reaching the upper soil interface, which combines the water flux flowing at the base of the snowpack (due to snow melt) with the liquid precipitation (rain) on snow-free ground. This variable is referred to as the “total liquid water reaching soil”. Figure 1 illustrates the water fluxes involved, which are represented by the SURFEX/ISBA-Crocus model.

2.2 Model simulations

In this work, consistent with many previous studies using snow cover modelling in French mountainous regions, the Crocus model is driven by meteorological conditions estimated by the SAFRAN reanalysis (temperature, precipitation, wind speed, radiation) (Vernay et al., 2022). We focus here on the time period from 1986 to 2015, used as a reference time period, and the 2019-2020 ski season used for some illustrations. Consistent with the geometry of the SAFRAN modelling system leading to the SAFRAN meteorological reanalysis, the simulations are performed by 300 m altitude bands within spatially homogeneous areas (massifs), on flat terrain and for slopes of 10, 20, 30, 40°, for 8 main aspects (N, NE, E, SE, S, SW, W, NW). The use of SAFRAN reanalysis data feeding the Crocus model including snow grooming and snowmaking has been used as such for other studies (Spandre et al., 2019; Gerbaux et al., 2020; Morin et al., 2021; Ebner et al., 2021), which demonstrated its ability to reproduce observed snow conditions on ski slopes.

2.3 Geographical representation of the ski resort and catchments

Our study uses the concept of Ski resorts Representative Units (SRUs), introduced in Hanzer et al. (2020). This approach identifies unit elements characterizing the ski pistes (or their surrounding environment), intersecting their elevation and aspect distribution with the presence or absence of snowmaking equipment. Here we use the topographical clustering of the SAFRAN

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Preprint. Discussion started: 29 November 2022

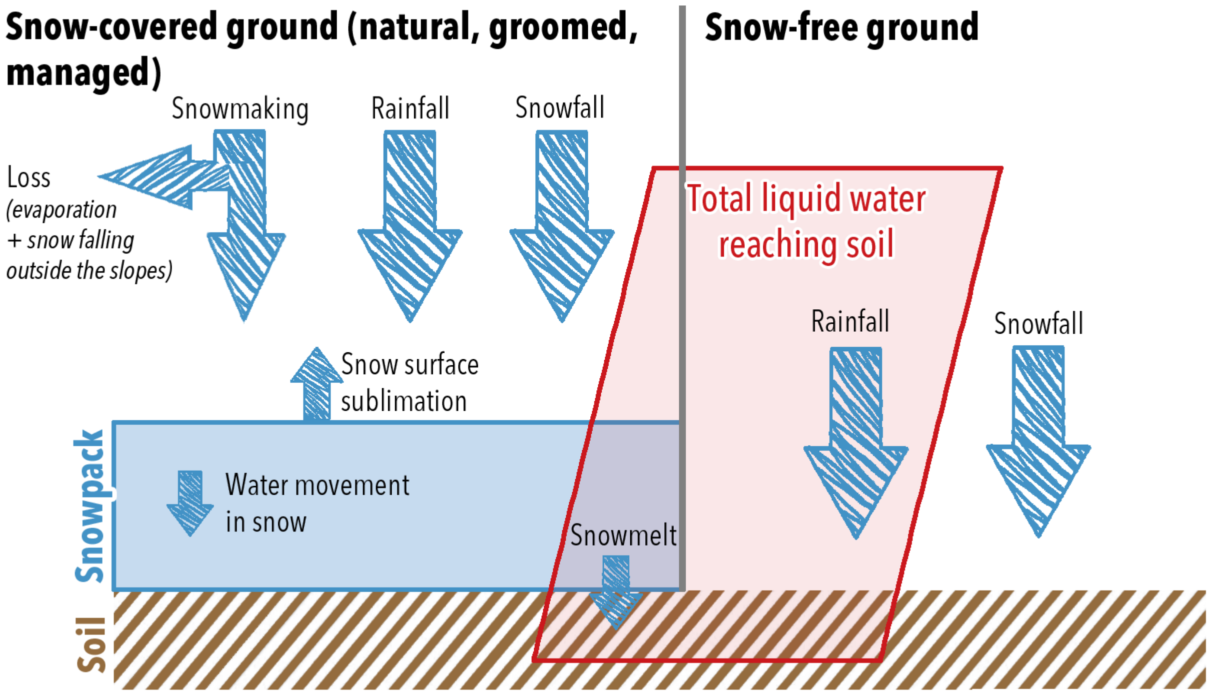

Figure 1. Schematic representation illustrating the total liquid water reaching soil, used in this study, calculated as the sum of rainfall over snow-free areas and liquid water fluxes exiting the snowpack.

reanalysis, described above. Due to the geographical location of the La Plagne ski resort, atmospheric forcing data are all taken for the Vanoise massif (Vernay et al., 2022). A given SRU is either concerned with natural snow (outside ski pistes), or, on ski pistes, grooming only, or grooming+snowmaking. Snow cover simulations are carried out for each SRU, and their results can be combined according to their surface area (Hanzer et al., 2020; Ebner et al., 2021).

The wider ski resort area is defined by its gravitational envelope. This concept was introduced by François et al. (2014) and later refined and implemented by further studies (François et al., 2016; Spandre et al., 2019; Berard-Chenu et al., 2022a). Indeed, there is no standard delineation of the ski resort domain. The gravitational envelope corresponds to the geographical domain accessible downhill from the top of all the ski lifts and reaching the bottom of one of the ski lifts. Not all of the gravitational envelope consists of ski pistes (they cover, on average 10% of the surface area according to Spandre et al. (2019)) and is even accessible to skiing, but it provides a representative and usable boundary for the area characterizing the ski resort, based only on the catalogue of ski lifts and the local topography.

Hydrological catchments at the scale of the ski resorts were derived from the high resolution DEM BD-Alti, using the method HydroDEM approach. HydroDem is a set of computer routines for processing digital elevation models from a hydrological perspective. Developed to support the scientific development of geostatistically based runoff mapping routines (e.g. Gottschalk et al., 2006), the HydroDem computer code is quite similar in its basic features to the well-known TauDem software (https:

//hydrology.usu.edu/taudem/taudem5/index.html). Over the years, HydroDem has been used as an aid for delineating drainage patterns in a variety of medium- and large-scale distributed hydrological model applications (e.g. Thierion et al., 2012, as in this study.

