IMPACTS OF ARTIFICIAL SNOWMAKING ON THE HYDROLOGY OF A SMALL STREAM

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Abstract: Ski areas often turn to artificial snowmaking, in an effort to provide a consistent and desirable product for their customers. This additional snow increases the water that contributes to spring runoff events, but the magnitude of the impact is not always clear. In this paper, we will discuss the hydrologic impacts of artificial snowmaking on Knowlton Creek, a small (~5km^2) watershed in Duluth, MN. Spirit Mountain Recreation Authority (SMRA) is a ski area that occupies 5% of the watershed (~0.25km^2) and relies extensively on artificial snowmaking. Increasing the potential impact on hydrology, the entirety of the water used for artificial snowmaking at this site is imported from outside of the watershed. We will discuss the development of a Hydrologic Modeling System (HEC-HMS) model for the watershed that has been used to compare the impacts of the artificial snowmaking on both the winter snowpack of the watershed and the spring runoff. We will also compare the magnitude of these impacts to those of common design storms.

INTRODUCTION

Knowlton Creek is a tributary to the St. Louis River, which drains to Lake Superior through the St. Louis River and Duluth-Superior Harbor in Duluth, MN and Superior, WI. Large portions of the watershed are within the City of Duluth and the entire watershed is in St. Louis County. Figure 1 shows the location of the watershed.

There has been significant sedimentation at the mouth of Knowlton Creek, behind Tallas Island, since the early 1960s. The timeframe for the increased sedimentation roughly coincides with the opening of a ski area (Spirit Mountain Recreation Authority, SMRA) in the watershed and the use of artificial snowmaking for the ski runs. The snow at SMRA is produced using treated City of Duluth water that is brought in from outside of the Knowlton Creek watershed.

The Knowlton Creek watershed is 5 km^2 (1.94 miles^2), while an additional 1.1 km^2 (0.4 miles^2) contributes to the same area of the St. Louis River Estuary, immediately behind Tallas Island. The majority of the watershed is forested. The exceptions are the ski runs at SMRA and associated buildings and parking lots; the I-35 corridor; and some light residential areas scattered throughout the watershed. The ski runs at SMRA account for approximately 0.25 km^2 (0.10 miles^2) or 5.0% of the Knowlton Creek watershed and 0.33km^2 (0.13 miles^2) or 5.4% of the entire area contributing to the region behind Tallas Island. The Knowlton Creek watershed and the adjacent contributing watersheds are shown in Figure 2.

The topography of the watershed can be roughly split into three categories. The uppermost portions of the watershed consist of rolling hills. The middle section of the watershed, where the ski area is located, is very steep with some areas approaching 25% slopes. The lowest portions of the watershed are relatively flat. The maximum elevation difference from the top of the watershed to Tallas Island is 232.9 m. Soils consist primarily of glacial tills with areas of exposed bedrock along Knowlton Creek.

