Snow Management and Local Hydrology:
a Case Study at Prospect Ski Area

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Abstract

As winters face declines of natural snowfall and frequent temperature fluctuations in a warming climate, industries that depend on natural snowfall have come to rely on machine-made snow to sustain their businesses. The advent of snowmaking in the mid twentieth century has revolutionized the capacity for snow-dependent industries to operate through increasingly warm and dry winters; a trend that will only become amplified over time in an increasingly warm climate. As an incredibly water-intensive process, the increasing demand for snowmaking at a large scale raises the question of how snowmaking and management may impact local hydrology. The aim of this study was to examine how machine-made snow and grooming processes — both common practices for ski industries — differ in water-holding capacity and melt rate from natural snowpacks, and lend insight as to how these changes might influence the timing of local hydrologic events as a whole. Using snow data collected from Prospect Ski Area (VT) and Jiminy Peak Resort (MA), results indicate that, compared to natural snowpacks, managed snowpacks yield higher water-holding capacities and delayed melt progressions. While these influences did not show clear significant changes to local hydrology, it is important to consider snowmaking and local hydrology at scale to best balance water uses and stressors.

Introduction

Snowmaking and Grooming

Snowmaking comes in many different forms, but the key components of the process are the same as natural snow: water and freezing temperatures. However, unlike natural snowfall, snowmaking involves robust infrastructure to deliver energy and water to create the snowy slopes that we love. To supply ample water for machine-made snow, surface water is pumped from local watersheds and diverted into a designated reservoir for storage (Wemple et al., 2007). Once temperatures are cold enough to begin making snow, stored water is pumped to a localized area where snow cannons pressurize the water and mix with compressed air, shooting the mixture through a specialized nozzle that breaks the water particles into extremely fine droplets as they exit the cannon (de Jong, 2011). This initial process is known as atomization, an important step in increasing the surface area of water droplets to facilitate rapid heat transfer for cooling and freezing as the droplet falls. Atomization of water is followed by nucleation, which describes the first phase change as water droplets freeze into tiny ice particles. These ice particles become the nucleus by which surrounding water vapor freezes around to form ice crystals, a process known as seeding. As these ice crystals continue their trajectory and start falling to the ground, further transformation happens through evaporation and cooling (de Jong, 2011).

The best climate conditions for snowmaking efficiency are determined by the wet-bulb temperature, a function of air temperature and moisture content, both of which play a role in water freezing and crystallization efficiency. Generally, a lower wet-bulb temperature, meaning a lower temperature and low humidity, yields higher snowmaking efficiency. Cooler temperatures and drier air lend themselves to more efficient cooling and ice crystal formation, whereas warmer temperatures and higher humidity content hinder evaporative cooling and thus ice crystal formation (de Jong, 2011).

After machine-made snow accumulates into piles near the snow cannon, it is moved by a snow groomer as needed to supplement the natural snowpack. For most ski areas, tending to the snowpack via grooming is a critical component of maintaining ski trails and optimal ski conditions. Grooming introduces mechanical compaction of the snow surface, inducing heat gain and loss through the snowpack, which changes the physical properties of snow crystals once they are on the ground, and increases the cohesion and density of layers (Thompson, 2009).

Snow Hydrology

Of the 828 downhill ski resorts in North America alone, an estimated 87% use snowmaking at some capacity to supplement natural snowfall (Giffen, 2022). But warming winters and dwindling snowpacks are not only a concern for winter-based industries. Snowmelt-runoff provides water to over 2 billion people globally and up to 75 percent of water supply in the Western US (USGS, Water Science School). In colder, dry climates, snow acts as a frozen reservoir where much of the local precipitation occurs in winter months ("From Snow to Flow", USGS). In turn, spring and summer melt is a critical component of the hydrologic cycle as snowmelt re-enters a basin, redistributing water downstream and through a landscape.

Critical components of these snow-based hydrologic cycles include the dynamics of soil saturation, snow water equivalent (SWE), melt timing, and streamflow in the span of one water year, which begins October 1st and ends the following September 31st. Soil saturation refers to the soil water content determined by a previous season's precipitation, which sets the stage for water infiltration during the onset of spring snowmelt. Snow water equivalent measures the amount of water held in a snowpack, while the melt timing describes the date at which half of the maximum accumulated SWE has melted (SWE50). Streamflow refers to the amount of surface water in a stream at a given time ("From Snow to Flow", USGS). This surface water cycle is a critical dynamic of snow-based ecosystems. Any changes in the timing, magnitude, and duration of a melt cycle can substantially alter streamflow and water availability ("From Snow to Flow", USGS).

As a water-intensive process, a primary concern in snowmaking and management is their effect on local hydrology. The first of these impacts occurs as water is diverted from local sources and stored in reservoirs, where this initial diversion results in a local, temporary deficit in water. Further losses are caused by evaporation that occurs when water is stored, during snow production, and in the redistribution of machine-made snow. As a result, a general estimate is that 30% of water initially diverted from local watersheds is lost without return to its basin (de Jong, 2011). The 70% of water that is successfully transferred onto a ski piste adds, in some cases, millions of gallons of diverted water on some slopes, contributing much more water content to the 'frozen reservoir' that naturally accumulates during a winter season (CBS

Colorado). With the altered physical properties of machine-made snow itself and the additional compaction from repeated grooming, these changes in natural snowpacks may introduce unintended changes to streamflow and the balance of the hydrologic cycle throughout the water year.