2.4 Climate change simulations

In addition to simulations spanning previous years based on the SAFRAN reanalysis (Vernay et al., 2022), we introduce simulations under future climate change conditions. These simulations are based on one model run of the GCM/RCM pair CNRM-CM5/ALADINv6, part of the EURO-CORDEX ensemble (Jacob et al., 2014; Kotlarski et al., 2022) for the high-emission scenario RCP8.5 for a 15 years time period in the middle (2043-2057) and the end (2083-2097) of the 21^{st} century. These simulations are carried out using the Crocus snow cover model configuration introduced earlier, driven by RCM model ouput adjusted with the ADAMONT adjustment method (Verfaillie et al., 2017) using the S2M reanalysis as the reference (see Verfaillie et al., 2018, for more details). These simulations are processed similarly to the SAFRAN-driven simulations, and are meant to illustrate how the results obtained in past and current climate conditions are potentially modified under a warmer climate - although this study does not address the diversity of the sources of uncertainty involved in climate change simulations. Note that the multi-annual temperature and precipitation values at the scale of the French Alps at 1800 m elevation, for the ADAMONT-adjusted results of the CNRM-CM5/ALADINv6 GCM/RCM pair correspond the median of an ensemble of 19 adjusted GCM/RCM pairs, for the time period 2090-2099 under RCP8.5 (Monteiro et al., 2022). This choice of GCM/RCM pair can therefore be considered as representative of the mean climate change signal, pending further investigations using a genuine ensemble of climate model simulations.

2.5 Pilot ski resort characteristic

This study uses the ski resort La Plagne to implement and demonstrate the method developed. La Plagne is the largest ski resorts in France, one the of world largest ski resorts, with over 2 million skier visits annually (Vanat, 2021), located in the Northern French Alps. It spans an elevation range from 1250 m to 3250 m above sea level, and includes 528 hectares of ski slopes (Ebner et al., 2021). Figure 2 shows the geographical location of La Plagne, and shows the geographical distribution of its pistes with and without snow grooming.

The main snowmaking technology used in La Plagne are lances, so that simulations used for this study consist of natural snow simulations, groomed snow simulations and snow simulations taking grooming and lance snowmaking into account. At the scale of the entire ski resort, 40.2% of the surface area of ski pistes is equipped with snowmaking, which is higher than the average value for French ski resorts (Berard-Chenu et al., 2022b). The surface area of ski pistes corresponds to 9.7% of the surface area of the gravitational envelope, so that, ultimately, the gravitational envelope is covered at 3.9% by ski pistes equipped with snowmaking. Snow production is ensured by water stored in five reservoirs (Prajourdan, Lovatière, Forcle, Pierres Blanches and Montchavin, see Figure 3) located in or near the ski resort. Water is taken from various sources (surface or ground) to fill these reservoirs. Some reservoirs are managed under a two-fold purpose, i.e. meeting water demand for snow production and water supply for domestic uses.

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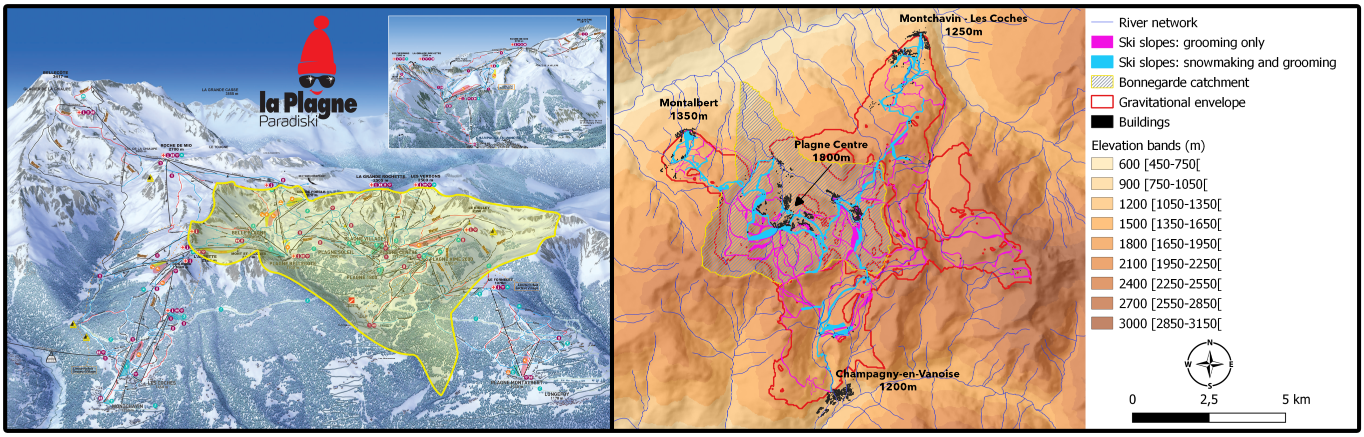

Figure 2. Maps of the La Plagne ski resort, with the Bonnegarde catchment in yellow. On the right hand side, detailed map of ski pistes with (blue) and without (pink) snowmaking, location of main villages. Left hand side : landscape image provided by the La Plagne ski resort, overlay of the Bonnegarde catchment by the authors. Right hand-side : Hillshaded background derived from EU-DEM v1.1 (Copernicus Land Monitoring Service), further geographical information from BD Alti provided by IGN at the 25m resolution, geographical information on location and status of ski pistes provided by the La Plagne ski resort (generation of the map by the authors, see text for methodological information).

Figure 3 shows the unit catchments intersecting the ski pistes for the Bonnegarde catchment and its subcatchments, including the Frasses catchment, which are analyzed in more details in this study. These catchments are located at the heart of the La Plagne ski resort, including major villages and ski tourism hosting infrastructure. This figure illustrates the complexity of the interaction between the spatial organization of the ski resort and the local hydrological context. The Frasses catchment has a surface area of 4.71 km^2 (471 ha), and 15.2% of its surface area is covered by ski slopes. The Bonnegarde catchment, which includes the Frasses catchment, has a surface area of 23.61 km^2 (2361 ha), and 19.4% of its surface area is covered by ski slopes. The outlet of the Bonnegarde catchment almost directly reaches the Isère river flowing though the Tarentaise valley. In this area, information on hydrology is rather sparse:

1. river flow measurements have been collected between June and mid-November at a single location (corresponding to a catchment surface area of 3.85 km^2) along the Frasses river since 2013 ;
2. a gauging station now closed ("Gauging station" in Figure 3; 4 km^2) recorded discharges over two discontinuous periods (1948-1968 and in 1980).