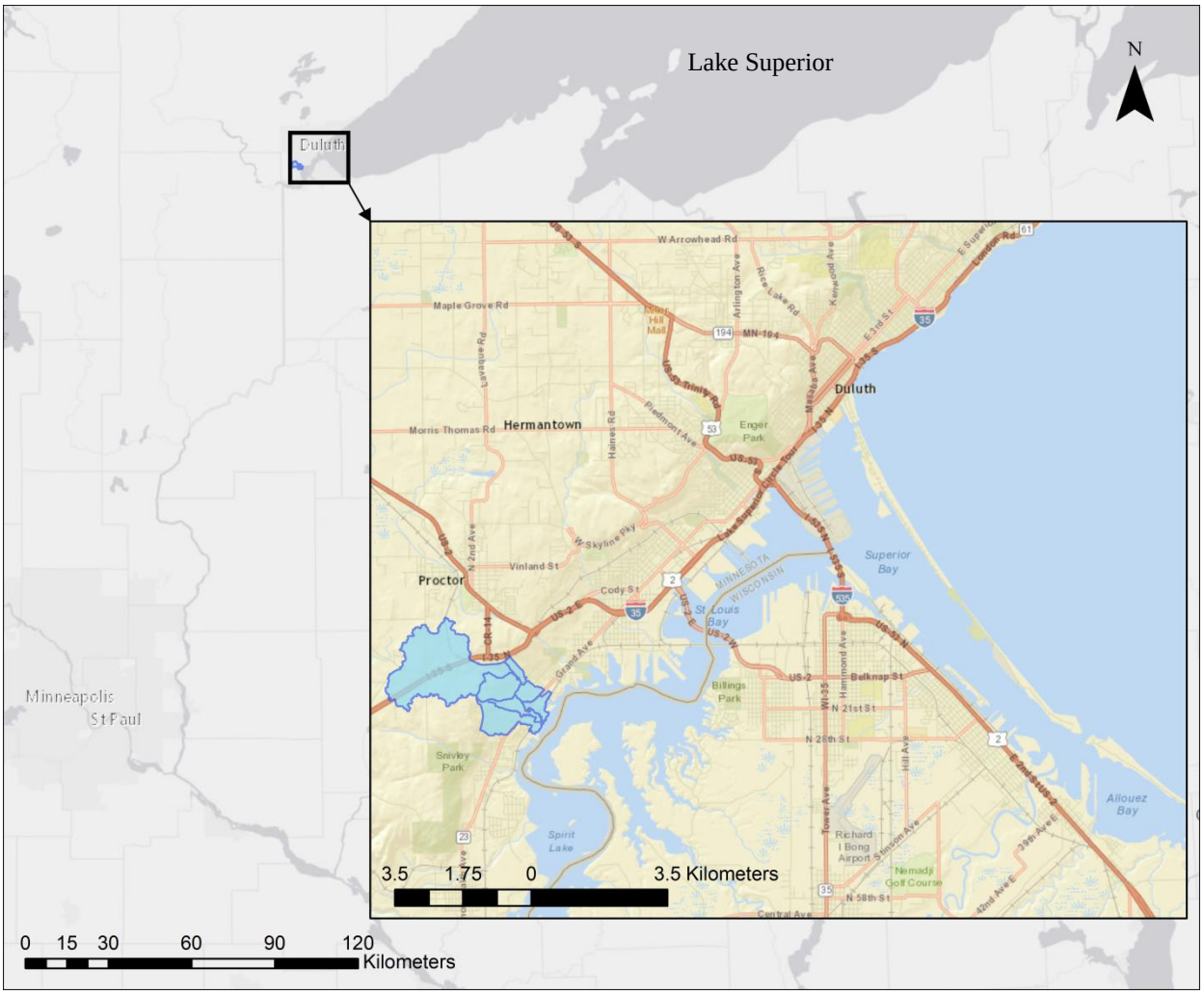

Figure 1 Location map of the Knowlton Creek watershed.

METHODS

In order to estimate the impacts of runoff and snowmaking activities, a hydrologic model was developed using the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) Version 4.0 (Scharffenberg, 2013). HEC-HMS is a process-based, lumped parameter hydrology model designed to simulate rainfall-runoff processes.

Two cross-sections were surveyed on 4-Nov-2010 as part of a separate, regional bank erosion study. One of the cross-sections was located on the mainstem of Knowlton Creek and one on the eastern tributary. Onset Hobo water level loggers, model U20-001-04, were installed at both cross-sections on 3-Jun-2011 (Figure 2). An additional logger was attached to a tree in the floodplain, approximately 30 m upstream of the mainstem gage, to record atmospheric pressure. The loggers recorded at five minute intervals from 3-Jun-2011 to 17-Aug-2011 and 17-Oct-2011 to 4-Nov-2011. Data were logged at 15 minute intervals from 4-Nov-2011 to 8-Jun-2012. The stage and water temperature data are shown in Figure 3. Water level data between 2-Dec-2011 and 19-Mar-2012 were considered unreliable, since the measured water temperature was 0°C, indicating frozen water. Additionally, the total volume of streamflow estimated for the snowmelt event was greater

than the combined water that was used for snowmaking and the winter precipitation from the entire contributing area. This problem was likely due to the presence of snow and ice in the channel.