Methods

Site Description

Snow data were collected at two main locations that have both natural snowpack and machine-made snow. The primary location for data collection was Prospect Mountain Ski Area, located in Woodford, VT. Prospect is situated around 656 meters, with a mean annual temperature of 4 °C, and 1122 mm of precipitation estimated for the 2024 water year (NRCS). Prospect is predominantly a cross-country skiing area that relies mostly on natural snowfall but has recently installed a snowmaking system to help support winter recreation through low snow periods. Total snowmaking coverage at Prospect is supplied from three snow guns, covering around 6 acres concentrated around the lodge and stadium (Fig. 1).

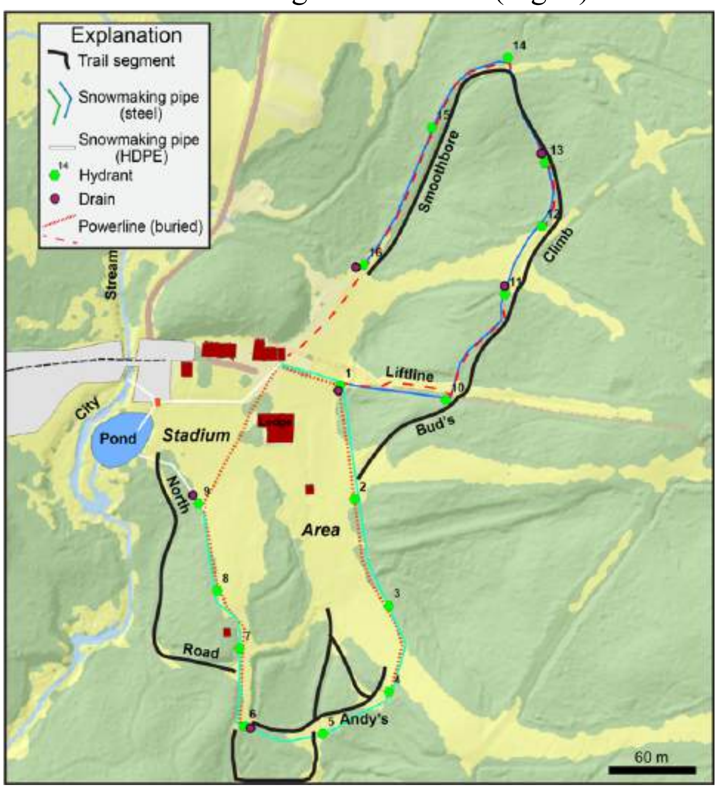


Figure 1. *Snowmaking layout at Prospect Mountain, Vermont (from Dethier and Racela, 2025)*

Water for snowmaking at Prospect is diverted from City Stream into a 380,000 gallon storage pond, water levels of which are currently monitored hourly by Keller Acculevel water-level recorders. Stream level monitoring at Prospect ensures that water diverted for snowmaking never exceeds conservation flows required by Section 16-03 and 16-06(2) of the state of

Vermont Department of Environmental Conservation flow determination (Dethier and Racela, 2025).

The secondary location was at Jiminy Peak Mountain Resort, located in Hancock, MA. The base of Jiminy Peak sits at 379 m, with a mean annual temperature of 7 °C, mean annual precipitation of 1259 mm, and an average of 16 days of snowfall per winter season ("Climatedata.org", "On the snow"). In the winter, Jiminy Peak is an alpine-ski area with a robust snowmaking operation, providing 96% machine-made snow coverage, which averages to 700 acre feet of snow (~228 million gallons) per winter. Permits for water diversions from Kinderhook Creek at high flow were obtained in 1993 for storage in two main ponds: the 6 million gallon Kinderhook Reservoir and 12 million gallon Summit Reservoir ("Sustainability").

Each location has a host of subsites representing the independent variable snow and snowpack types (Table 1 and supplemental figures). Sites 1- 4 are located at Prospect and sites 5 and 6 are located at Jiminy (Figures 2a and 2b).

Table 1: Sample Sites

Site	Location	Snow type	Groom Type
1	Prospect	Natural	Undisturbed
2	Prospect	Natural	Groomed
3	Prospect	machine-made	Undisturbed
4	Prospect	machine-made	Groomed
5	Jiminy	Natural	Undisturbed
6	Jiminy	machine-made	Groomed