The discharge data were corrected for upstream water diversion (transfer out of the gauged catchment mainly in summer for irrigation purposes through an open channel) to assess natural water resources. Water abstraction data were provided by the French national database BNPE (Banque Nationale des Prélèvements quantitatifs en Eau, https://bnpe.eaufrance.fr/), including time series of annual withdrawals, location, use (industry, energy production, irrigation. . .) and source (surface- or

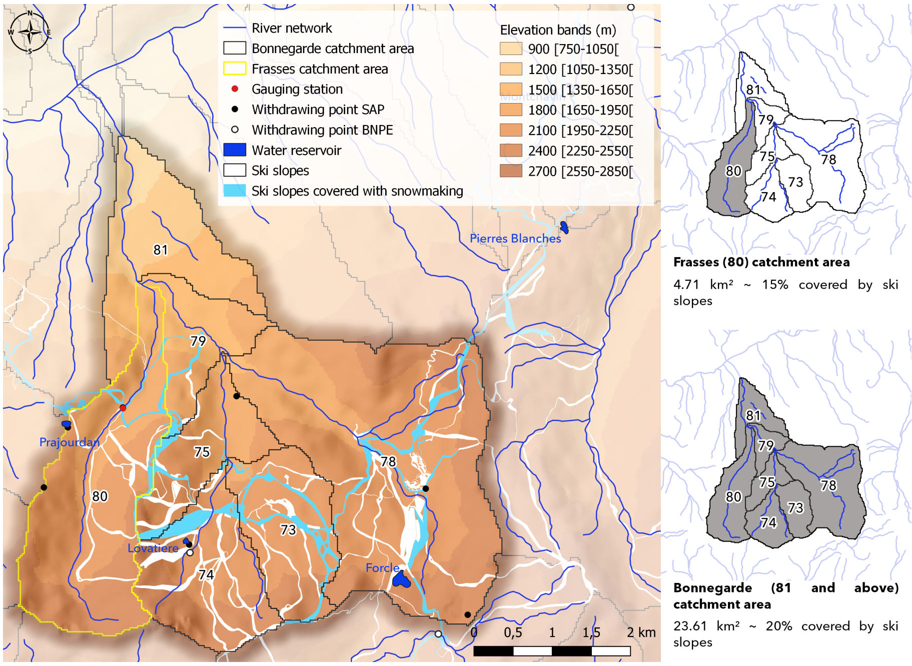

Figure 3. Detailed map of the Bonnegarde catchment, illustrating its various subcatchments, including the Frasses catchment. Hillshaded background derived from EU-DEM v1.1 (Copernicus Land Monitoring Service), further geographical information from BD Alti provided by IGN at the 25m resolution, geographical information on location and status of ski pistes provided by the La Plagne ski resort (generation of the map by the authors, see text for methodological information).

groundwater) since 2008. Local databases provide complementary information on water management such as the location of the main withdrawing point for snowmaking ("Withdrawing point SAP"), weekly water volumes stored in each reservoir for snow production between 2007 and 2020, contribution of each reservoir to snow production over each ski piste, synoptic diagram of the drinking water networks, monthly volume abstracted for and released from reservoirs for drinking water supply between 2016 and 2020. For reasons of national security, the exact location of the pumping structures for drinking water (referred as "Withdrawing point BNPE" in Figure 3) is not publicly available.

3 Results

3.1 Influence of grooming and snowmaking on snow cover characteristics and total liquid water reaching soil at 1800 m elevation

Grooming and snowmaking influence the characteristics of the snowpack and this translates into its hydrological behaviour. As an example, figure 4 displays, for the winter season 2019-2020, the time evolution of the snow depth for natural, grooming

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and grooming+snowmaking simulations at 1800 m elevation in the Vanoise massif, typical of the situation of the La Plagne ski resort. Several key features are highlighted on this figure. First of all, it shows that simulations with groomed snow result in lower snow depth, due to the compaction induced by the grooming process. At the end of the season, the snow melt-out date occurs later in groomed snow simulations compared to natural snow simulations. This effect, described and analyzed in Spandre et al. (2016b), is due to the generally higher snow density due to grooming, thus higher thermal conduction through a groomed snowpack, leading to more efficient loss of energy from the snowpack (and underlying ground), especially at night, progressively inducing colder conditions in the snowpack (and underlying ground) and delaying melt processes. Simulations with snowmaking lead to higher snow depth values since the beginning of the season (due to additional snow mass added to the snowpack through snowmaking). The melt-out date is further delayed compared to grooming-only simulations (but comparatively less than between groomed and natural snow simulations), due to the additional mass that needs to be melt until complete melt-out. The cumulative total precipitation over the entire hydrological year matches exactly the cumulative total liquid water reaching soil for the natural snow and grooming snow simulations, which indicates that evaporation from the snowpack plays a negligible role in the simulation results. In contrast, when snowmaking is taken into account, the cumulative value of total liquid water reaching soil exceeds total annual precipitation, due to the addition of snow through snowmaking.

3.2 Influence of grooming and snowmaking on total liquid water reaching soil aggregated over the gravitational envelope of the ski resort

We now turn to the aggregated influence of grooming and snowmaking on liquid water reaching soil, at the scale of the entire La Plagne ski resort (gravitational envelope). Note that this does not bear direct hydrological relevance because the ski resort intersects independent catchments on different aspects of the mountain over which the ski resort develops (see Figure 3). Here, we also assume that 100% of the ski pistes are covered with snowmaking.

Figure 5a shows the aggregated amount of liquid water reaching soil for the hydrological year 2019/2020, aggregated only over the ski pistes, i.e. neglecting all areas surrounding the pistes. The figure displays daily (instantaneous) and cumulative (from August 1^{st} 2019 to August 1^{st} 2020) values. In this case, the simulation shows that for most of the winter season, the simulations including grooming (with and without snowmaking) lead to lower values of the total liquid water reaching soil, almost none during the winter, than natural snow simulations. In terms of cumulative amounts, not only the cumulative values for the natural snow cover simulation increases steadily during the winter season due to higher basal snowmelt than for groomed or grooming+snowmaking snow simulations, but the late season melt peak starts earlier. Natural and grooming+snowmaking snow cover simulations converge, in terms of cumulative total liquid water reaching soil, in early June, and the cumulative values remain very close until the end of the season (with slightly higher cumulative values for the groomed snow than the grooming+snowmaking simulations by 1.7% on July 1^{st}). Simulations including snowmaking converge around the same date, but then keep increasing over the end of the season, exceeding the total amount of liquid water reaching soil by about 800,000 m^3, corresponding to 11.1% of the annual total liquid water reaching soil. Aggregated over the ski pistes only, the results reveal that grooming (with or without snowmaking) exerts a substantial influence on the water balance. This is mostly due to the fact that grooming leads to essentially suppressing winter snowmelt (leading to deficits, reaching more than