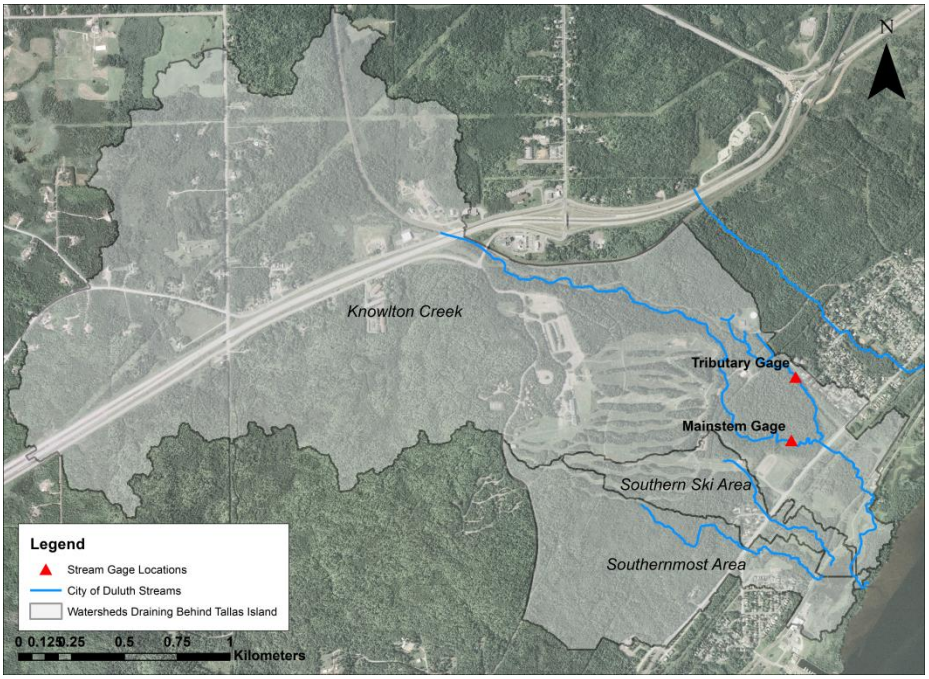

Figure 2 Aerial photo of Knowlton Creek and adjacent watersheds draining to the region behind Tallas Island. The largest watershed, to the north, is Knowlton Creek. The two watersheds on the south side of the aerial photo also drain portions of the Spirit Mountain ski area the same vicinity. The ski runs are visible as the East-West stripes in this picture. Stream gage locations are indicated by red triangles.

Flow measurements were made using a Sontek FlowTracker handheld ADV. Flows were measured on 17-Oct-2011, 19-Oct-2011, 4-Nov-2011, 7-Jun-2012, and 8-Jun-2012. Due to the small size of the watershed and the lead time necessary to reach the site, it was not possible to measure a high flow event. In order to convert the water levels to flows at each site, the collected data were used to estimate a roughness coefficient for Manning's Equation (Chow, 1959). Manning's Equation was then applied to the remainder of the water level data to generate a time series of streamflow. The resulting flows can be seen in Figure 4.

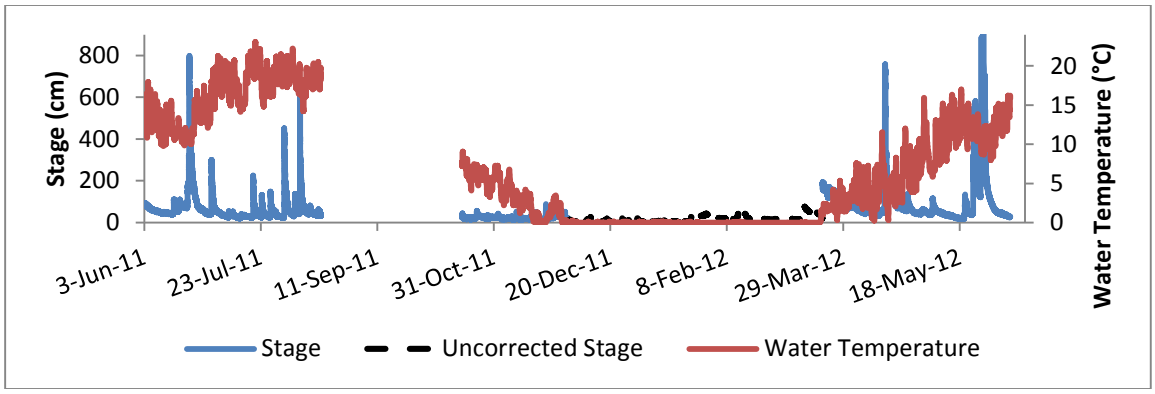

Figure 3 Stage and water temperature observations at the Knowlton Mainstem Gage. The uncorrected stage (black dashed line) indicates the portion of gage record that was not used due to concerns about its reliability.