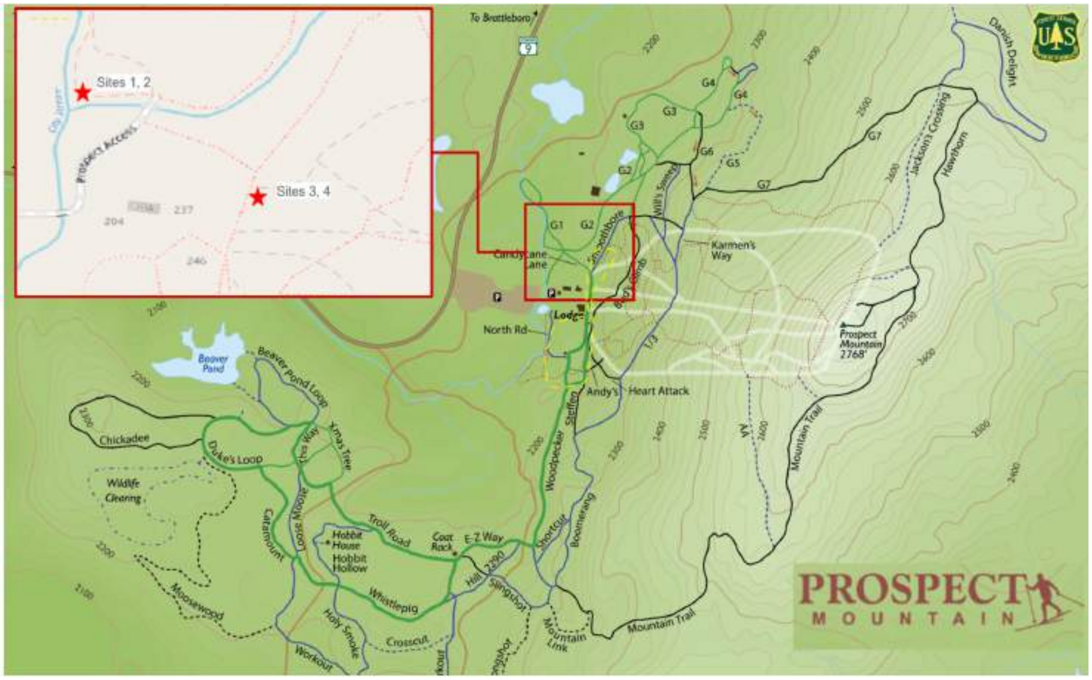


Figure 2. *Prospect Mountain trails and snow sample sites*

Figure 2b**:** *Snow Sample Sites at Jiminy Peak Mountain Resort.*

Field Collection

Field methods for data collection followed standard snow pit and transect protocols, outlined by NOAA and the US Forest Service. For each site, a snow pit (Fig. 3) was dug to

Figure 3**.** *Glimpse into field methods. Representative snowpit (sites 1 and 2) on 2/24/2025 (left). Me at site 2, having just refilled the snowpit at Prospect, PVC coring device is on the right, not in use (right); Photo by David Dethier*

gather qualitative representations of depth, stratigraphy, wetness, and grain size of the snowpack in the area for each transect. Layer densities were also recorded for each pit using the Hydro-Tech (100 cm^3) wedge cutter and weighed using the spring scale (200g). Depth of the snowpack at each site was recorded along transects at regular, 50 cm intervals using an aluminum snow probe. Temperature and general weather conditions were noted per standard NOAA protocol. Snow cores were taken at each site to determine a relative snowpack density of each snowpack variable: natural snow, machine-made snow, natural and machine-made snow, and groomed or undisturbed areas. Cores were taken at each snow pit, as well as at regular intervals (1 meter) along the groomed transects. The coring device was modeled after the 'Federal/Mt. Rose Sampler' using a 3' PVC pipe with a serrated base and turning handle. Once extracted, cores were then transferred into a bag for weighing (g). Depth measurements were recorded at each site to calculate the volume of the snow sample (cm^3). Density was then calculated for each site. Snow water equivalent (SWE) measurements were taken at both locations (Prospect and Jiminy) to compare natural and machine-made snow. 50 ml flasks were filled with unpacked machine-made or natural snow to approximate the water holding capacity of each type. See Figure 2 for representative methods.

Results

To examine characteristics of machine-made and groomed snowpacks and their water-holding capacity, various snowpacks around Prospect Mountain and Jiminy Peak ski areas were analyzed. Snowpack variables included natural snow, machine-made snow, in either undisturbed or groomed areas. Elevation, exposure, and slope were relatively similar across sites in either Prospect or Jiminy Peak in an effort to diminish the influence of other weather variables in the snowpack behavior and settling throughout the melt season. Snow pits were dug to gather snowpack history for each site and as a relative control to each variable. Pit 1 represents the snowpack history for sites 1 and 2, pit 2 represents sites 3 and 4, and pit 3 represents the Jiminy sites 5 and 6 (Fig. 2b). Pits 1 and 2 at Prospect yielded similar depths at 68 and 64 cm, respectively, and similar layering with some variation on the base layer and larger, faceted layers at a mid-depth. The main difference between the Prospect snow pits was a layer of machine-made snow between 33 and 41 cm for the pit dug at sites 3 and 4 (Figs. 4a, b).

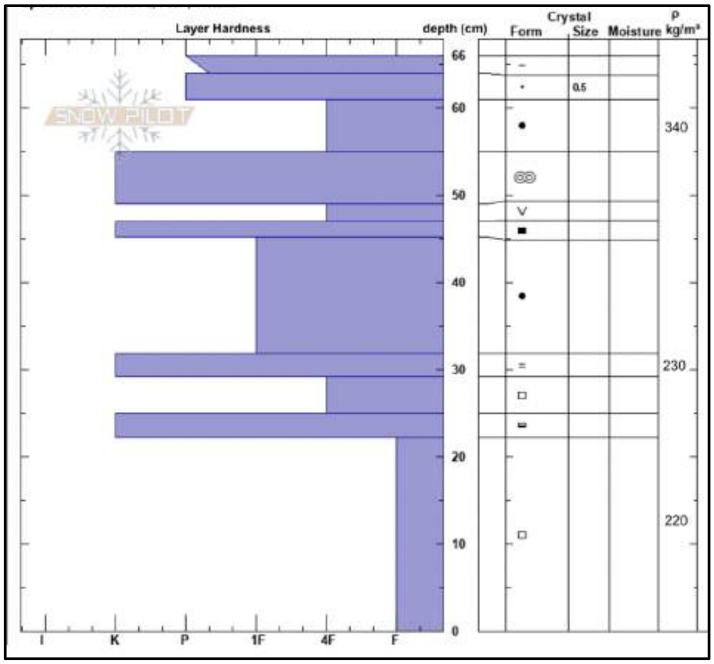


Figure 4a. *Natural snowpack profile for Sites 1 and 2. Snowpit shows a varied layer profile consisting of a deep, faceted base below varied subsequent rounded or ice layers. Total pit depth was 68 cm. Air temperature hovered at 2°C in the afternoon with partially sunny conditions. Located at 42°52'35.83" N and 73° 4'40.65"W, the elevation of this site is 647.7 with a slope of roughly 0°.*