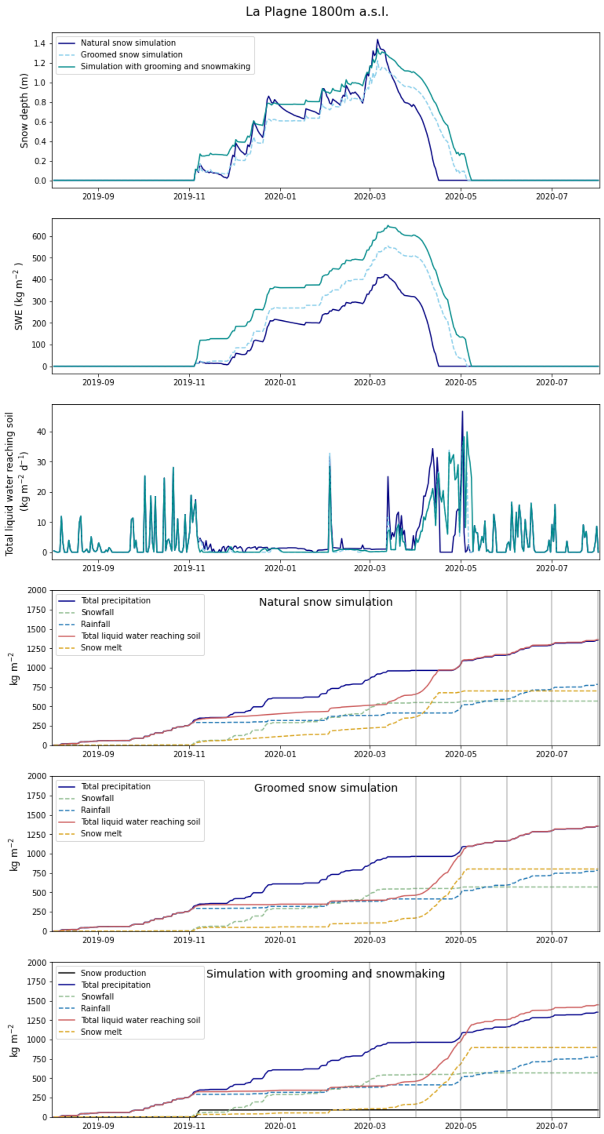
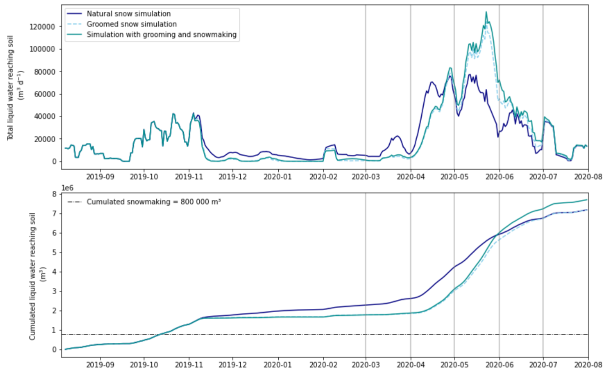


Figure 4. Model simulations at 1800 m elevation, representative for the La Plagne ski resorts, with natural snow simulation (blue solid line), groomed snow simulation (dashed light blue line) and the simulation with grooming and snowmaking (green solid line), for the hydrological 2019-2020. From top to bottom, the panels display snow depth, snow water equivalent (SWE), liquid water reaching soil surface, and cumulative water fluxes for the three simulations. These show total precipitation (solid blue line), snowfall (green dashed line), rainfall (blue dashed line), liquid water reaching soil (red solid line), snow melt (orange dashed line). The last panel further shows snow production (black solid line).

-40%, on cumulative total liquid water reaching soil in April), while snowmaking influences mostly the water balance towards the end of the melt season.

a) Aggregation over all ski slopes (assuming 100% snowmaking coverage)



b) Aggregation over gravitational envelope (about 10% of surface covered with ski pistes)

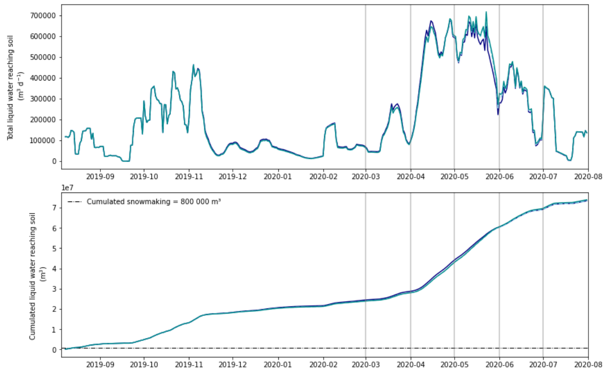


Figure 5. Aggregation over all ski slopes (a) and for the entire ski resort gravitational envelope (b) of the daily liquid water reaching the soil and cumulative liquid water reaching soil, respectively, for the natural snow (blue solid line), grooming snow on ski pistes (green dashed line) and grooming and snowmaking on ski pistes (green solid line).

Figure 5b provides similar types of results as Figure 5a, but the aggregation now extends to the entire gravitational envelope of the ski resort. The differences between the configurations is smaller, with a deficit of cumulative total liquid water reaching soil on the order of -5% as of April for the grooming and grooming+snowmaking configurations on ski pistes, compared to a simulation when natural snow cover processes only are considered for the whole domain. In the case when snowmaking is taken into account, the excess in total annual liquid water reaching soil amounts 1.1% of the value for natural snow processes only. The difference between the results of the two scales of aggregation is directly linked to the surface area covered with ski pistes, which is generally on the order of 10% in French ski resorts (François et al., 2016), and specifically 9.7% for the La Plagne ski resort.

3.3 Results for the Frasses and Bonnegarde catchments

We now introduce results focusing on two actual hydrological catchments, Frasses and Bonnegarde (Frasses is a subcatchment of Bonnegarde, see Figure 3). Here, the water balance is assessed at different time scales (from week to year) to quantify the impact of the snowmaking operations on river flow regime within the ski resort, regarding natural resources and other water uses. The approach is purely empirical, combining information on snowmaking process, water abstraction and consumptions, and numerical snow cover simulations. It enables the quantification of how the grooming and snowmaking water footprints develop along the river network.

The Bonnegarde catchment is ungauged. There is only one gauged catchment in the neighbourhood, which prevents from using advanced regionalisation approaches to predict river flow characteristics at this location. The drainage-area ratio method was thus applied considering that the runoff per unit drainage area is equal over the ski resort catchment. The other working hypotheses are the following:

- Transfers between reservoirs do exist but are neglected,
- Monthly volumes for drinking water are evenly distributed within the month at weekly time step,
- The effect of the snow grooming and snowmaking is provided by the simulated values of total liquid water reaching soil described above, and is given by the average difference between natural snow and grooming+snowmaking simulations of total liquid water reaching the soil at the weekly time scale over the period 1961-2020 and for the entire ski resort gravitational envelope. The obtained values are then divided by the total volume to provide a dimensionless pattern for each ski slope. The hydrological alteration is calculated for each ski slope as the sum of this pattern multiplied by 60% of the total volume of water used for snowmaking, and the mean pattern of total liquid water reaching soil simulated considering natural snow, multiplied by 30% of the total volume of water used for snowmaking.
- Values for the volumes of snow produced are given for each equipped slopes and are aggregated at the catchment scale in proportion to the length of the slope crossing the catchment.

The results are presented starting the series at week 31 (which includes August 1^{st}) on Figures 6 and 7. Inter-annual averaged values for week 53 are added to those for week 52. Because of the skewed distribution of mean weekly discharges, the y-axis is represented with a square root scale. Negative values represent water losses. The water balance is computed at the seasonal and yearly time scales (Table 1), from data with distinct periods of availability (e.g. 2007-2020 for reservoir management, 2014-2020 for water used to produce snow, 2016-2020 for drinking water amounts, and 1948-1968 for water resources). Hence, the results can be viewed as a "typical" water year, compositing information from different time periods, due to the heterogeneities of the data sources.