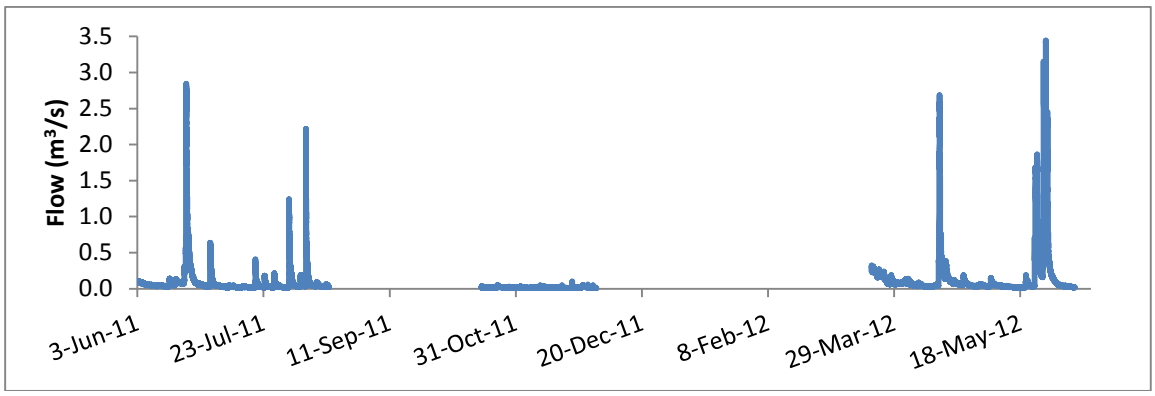

Figure 4 Flow at the Knowlton Mainstem Gage calculated from the level logger stage.

A number of data sets were collected for use in developing the HEC-HMS model. A high resolution LIDAR digital elevation model (DEM), collected in 2011, was obtained from the Minnesota Department of Natural Resources, as was a 2009 aerial photo. A shapefile of the stream network in and around Knowlton Creek was provided by the City of Duluth. SSURGO soils data were acquired from the U.S. Department of Agriculture.

In order to estimate the primary physical characteristics of the watershed, data were processed using the Geospatial Hydrologic Modeling Extension (GeoHMS, version 2010 EAP) for ArcGIS 10 (ESRI, 2011). The stream network from the City of Duluth was modified to include the section of stream extending up to the City of Cloquet pump station. This modified stream shapefile was then "burned" into the digital elevation model (DEM), in order to ensure that water would move along the known flowpaths. The DEM Reconditioning in GeoHMS was iterated several times in order to arrive at a stream network that matched the aerial photo data.

Several of the smaller subwatersheds were combined for modeling purposes. The final watershed map is shown in Figure 5 and the HMS schematic is displayed in Figure 6.

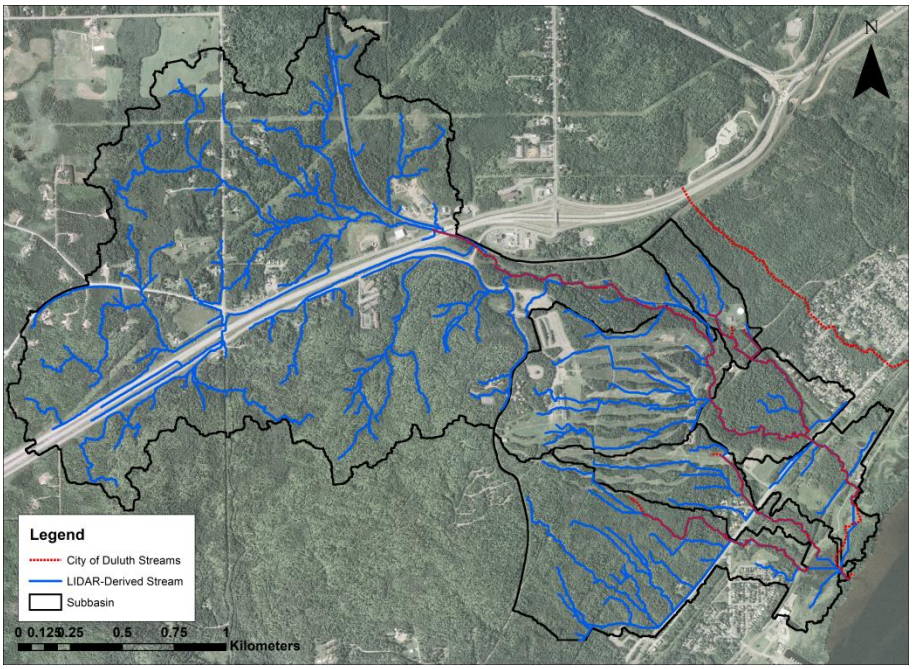

Figure 5 Modeled subwatersheds are outlined in black. The dashed red lines are the stream network provided by the City of Duluth. The blue lines indicate the LIDAR-derived stream network.