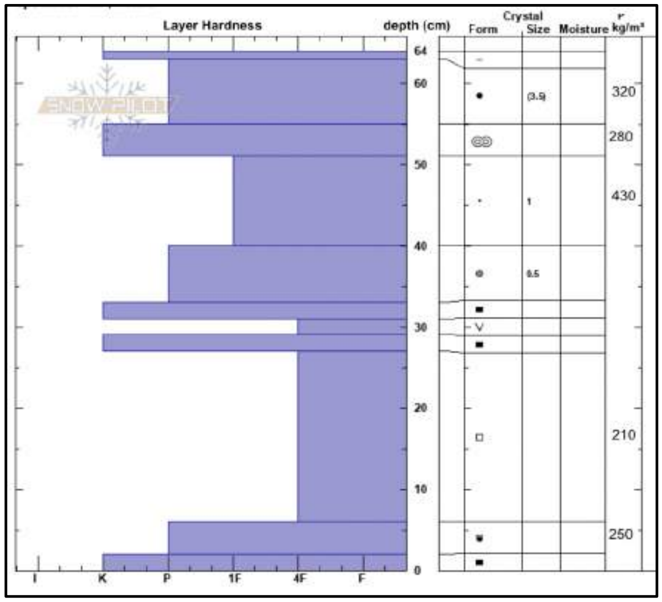


Figure 4b: *Machine-made snowpack for sites 3 and 4. Snowpit reveals a profile of varied snow grain types (faceted or rounded). The machine-made snow layer is between 33 and 41 cm. The total pit depth is 64 cm. Collection occurred on February 24, 2025. Air temperature hovered at 2°C in the afternoon with partially sunny conditions. Located at 42°52'36.06"N and 73° 4'40.45"W, the elevation of this site is 647.0 with a slope of roughly 0°.*

The snowpack history from pit 3 revealed a large base of faceted grains with thicker, icy layers present both mid-pack and on top. This snowpit profile is typical of a thinner overall snowpack at 49 cm in warmer conditions (Figure 3c).

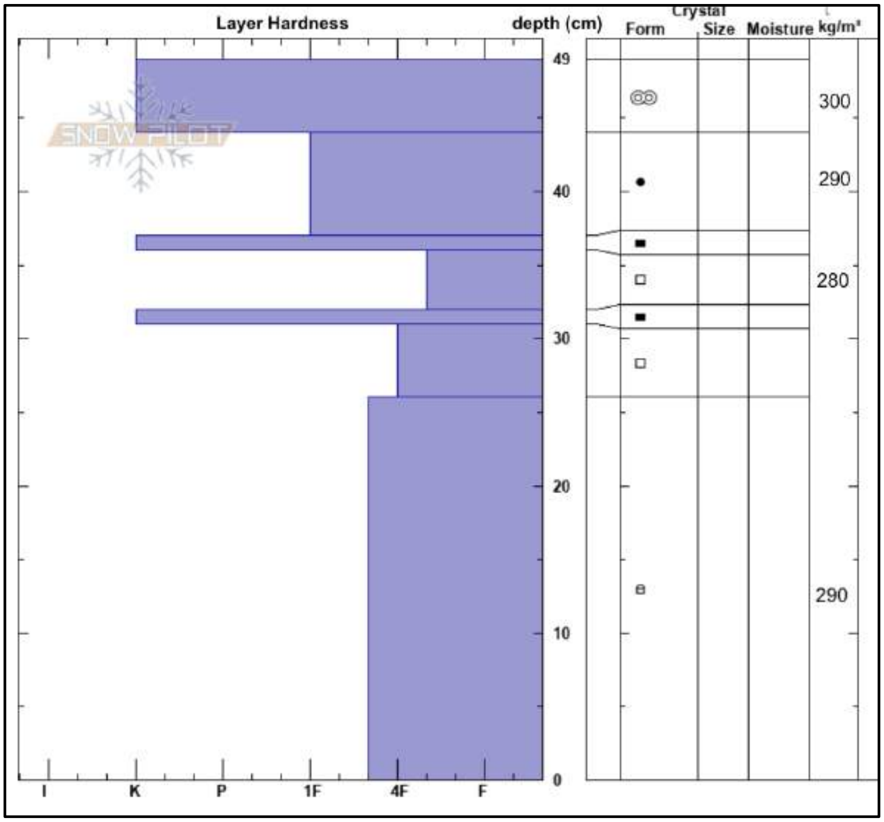


Figure 4c. Natural snowpack for sites 5 and 6. Snowpit profile reveals a large base of faceted grains. Icy layers are present both mid-pack and on top. This snowpit profile is typical of a thinner overall snowpack at 49 cm in warmer conditions. Collection occurred on March 4, 2025. Air temperature hovered at 4°C in the afternoon with partially sunny conditions. Located at 42° 33 '14.54"N and 73° 17' 43.45"W, the elevation of this site is 426.72 m.

Machine-made snow had a greater water-holding capacity than a similar mid-layer collection of natural snow. The snow water equivalent for 50 ml of unpacked snow for the machine-made sample was 32 ml, compared to 27 ml for natural snow. Likewise the density was much higher for machine-made snow at 440 kg/m^3 compared to that of natural snow, which had a density of 330 kg/m^3 (Figs. 5 and 6).