Figures 6a and 7a show that the seasonal pattern of river flows for both catchments is typical of snowmelt-dominated regimes with high flows in spring or early summer and winter minima caused by freezing. The different types of water use alter in different ways the river flow regime. The impact of water supply (Figures 6b and 7b) is highly variable in both space and time even within a rather small ski area. According to the schematic diagrams of water supply, all the volumes abstracted for domestic uses within the Frasses catchment are consumed and returned to rivers outside the catchment. The effect of tourism is noticeable for the Bonnegarde catchment, which includes the main village La Plagne Centre with the highest capacity of tourist accommodation (Figure 2): two peaks occur - one during the ski season (from December to April) and the second one in summer (July and August) - for areas at high elevation while drinking water consumption shows less seasonal variation at lower elevation where the influence of tourism is reduced.

The patterns of weekly water abstraction for snowmaking (Figures 6c and 7c) is quite similar for the two catchment. However, analysing abstracted volume at the catchment scale hides heterogeneities. The seasonal patterns differ from one reservoir to another, and from one year to another, due in particular to technical constraints (availability of an overflow on intakes shared with the water supply) and regulatory constraints (compliance with ecological flows). Withdrawals to the Prajourdan reservoir (sub-catchment 80, see Figure 2) are concentrated in autumn and winter, while those to the Lovatière reservoir (sub-catchment 74) are evenly distributed throughout the year and those to the Forcle reservoir (sub-catchment 78) are concentrated in summer.

Grooming and snowmaking modifies river flows throughout the year except in summer. Snow is first produced to provide a ground layer of snow before natural snowfalls (November-December), and afterwards (up to end-March) to maintain a minimum snow depth for skiing (Figures 6d and 7d). Melting processes as described in the previous section are delayed and the snowmelt peak is observed between April and May (Figures 6e and 7e).

The effect of the grooming and snowmaking operations on river flow regime (Figures 6f and 7f) is the sum of individual alterations. Alterations are mainly due to abstractions for filling reservoirs. Grooming and snowmaking modify the natural flow regime of rivers crossed by the ski area in different ways. At the catchment scale, the first modification is linked to the process of filling the reservoirs for snow production; the filling up is constrained by regulations on ecological flows and by the water availability in reservoirs shared with other uses (water supply for the La Plagne ski resort). The filling starts in autumn, before the first phase of snow production. The second effect is related to the presence of groomed snow on the ski slopes and on the hillsides. Water in solid form is added to the natural snow cover and delays snow melting processes. In winter, the presence of this additional stock leads to more severe low flows while, later, river flows increases due to increased amount of snowmelt water in spring. When points and sources for water abstraction, and equipped ski slopes, are located within the same basin, the effects are only apparent at the seasonal scale (machine-made snow then plays the role of an additional buffer reservoir with storage in autumn and release in next spring) and rather neutral on the annual scale in terms of water resources.

In the two catchments, snowmaking causes water losses because water abstracted for production is transferred to other nearby areas: the water balance is overall negative for both catchments (Table 1), but it is overall positive for the surrounding areas, which benefit from the water imported from the reservoirs. Note also that the pressure on the resource is not evenly distributed within the year. The pressure is highest in winter, with total withdrawals of around 20% of the resource for the Frasses catchment and around 10% for the Bonnegarde catchment. This is the low-water period in mountainous areas and this use may compete with water supply for domestic use (Leroy, 2015).

Table 1. Water balance at the catchment scale (× 1000 m^3)

	Water resources	Drinking water consumption	Abstraction for reservoir filling	Snow production	Grooming and snowmaking effect	Alteration due to snowmaking and grooming
	Frasses catchment					
DJF	518.9	-35.3	-91.4	34.1	-10.2	-101.6
MAM	2210.2	-25.7	-5.7	0.7	13.9	8.1
JJA	3476.8	-25.4	-19.3	0.0	50.0	30.8
SON	1261.5	-13.2	-27.6	23	-1.6	-29.3
Year	7467.4	-99.6	-144	57.9	52.1	-91.9
	Bonnegarde catchment					
DJF	2600.9	-67.8	-215.5	113.2	-30.0	-245.5
MAM	11079.2	-44.9	-26.5	2.9	-11.2	-37.6
JJA	17428.4	-36.1	-67.6	0.0	212.5	144.8
SON	6323.7	-19.2	-92.2	64.3	-9.0	-101.2
Year	37432.2	-168.0	-401.8	180.4	162.3	-239.5

3.4 Climate change simulations

Figure 8 shows, for the Bonnegarde catchment, the evolution of the monthly cumulative values of total liquid water reaching soil under past climate (1986-2015, based on the S2M reanalysis) and for two future time periods in the middle (2043-2057) and the end (2083-2097) of the 21^{st} century using the adjusted GCM/RCM pair CNRM-CM5 /ALADINv6 for the high-emission scenario RCP8.5. Figure 8a shows the evolution of the total liquid water reaching soil for grooming snow conditions on ski slopes, showing the typical trend towards an earlier snowmelt peak under a warming climate in mountainous catchments (Hock et al., 2019). Figure 8b shows the results accounting for snowmaking on the ski slopes equipped with snowmaking, with an overall similar pattern. Figure 8c shows the difference, for each future time period, between the simulations with and without snowmaking (on ski pistes equipped with snowmaking), in absolute terms, and for Figure 8d in relative terms. It shows that the impact of snowmaking on the monthly total liquid water reaching soil is maximum in June under past climate conditions (on the order of 10% of the monthly value, on average), and progressively shifts towards earlier time period under a warmer climate, peaking to 20% difference, on average, in May, at the end of the 21^{st} century under RCP8.5. The difference in cumulative total liquid water reaching soil as of July 1^{st}, whose base values is 1.80%, on average for the reference period 1986-2015 based on reanalysis simulations, reaches 2.02% for the time period 2043-2057 and 2.16% for the time period 2083-2097, under RCP8.5. This moderate change is mainly due to the fact that the amount of snowmaking remains rather constant in the simulations under future climate change, mostly because the total amount of snowmaking early in the ski season is bounded in the model. The impact of snowmaking on monthly total liquid water reaching soil remains lower, on the order of 2 Mm^3, than shifts in snow melt seasonal patters due to climate change, both in terms of annual and monthly values.