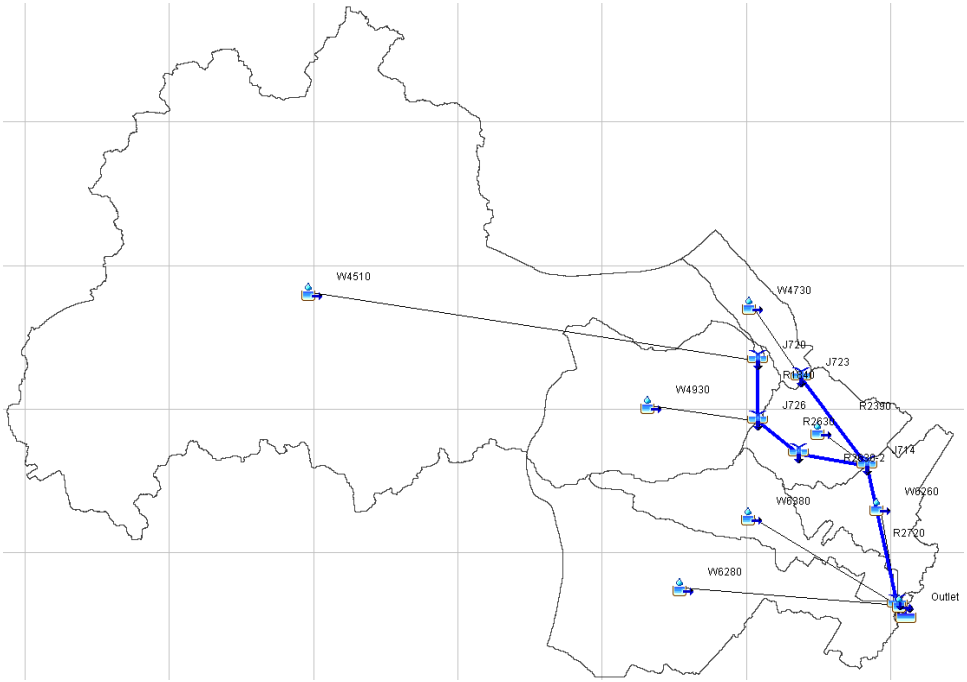

Figure 6 Schematic of the HMS model showing the relation to the modeled subwatersheds.

Precipitation and temperature data were obtained from the National Climatic Data Center (NCDC) for both Duluth International Airport (Duluth, MN) and Richard I. Bong Airport (Superior, WI). In conversations, Spirit Mountain personnel indicated that the precipitation measured at Duluth International Airport tends to be much higher than what is received at the ski area. It was decided to use the precipitation data from the Richard I. Bong Airport for the entire watershed.

HMS subwatersheds were set up with the Soil Moisture Accounting loss method. Clark Unit Hydrograph was chosen as the transform method to calculate runoff timing. The Simple Canopy and Simple Surface methods were also used. Baseflow was set to the Linear Reservoir method and the initial baseflow discharge was calculated by dividing the low flow in Knowlton Creek by the contributing watershed area.

The Kinematic Wave method was used for routing in the reach elements, due to the steep slopes (up to 6%) in the area. Channel parameters were estimated using the survey data and LIDAR-derived DEM.

The model was calibrated at the mainstem gage for the time period 24-Apr-2012 to 4-Jun-2012, since this included both a dry period and a large rain event. Calibration parameters included the Clark Unit Hydrograph time of concentration and storage coefficients, the maximum canopy and surface storages, and the Manning's roughness coefficient of the reaches. The results from the final calibration can be seen in Figure 7. After calibration, the Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970), a measure of how well the modeled values match the observed data, was 0.89. Nash-Sutcliffe efficiencies can range from $-\infty$ to 1, with 1 indicating a perfect fit of the observed data. A Nash-Sutcliffe efficiency above 0.5 is considered necessary for a good model (Moriasi et al., 2007).