Snowpack History and Grain Observations

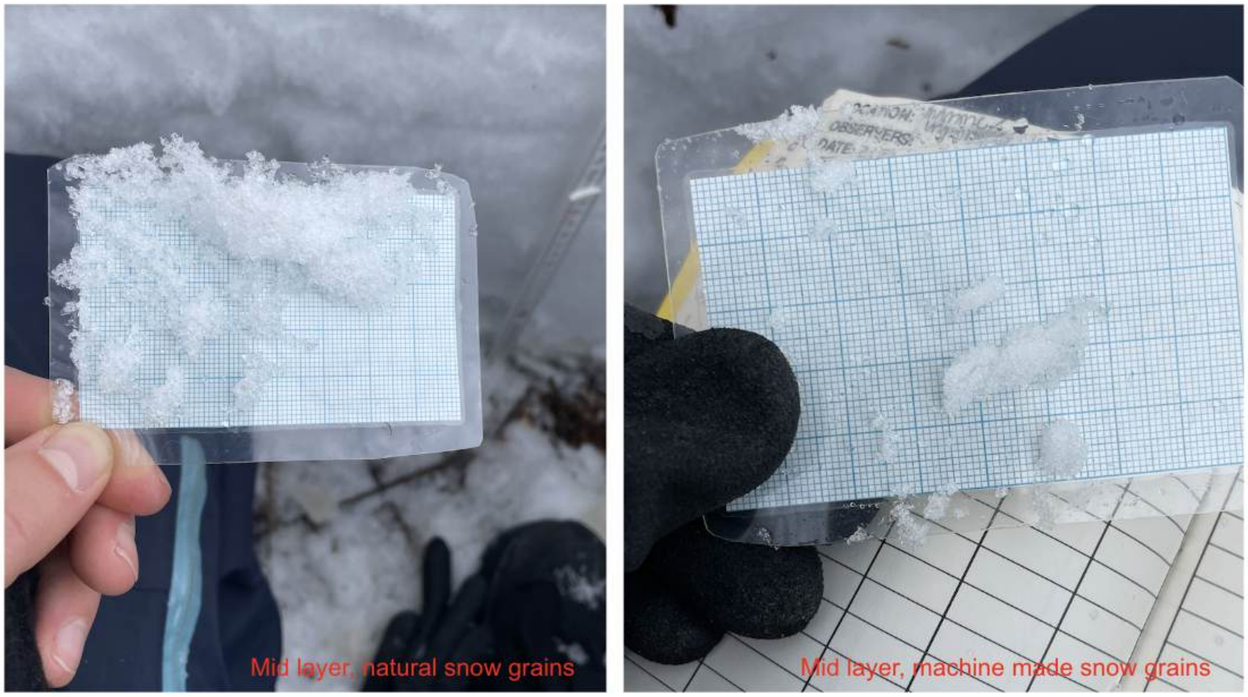


Figure 5. *Size difference between natural, mid-layer snow grains (~ 2-3 mm) on left, and machine-made snow (~0.5-1 mm) on right.*

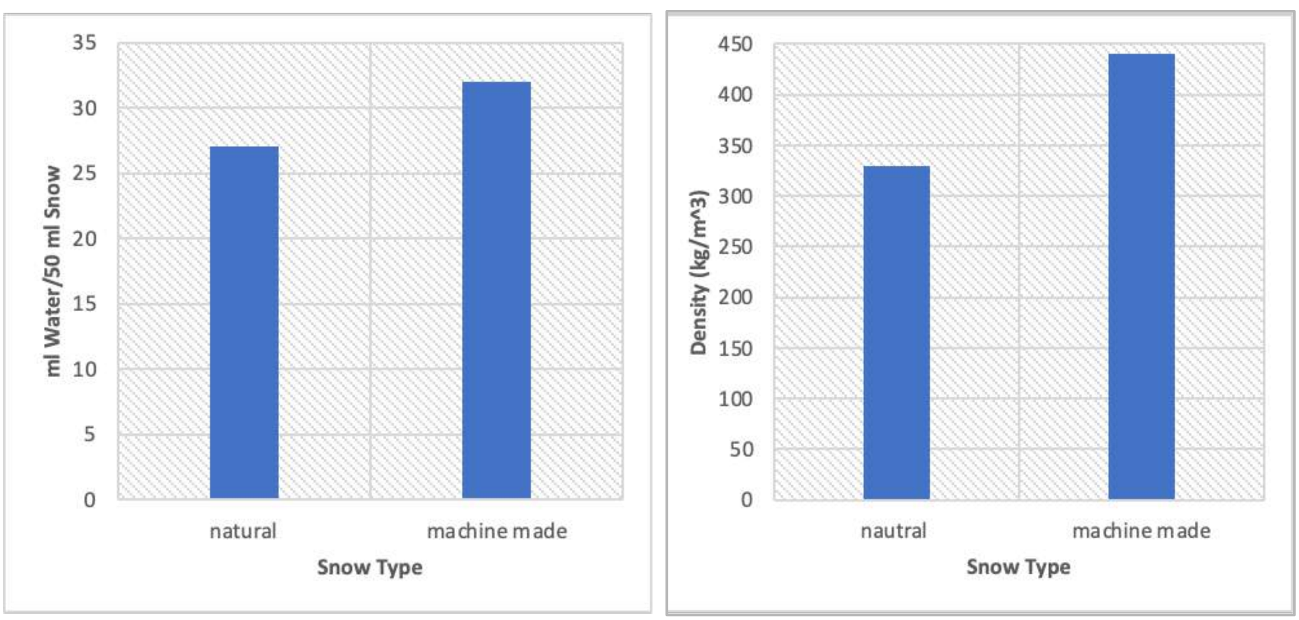


Figure 6: *Water holding capacity characteristics of natural and machine-made snow. Machine-made snow has a higher snow water equivalent (left panel) and density (right panel) compared to settled,*

natural snow. Both samples (natural and machine-made) were collected on Feb 26, 2025 from Prospect.