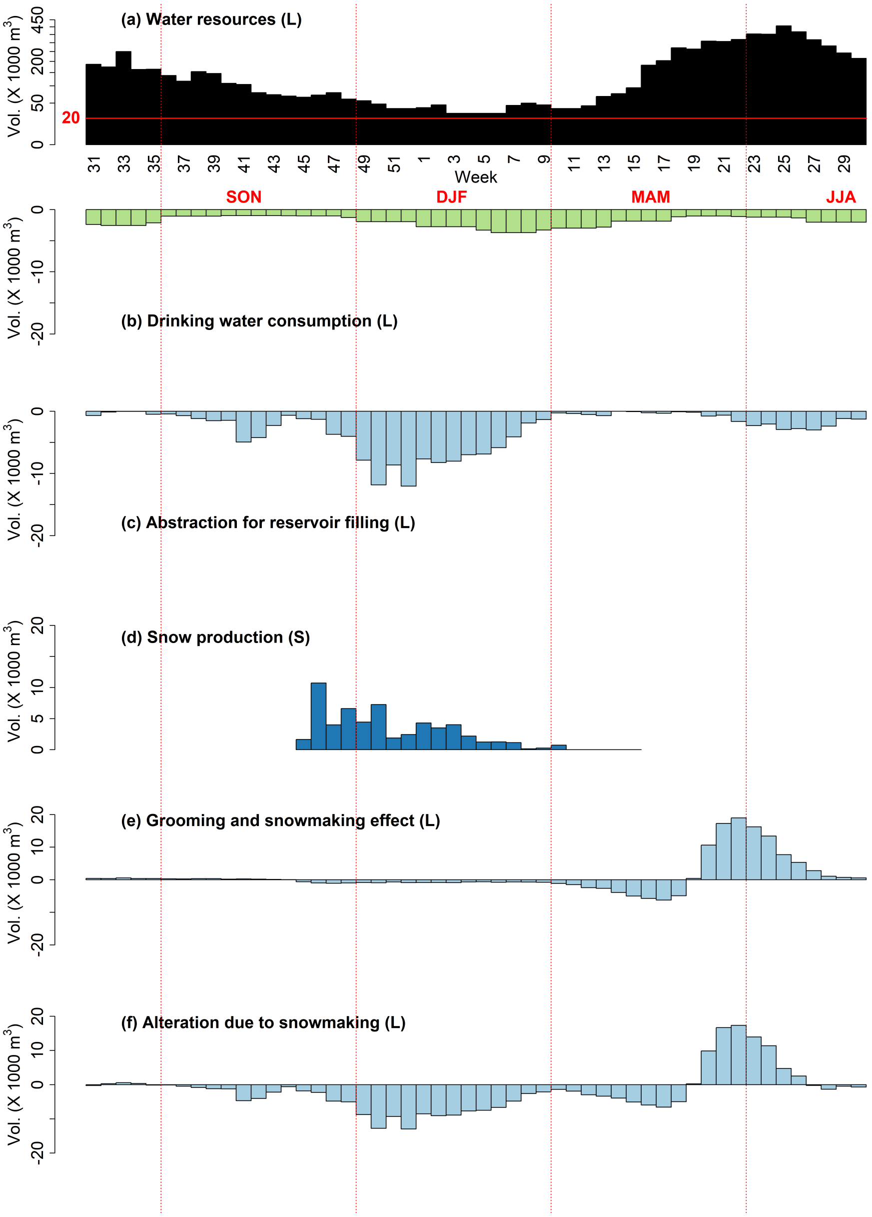


Figure 6. Water resources, abstraction and consumption for the Frasses catchment including water phases (S: solid; L: liquid).

4 Discussion

The hydrological influence of snow grooming and snowmaking in ski resorts is a critical issue related to the governance of water resources in mountain areas under climate change. This requires that adequate data and knowledge is produced and conveyed to relevant parties, both at the local scale but also taking into account the upstream/downstream connection that binds together

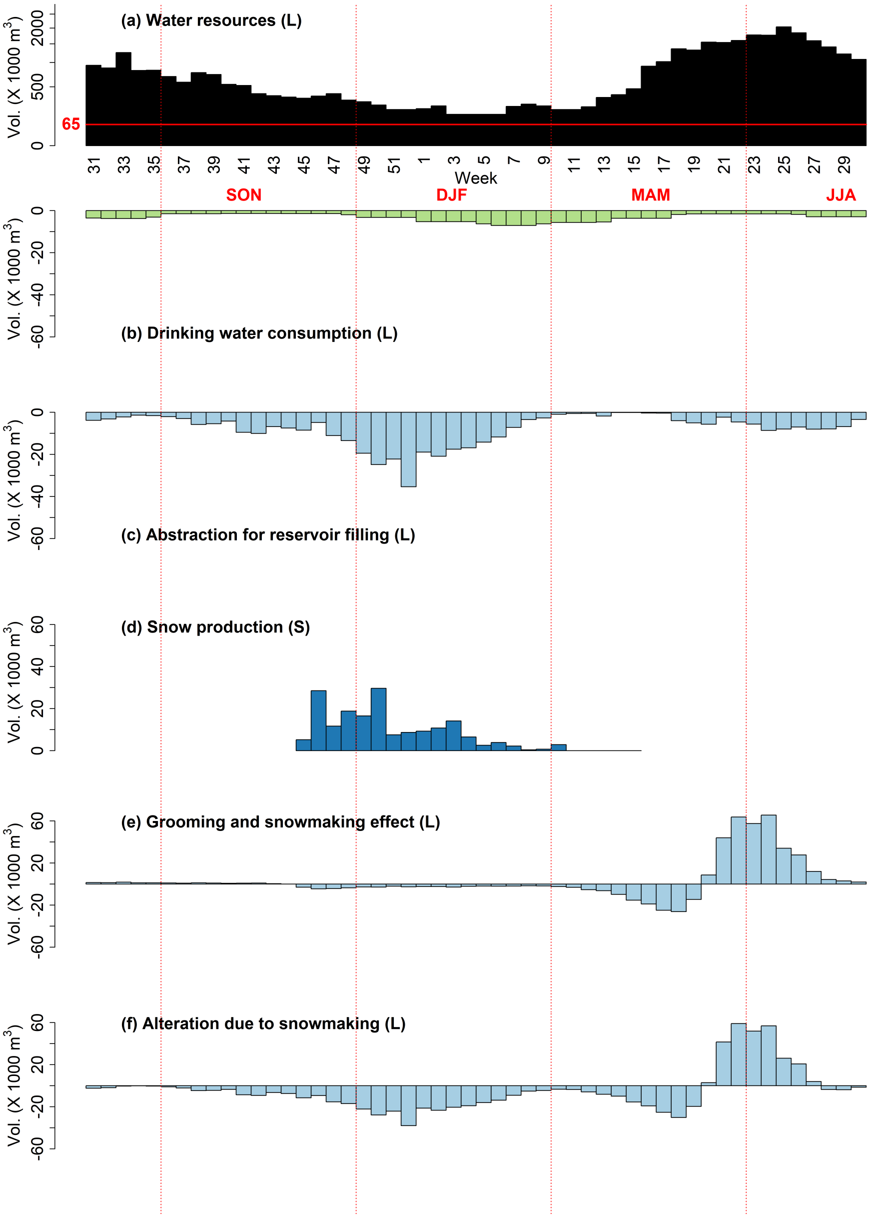


Figure 7. Water resources, abstraction and consumption for the Bonnegarde catchment including water phases (S: solid; L: liquid).