The parameters from the subwatersheds upstream of the mainstem gage, including those associated with the Clark Unit Hydrograph and Soil Moisture Accounting methods, were translated to the other subwatersheds by scaling relative to the longest centroidal flowpath. The calibrated model was then run for the 2-year SCS Type 2 24-hour storm as an example of a common rainfall-driven event that would be likely to move significant sediment and could be compared to snowmelt events.

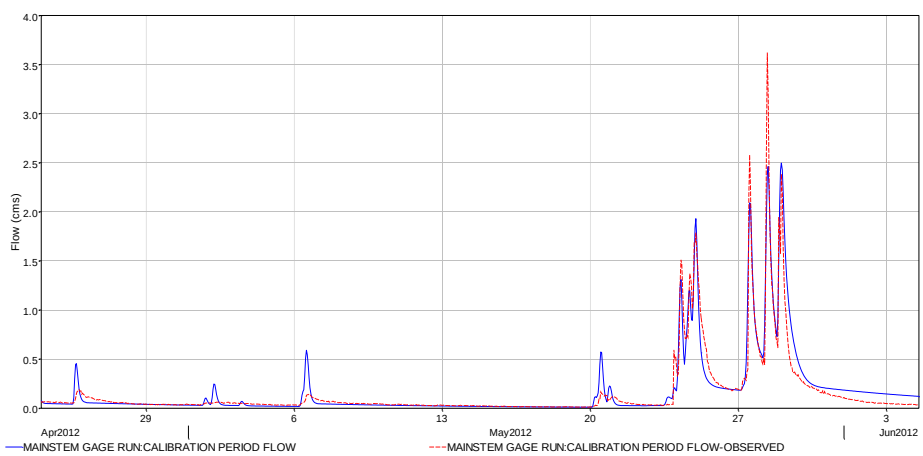

Figure 7 Calibration of the HMS model. The red line is the gaged data while the blue line is the output from the HMS model.

According to SMRA's records, provided by Johnson Controls, the ski area used an average of 238,073 m^3 of water per season between the winter of 1999-2000 and the winter of 2011-2012. It was applied at an average rate of 0.09 m^3/s. In order to determine the impacts of these snowmaking activities on the hydrology of Knowlton Creek, the HMS model was modified to calculate snow accumulation and melt. This version of the model was then run both with and without the additional water applied during snowmaking.

The accumulation and melt of snow were handled by using the Temperature Index snowmelt routine in HMS (Daly et al., 2000). To simulate the effects of frozen ground, the maximum infiltration rates for all of the watersheds were decreased. The lack of valid winter streamflow data prevented calibration of the snowmelt modeling. Instead, two sets of simulations were conducted in order to provide a range of values that would likely contain the actual snowpack and flows. The first set used typical values for the temperature index model parameters (Scharffenberg, 2013; Steve Daly, personal communication) and is referred to as the "Base" snowmelt model in this document. The second set used the high end of the suggested parameter ranges, in order to produce greater snowpack and melt. This set of parameters is called the "Peaked" snowmelt scenario. Due to the uncertainties regarding infiltration and frozen ground under the snowpack, each set of simulations was run for three different infiltration conditions: 100%, 10%, and 0% of the unfrozen infiltration.

According to SMRA, snowmaking operations run 24-hours per day during the entire snowmaking period. It was assumed that the water was applied equally to all of the ski runs maintained by SMRA. The precipitation equivalent of the snowmaking was calculated by dividing the total amount of water used by the hours of snowmaking for each season and then divided by the total area of all of the ski runs.

The ski runs are spread across three different subwatersheds in the model. HEC-HMS is a lumped parameter model and the watersheds were defined to include both ski run and non-ski run areas, so the water used for snowmaking was apportioned to each subwatershed based on the percentage of ski run area they contained. For example, 23.37% of the Southern Ski Area receives artificial snowmaking, so the hourly precipitation for the entire subwatershed was increased by multiplying the average amount of water used for snowmaking on all ski runs (as a depth in mm) by 23.37%, during the entire snowmaking period. This is illustrated graphically in Figure 8. This precipitation equivalent was calculated for each subwatershed and added to the precipitation applied using HEC-DSSVue. The area of each subwatershed, the area of ski runs, and the percentage of watershed area occupied by ski runs are summarized in Table 1.