Core densities revealed that groomed snowpacks exhibited a higher density than their undisturbed counterparts, regardless of snowpack type and whether or not machine-made snow was incorporated into the snowpack (Fig. 7). Melt rate between natural groomed and

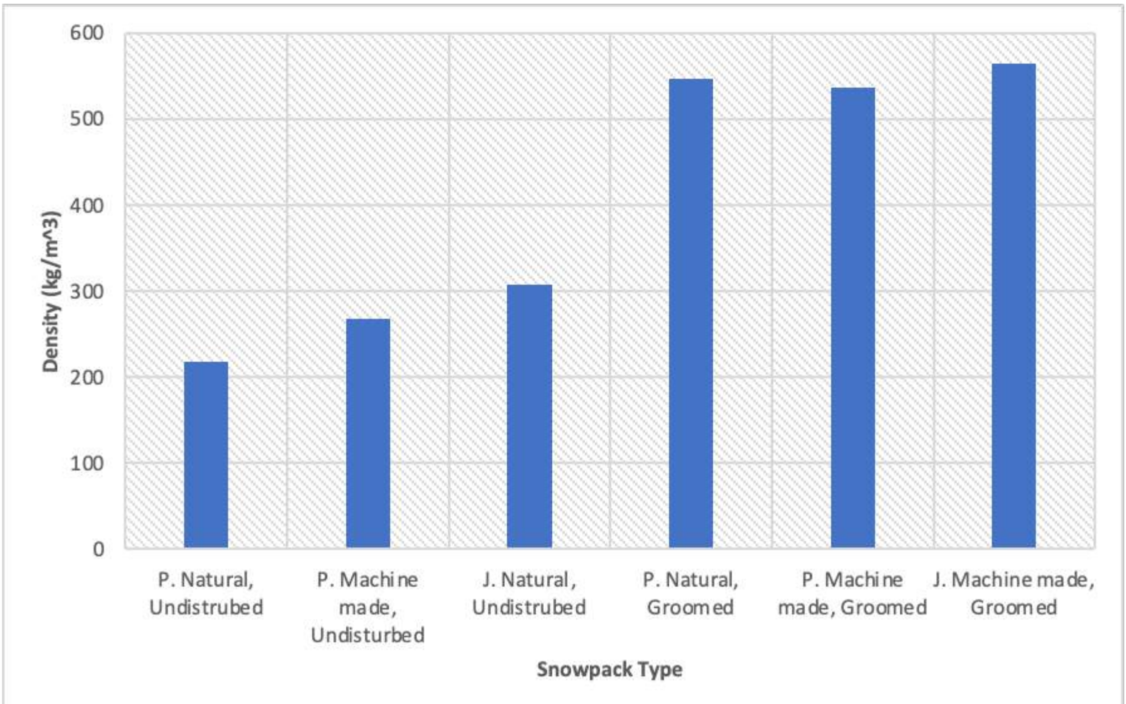
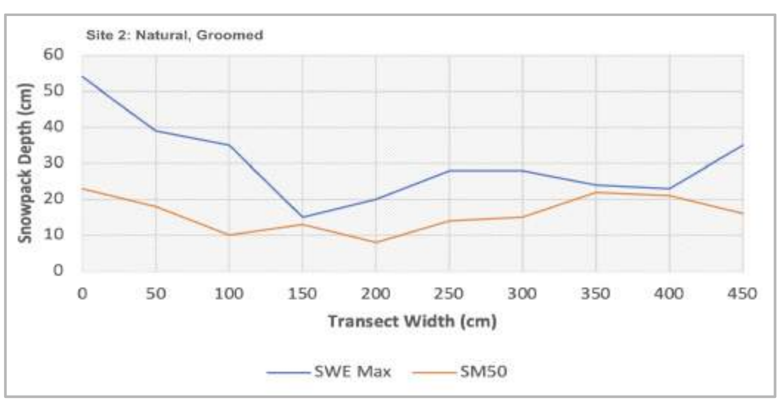


Figure 7. *Snow core densities of each snowpack type across sites. Groomed snowpacks have a greater density than their undisturbed counterparts.*

machine-made groomed snowpacks show that natural snowpacks melt out at a faster rate than their machine-made, groomed counterparts (Fig. 8). However, groomed, well-protected



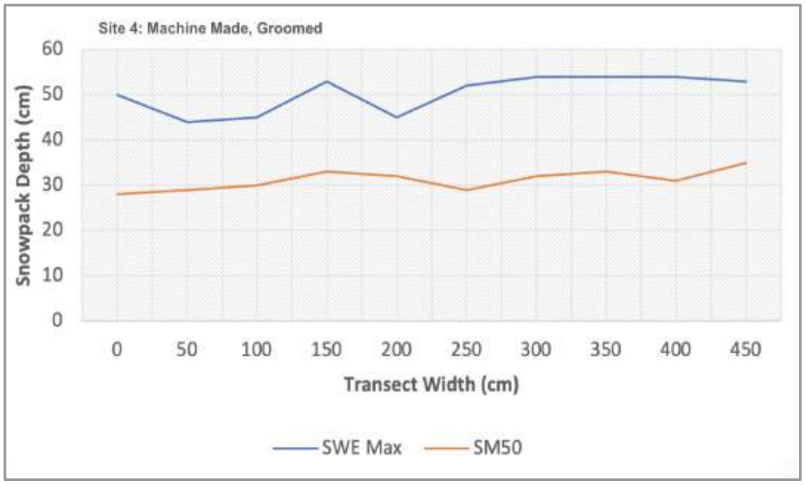


Figure 8. Melt progression for a natural, groomed snowpack (top panel) and a machine-made, groomed snowpack (bottom panel). Blue line represents snow depth at a seasonal maximum (SWE max), measured on February 26, 2025. Orange line represents snow depths around mid to late melt (SM50), measured on March 10, 2025. For the natural, groomed snowpack, snow depth had an average decrease of 43% between the two measurements. For the machine-made, groomed snowpack, snow depth had an average decrease by 37% across the transect.

trail areas at Prospect (Fig. 9) still retained considerable snow on March 20 2025 and machine-made snow on more exposed parts of the stadium had melted substantially.