mountain areas water with lower lying areas (Leroy, 2015; Hock et al., 2019; Adler et al., 2022; Tschanz et al., 2022). In order to contribute to addressing this knowledge gap, the present study explores the influence of grooming and snowmaking on the hydrological regime of alpine catchments within which ski pistes are located. It introduces a method for such an investigation,

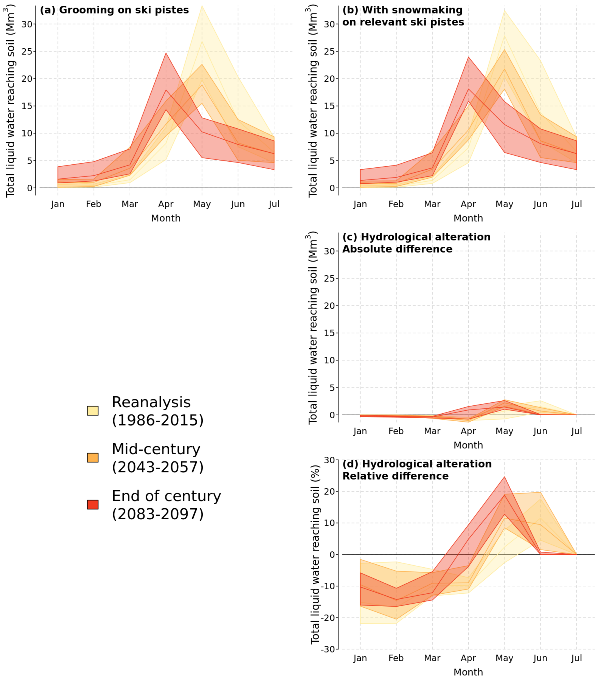


Figure 8. Monthly cumulative total liquid water reaching soil for the Bonnegarde catchment for the time periods 1986-2015 (reanalysis) and for two future time periods in the middle (2043-2057) and the end (2083-2097) of the 21st century using the adjusted GCM/RCM pair CNRM-CM5/ALADINv6 for the high-emission scenario RCP8.5. For each time period, the central line corresponds to the median value, and the shaded area spans the 20-80 quantiles of multi-annual values. (a) Natural snow cover around ski slopes, grooming-only over ski pistes; (b) natural snow cover around ski slopes, grooming over ski pistes, with snowmaking over ski pistes equipped with snowmaking ; (c) absolute difference between (a) and (b) ; (d) relative difference between (a) and (b).

which is demonstrated using the case study of the La Plagne ski resort, specifically. Prior to discussing the implications of the results, we first highlight some of the key limitations of this work.

4.1 Limitations

The current study introduces a method, based on existing snow cover modelling tools designed to carry out numerical simulation of the snow cover in ski resorts (Spandre et al., 2016b; Hanzer et al., 2020; Ebner et al., 2021), in order to assess the influence of snow management on the hydrology of associated catchments. Using such tools enables to place emphasis on the simulation of snow cover, with and without grooming and snowmaking, yet this does not pretend to encompass the complexity of hydrological processes that a detailed hydrological model would allow to account for. Yet, our results provide novels insights, which have not been described before, to the best of our knowledge. For example, our study illustrates the substantial role of grooming on the behaviour of the snowpack and in particular basal melt, which is essentially suppressed due to groom-

https://doi.org/10.5194/egusphere-2022-1186
Preprint. Discussion started: 29 November 2022

ing. Such results would not be revealed using snowpack models not accounting for snow physics, in a way sufficiently detailed so as to account for the influence of the grooming process. For example, snowpack components of hydrological models, which are formulated in terms of a single snow mass reservoir (snow water equivalent), with a melt rate formulation only dependent on air temperature and, potentially, radiation (temperature-index models), cannot account for the different physical behaviour of snow on ski pistes, compared to the surrounding natural snow cover. Likewise, our approach enables to explicitly account for snowmaking on the snowpack properties, although we here use a standard modelling approach for snowmaking, which could be adjusted to better represent local snow management practices in the model (Abegg et al., 2020). Yet our approach provides a quantitative appraisal on the influence of snowmaking on the water budget of the related catchment.

However, several key hydrological processes are missing in our approach and can affect the results. Indeed, our modelling approach provides estimates of the total liquid water reaching ground, but does not represent subsequent processes, such as evapotranspiration from the ground and vegetation, ground water dynamics and runoff routing and generation at the outlet of the catchment. However, we reduce the impact of this limitation by comparing simulations with and without snow grooming and snowmaking, which enables to focus on the hydrological forcing induced by the snowpack, independent on the other hydrological components. The current study can be used to trigger the development of more complex, integrated modelling approaches, within which snow cover processes can be represented consistent with the approach described here, while hydrological processes can be represented with more details. This also applies to the representation of the balance between the water demand induced by snowmaking, and the water availability from various sources, including the fact that water can be withdrawn from one catchment, stored, and used in another catchment. However, developing models capable of representing this full complexity through a genuine, two-ways coupling between snow cover simulation, including snowmaking, and the hydrological functioning of mountainous catchments at the local scale of a few hundreds of meters of horizontal resolution, represents a very challenging endeavour (Hanzer et al., 2014). Furthermore, this approach would be difficult to transfer to other locations. In contrast, we suggest that our approach can be further tested by other teams, and used in combination with other data sources, in order to better assess the balance between water demand and water availability, and local and downstream impacts, and contribute to better informing discussions relevant to water management in mountain regions.

4.2 Implications

Notwithstanding the limitations highlighted above, this study brings novel insights into the influence of snow management on the hydrology of mountain catchments intersecting ski resorts. While the detailed results are provided and directly applicable to the case study under scrutiny, the ski resorts of La Plagne, in the Northern French Alps, this study bears implications for the related scientific domain, and for water resources management and ski resorts in mountainous areas. First of all, our results highlight that the hydrological disturbance due to snow management scales, to a large extent, with (i) the surface area covered with ski pistes, driving the deficit in winter snowmelt due to grooming, and the (ii) fractional snowmaking coverage, driving the amount of excess snowmelt due to snowmaking (and the corresponding amount of prior water abstraction). Further, the influence of snowmaking is directly related to the ratio between the amount of machine made snow produced and total precipitation (aggregated over the surface equipped with snowmaking). In fact, our study points to the rule of thumbs that multiplying the ratio between snowmaking amount and winter precipitation, with the fractional coverage of snowmaking on ski pistes and the fraction of the catchment covered by ski pistes, provides an estimate of the magnitude of the difference in hydrological regime induced by snowmaking. In the case of the La Plagne ski resort studied here, the annual snow production corresponds to 10 to 20% of the annual precipitation. Ski pistes cover about 10% of the surface area of the entire ski resort, but can cover up to 20% of some smaller catchments. The fractional coverage of snowmaking is an additional multiplying factor to infer the influence of snowmaking on hydrological regime at the outlet of the concerned catchments.