While the magnitude of the streamflows collected during the snowmelt event in 2012 were not considered valid, the timing of both the onset of flow and the peak indicated by the gage data matched those from the simulation to within a day.

Table 1 Information used in calculating the contribution of snowmaking water to each subwatershed.

	Watershed Area (m^2)	Ski Run Area in Watershed (m^2)	% of Watershed occupied by Ski Runs	% of Total Snowmaking Water	Average Increase in Winter Precip (2007-2012)
Main Ski Area	605,740	249,866	41.25%	75.0%	326%
Southern Ski Area	292,010	68,235	23.37%	20.5%	50%
Southernmost Area	792,900	14,905	1.88%	4.5%	1%

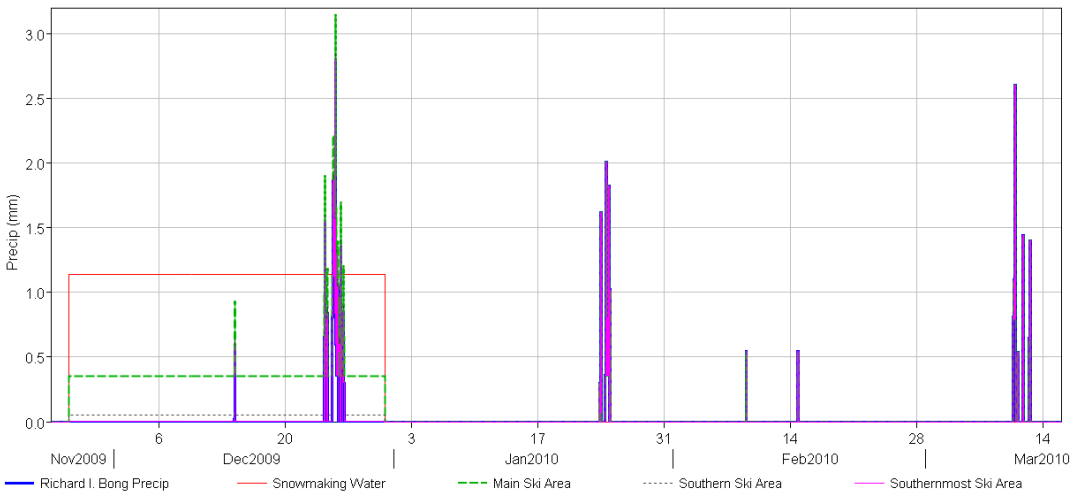

Figure 8 Example of snowmaking precipitation, for the winter of 2009-2010. The blue line is the background precipitation at Richard I. Bong Airport. The red line is the average rate of water applied for snowmaking. The dashed green line is the precipitation applied to the Main Ski Area subwatershed. Outside of the dates of snowmaking, all of the lines are identical.

The HMS model was run for five different winters (1-Oct to 1-May) between 2007 and 2012. The results were then examined and the dates of the snowmelt event, the time period that represents the conversion of the majority of the snowpack to runoff, for each winter were determined by looking at the air temperature records. The snowmelt event was started a few days before the temperature first reached 0 °C and was extended until after all of the snow had melted in the model. The same date range was used to summarize the output for each scenario covering that winter. The dates used for the modeled winters are listed in Table 2.

Table 2 Dates used to summarize the snowmelt event for each simulated winter.

Winter	Snow Melt Dates
2007-2008	30-Mar – 11-Apr-2008
2008-2009	15-Mar – 17-Apr-2009
2009-2010	7-Mar – 20-Mar-2010
2010-2011	15-Feb – 9-Apr-2011
2011-2012	11-Mar – 19-Mar-2012

RESULTS

Peak flow and volume were both reported, in order to better understand the hydrology and potential impact on sediment transport in Knowlton Creek. Figure 9 displays the locations where flow was summarized for this report. Table 3 shows the five-year average peak flow and Table 4 gives the average outflow volume results for all of the snowmelt simulations. These two tables also report the results for the simulation of the 2-year storm event. The Base and Peaked simulations produced nearly identical peak flows, but differed in the volume of the snowmelt event. On average, snowmaking increased the peak flow at the mainstem gage location by 0.2 – 0.3 m^3/s, or 27 - 66% (assuming the same infiltration conditions). The average volume of water in the snowmelt event at this location increased by 124,400 - 152,100 m^3, or 230 - 307%, on average (with identical infiltration conditions). The total volume of water delivered to the area behind Tallas Island increased by 149,300 – 208,500 m^3 (253 - 296%) and the five-year average peak flow at this point increased by 0.3 – 0.5 m^3/s (35 - 76%), assuming unchanged infiltration.