Figure 9. Groomed snow at Prospect Mtn on 20 March 2025. Left panel shows protected area of trail; right panel is view near my snow pits, which had melted.

Early spring 2025 was exceptionally warm, melting machine-made snow and snow in most other areas by early April (Fig. 10).

Figure 10. Views of machine-made snow on S-facing Buds Climb (Prospect Mountain) in 2025. Left panel 20 March; right panel 4 April.

Prospect water data were plotted between 2023 and 2025, after snowmaking was introduced to the ski area. Water levels for City Stream and the snow storage pond were monitored and discharge rates were measured for City Stream (Fig. 11). Decreases in the pond

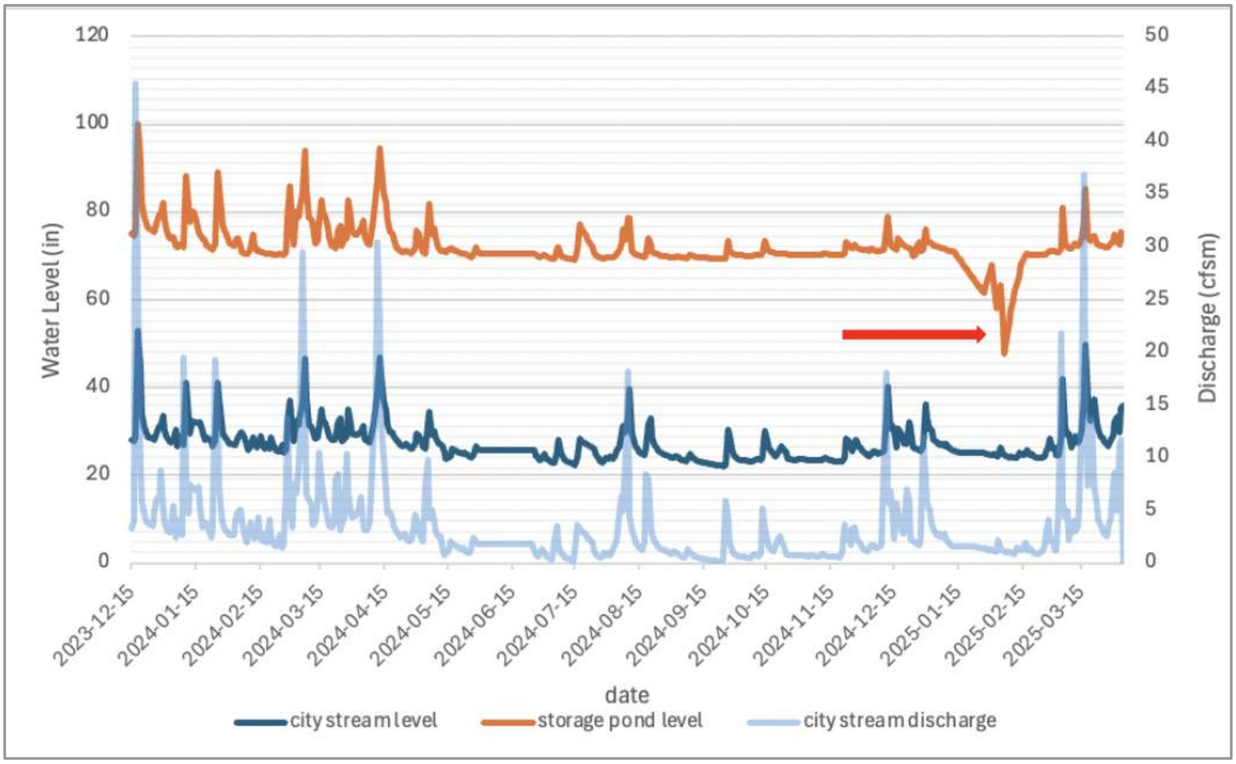


Figure 11. *City Stream, storage pond, and discharge at Prospect Ski Area for first two snowmaking years (2023-2025). Prospect storage pond (orange), City Stream (navy), and City Stream discharge (light blue) follow similar trends over time since the onset of snowmaking operations at Prospect in 2023. Decreases in storage pond level while City Stream water level and discharge remain steady indicate water extraction for snowmaking, as seen between January and February, 2025. Data from David Dethier (unpublished).*

storage water level where City Stream water levels and discharge rates remain steady indicate water use for snowmaking. To gauge possible changes to City Stream levels prior to snowmaking, water levels between 2020 -2023 and 2023-2025 were approximated from the USGS data on the Walloomsac River, which is highly correlated with City Stream levels. The average water level prior to snowmaking was 26.78 in, which is slightly higher than the average for 2023-2025 at 26.43 inches, though this decrease is not likely to be significant.

Discussion

The aim of this study was to examine potential effects of snow management practices — snowmaking and grooming — on the snowpack dynamics and related hydrologic processes in a local case study. Primary observations from the results of this study find that the altered characteristics of managed snowpacks have an increased water holding capacity compared to natural snowpacks. Machine-made snow had a higher snow water equivalent than mid-layer natural snow, and groomed snowpacks had a much higher snow density than undisturbed snowpacks. These findings were largely expected. Grooming increases snowpack density as the mechanical process of compaction introduces heat into the snowpack, causing individual snow grains to undergo a rounding metamorphosis, the result of which is higher density and increased layer cohesion, preferable for recreational purposes (Thompson 2009). Machine-made snow grains differ from natural snowflakes as they are typically smaller and more rounded as they form, leading to denser layers and a higher snow water equivalent as they settle (de Jong, 2011). Layers of machine-made snow within snowpits compared to similar mid-layer natural snow confirmed this difference in grain size and density (Figs. 5 and 6). These findings on the altered water holding characteristics of managed snowpacks are consistent with recent research in the field. In a 2023 study, Morin et al. used models to simulate the hydrological effects of snow management at La Plagne ski area and corroborated their results with in-situ measurements. In a comparison between a natural snowpack, groomed snowpack, and groomed and snowmaking snowpack, Morin et al. show that the aggregated influence of snowmaking and grooming exhibits the highest snow water equivalent throughout a winter season.