Our results enable to discuss to what extent water is only "borrowed" to be used for snowmaking. This term is often mentioned by snowmaking promoters, and condemned by opponents, who consider that water withdrawn for direct or indirect (through filling reservoirs) use for snowmaking is lost. Our analysis, based on the detailed snow cover model Crocus, which represents the mass and energy fluxes at the interface between the snow cover and the overlying atmosphere, shows that there is little to no additional evaporation from the snow cover in the situation where snowmaking is applied. Besides the 10% evaporative water loss during the process of ice droplet solidification into ice spheres which forms the basis of snowmaking (Eisel et al., 1988, 1990; Spandre et al., 2016a; Grünewald and Wolfsperger, 2019), our results indicate that, in the situation prevailing in the Northern French Alps, there is little to no further loss of water through snowmaking. This situation is in contrast with the substantial water loss associated with irrigation, in agriculture (Boulet et al., 2020), to which snowmaking is often compared (Steiger et al., 2019). Water storage for agriculture is often questioned, in particular due to the fact that strong evaporation from the reservoirs can occur, leading to direct loss of stored water (Rodrigues et al., 2020), and that water used for irrigation is lost through the evapotranspiration of the agricultural plants and soils. Due to colder temperature prevailing at the location where water reservoirs used for snowmaking are built, it is likely that the evaporation rate from such reservoirs is much smaller than from lower elevation agricultural reservoirs. Nevertheless, this needs to be assessed in detail. Through these two aspects (lack of "evapotranspiration" from the snowpack, and different, probably lower evaporation rate from water storage reservoirs), it appears that snowmaking differs markedly from water use for agriculture irrigation, thus this comparison may be partially misleading from a water management perspective. To a large extent, it appears from our study that the effect of snowmaking on the hydrological regime of the catchments affected by the presence of ski resort is rather neutral at the annual scale, and mostly operates at the seasonal scale, by storing water masses temporarily, on the order of a few % of the water at the scale of the catchments, either in reservoirs prior to snowmaking, or in the form of snow itself through snowmaking. In terms of water quantities, snow grooming and snowmaking mainly leads to shifting the water cycle in time (at the seasonal scale) and space (through water transfers in some cases).

4.3 Future climate

Our analysis was applied not only over past ski seasons based on the SAFRAN reanalysis but also using one adjusted GCM/RCM pair from the EURO-CORDEX ensemble. The results indicate that the impact of snowmaking on the hydrological cycle at the local scale will moderately increase in a warmer climate, although the impact of climate change on the hydrological balance of the related catchment (in particular, earlier and smaller snowmelt peak) will be of a larger magnitude. This method, pending the use of a larger set of climate change simulations to better quantify the uncertainties at play, can be

https://doi.org/10.5194/egusphere-2022-1186
Preprint. Discussion started: 29 November 2022

used to provide quantitative information combining the influence of (i) grooming and snowmaking and (ii) climate change on the local water cycle in mountain catchments intersecting with ski resorts. This will require the use of a full ensemble of climate change projections in order to provide quantitative assessments of the rate of change, along with the uncertainties at play (Verfaillie et al., 2018; Gerbaux et al., 2020). Furthermore, using ensembles of climate change simulations will enable to compute the time evolution of water resources in the ski resorts under consideration, for future climate conditions. However, such simulations are performed using current snow management rules, which may evolve in the future, due to potential changes in the technologies used for snow management (snowmaking equipment, grooming techniques etc.) but also changes in the operational practices implemented in ski resorts, including those due to future changes in skier demand and other future changes in the local economies and the future role of ski tourism.

5 Conclusions

This study introduces a new framework for analyzing the impact of snow management on the hydrological regimes at the scale of individual ski resorts, based on typical information characterizing mountain catchments and ski resorts. The method was implemented and demonstrated results for the pilot ski resorts La Plagne. Its generic formulation makes it possible to be replicated for other ski resorts and related catchments. The results of the case study at La Plagne shows a substantial influence of the ski resorts at the local scale on the seasonality of runoff amounts, especially due to grooming in winter. The effects of snowmaking on runoff generation occurs mainly at the time of snowmelt, and its magnitude depends on the geographical scale of aggregation, up to about 1% to 2% under current climate for the catchments under consideration.

The study provide hints into the impact of future climate change on the hydrological disturbance due to grooming and snowmaking. For the catchments under consideration, the amount of snowmaking, under current snowmaking practices and technology, increases in a warmer climate, consistent with previous studies (Spandre et al., 2019). However, tat the catchment scale, the main influence of climate change on the hydrological regime proceeds through the well documented earlier and smaller (mostly natural) snowmelt peak, over which the influence of grooming and snowmaking overimposes a secondary modulation. Thus, under current and future climate conditions, grooming and snowmaking appear to have a rather limited impact on total runoff at the catchment scale. The main issue raised by the use of snowmaking in a warmer climate is the ability to have sufficient water available when needed (e.g. Gerbaux et al., 2020).

Although our study provides quantitative estimates of the impact of grooming and snowmaking on the hydrological regime of mountain catchments influenced by the presence of ski resorts, it also reveals the complexity of using in-situ hydrological observations in such contexts. Often, the data do not exist, or are too incomplete to provide a consistent picture, based on observations, of the hydrological context. This is a clear area of potential improvement for better integrated water management in mountain areas, under current and future climate conditions (Hock et al., 2019).

Ultimately, this study is consistent with the conclusions of IPCC (2019): "Integrated water management approaches across multiple scales can be effective at addressing impacts and leveraging opportunities from cryosphere changes in high mountain areas. These approaches also support water resource management through the development and optimization of multi-purpose storage and release of water from reservoirs (medium confidence), with consideration of potentially negative impacts to ecosystems and communities." Indeed, we highlight here that this study does not address all the issues related to the impacts of ski resorts operations and snowmaking on the mountainous environments. The influence on the water cycle, quantified in this study, is only addressed in terms of the effects of snow grooming and snowmaking (hence, not accounting for other water uses related to tourism activities, including housing), and only in terms of water quantity but not water quality. Also, water storage for snowmaking is only considered here in terms of water amounts and the related disturbances of the water cycle, but does not address the environmental disturbances and impacts on biodiversity and mountain landscape related to the construction and use of mountain water reservoirs and surrounding ski resorts. Implications relevant to the positioning of snowmaking and ski tourism within the future path development of mountain tourism and broader mountain economies (Steiger et al., 2022; Berard-Chenu et al., in press) are beyond the scope of this particular study, which solely focuses on downstream hydrological impacts.

Author contributions. SM, HF and ES designed the research; MR, HF, ES, LC, FB and EL produced the data; MR, HF and ES produced the figures and the table with support from co-authors; all authors contributed to the analysis and interpretation of the results; SM wrote the paper, using feedback from all co-authors.

Competing interests. The authors declare no competing interests.

Acknowledgements. The project conducive to this manuscript has received funding from Compagnie Des Alpes and the European Union's Horizon 2020 research and innovation programme (grant agreement no. 730203).

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