Expanding upon the findings that managed snowpacks have a higher density and therefore snow water equivalent, transects from this study reveal that the melt progression of managed snowpacks — specifically snowpacks that have machine-made snow — occurs at a slower rate than the natural snowpacks (Fig. 4). Morin et al (2023) came to a similar conclusion. Managed snowpacks that have undergone compaction, and are therefore more dense, are less insulative, which progressively induces cooler snowpack conditions that prevent and delay melt processes (Morin et al. 2023). Their model illustrates that in the aggregated snow management condition, total liquid water reaching the soil is virtually eliminated throughout the winter months and the compensatory melt peak is much higher come the spring when compared to the natural snowpack. These results illustrate how snow management practices have an increased temporary, immobilizing impact on the movement of liquid water throughout a winter season.

This temporary lag in the movement of liquid water in managed snowpacks remains poorly understood in its implications for hydrologic cycling, as disentangling causes of water regime shifts from snow management practices and other climate and ecosystem factors is difficult. For Prospect Ski area, analysis of water use and levels yielded no evidence that the recent development of the snowmaking operations that began in 2023 have changed available water volume for the surrounding City Stream (Fig. 11). This lack of change indicates successes on the front of local water level management and compliance with the Vermont Department of Environmental Conservation flow determination.

Nonetheless, it is important to consider the scale of various operations and the ecosystems they take place in. The implications of snowpack alterations are dependent on the ecosystems they occur in, but changes to snowmelt peaks and timing could influence habitat structures for riparian organisms through winter seasons, contribute to phenological mismatch in spring primary production, and overall influence water availability and stress in more constrained systems (Morin et al 2023; “From Snow to Flow”). Where snowmaking and water use occur at different scales across the nation, it is generally accepted that these changes occur at a seasonal time frame and at a more localized scale (Vanham et al. 2009). In certain scenarios, the lack of winter liquid water infiltration and larger spring melt peaks that result from managed snow generates surface runoff in the springtime leading to rapid peaks in streamflow and less overall ground infiltration ("From Snow to Flow", USGS). This shift in snowmelt can lead to downstream consequences for streamflow and varying water availability throughout the spring season and after peak melt. Where snowmaking also significantly adds to the stored water on ski pistes, this drives up total excess melt to catchments that may contribute to increased magnitude of mudslide and flooding events in the spring (Morin et al. 2023). The overall effect of this added water content also depends on which catchment the snowmaking water was initially diverted from and if the meltwater returns to an initial or new basin. Morin et al. (2023) discuss the importance of this distinction in regard to the common perception that water used in snowmaking operations is merely 'borrowed'. The overall impact of these implications likewise depends on local environmental and economic factors related to water stress.

Conclusion

Under a warming climate, winters will continue to see a decrease in days of snow cover (Lindsey, NOAA). While one of the biggest challenges facing snowmaking is water diversion and evaporative water loss, further investigation as to the impacts of shifting snowmelt regimes is critical to consider, especially as climate change generates water stress in many of the same regions. This study emphasizes the altered water-holding characteristics of managed snowpacks compared to natural snowpacks. Study limitations due to time constraints reduced the amount of data that could be collected in the field. Expansion to further investigate the implications of snow management practices on hydrologic cycles should include region specific modeling that incorporates local climate variables and monitoring specific water use for snowmaking, melt progressions, and year round streamflows.

Discussion over the viability and potential impacts of snowmaking, grooming, and other commonly used practices for snow management in winter recreation industries must include the recognition that these industries are somewhat self-contradictory in nature. As winters decline, ski industries must increasingly rely on intricate snow management practices to supplement natural snow to maintain interest in snow-based recreation and economic viability; decreases in snow cover has a direct correlation to reduced yearly revenue for the industry (Protect Our Winters). These snow management practices are extremely water and energy-intensive, and this energy is often supplied by the burning fossil fuels, a process that lies at the heart of global warming. Even as the majority of major winter-based industries have recognized their own role in climate change, transitions to alternative energy sources are slow to be realized (Protect Our Winters). This study does not call for reductions or major reform in the practice of snowmaking, especially where snow management makes winter recreation more reliable, accessible, and economically viable. Rather, the aim is to raise consideration for potential shifts in local hydrologies.

As the demand for snowmaking and management practices is expected to increase to sustain the economic value of snow-based industries, it is critical to evaluate how these water-intensive practices might interact with local hydrologic cycles and broader ecosystem level impacts. In relatively less water-stressed systems, such as that at Prospect Ski area, water use for snowmaking seems to pose less strain on local hydrology. In many prominent winter industry regions like the American West and European Alps, the decline of freshwater sources are another resource of concern in a warming climate; conservation must also be balanced with economic incentives for the ski industry. It will become increasingly important in such areas to monitor how even small alterations to natural hydrological cycles could have broader impacts on local environments and the people in them. With increased understanding of these dynamics, implementing meaningful policy and regulations can support the sustainability of winter industries.

Acknowledgements:
Thank you Jay and David for your guidance and expertise!

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