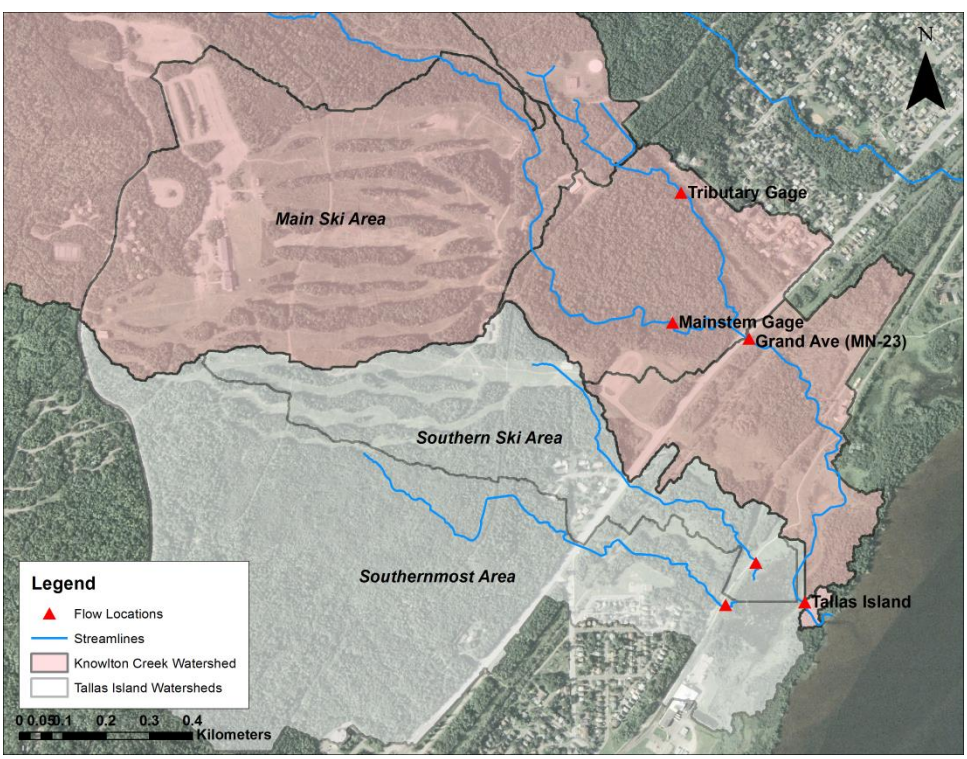

Figure 9 Map showing flow locations and watersheds where Maximum SWE was reported. The Tallas Watershed includes the shaded areas of both colors.

During the course of the winter, the accumulation of snowpack, measured as Snow Water Equivalent (SWE), is also calculated by the model. Figure 9 shows the watersheds where the snowpack was calculated for this report. Table 5 contains the five year average of maximum SWE that occurred for each scenario. Changing the infiltration did not affect the peak SWE, so only one set of results is reported for each combination of snowmaking and snowmelt parameters. The numbers shown for "Knowlton Watershed" and "Tallas Watershed" are area-weighted averages of all the component subwatersheds. This table shows that the peak SWE of the Knowlton Creek watershed increased by 40.9 - 45.3 mm while the peak SWE for the entire area contributing to the flow by Tallas Island increased by 41.4 – 47.3 mm due to snowmaking. The peak snowpack volumes (SWE) in the subwatersheds where the snowmaking took place were affected even more dramatically. The most extreme example of this is the "Main Ski Area" watershed that contains most of SMRA's ski runs. This area experienced an increase in peak SWE of over 340 mm due to snowmaking, during an average winter.

Table 3 Peak flow due to snowmelt (average of winters 2007-2012, m^3/s) and the 2-year design storm

	Snow-making	Infiltration	Mainstem Gage	Grand Ave (MN-23)	Southern Ski Area	Southernmost Area	Tallas Island
Base Snowmelt	**No**	**100%**	0.4	0.4	0.0	0.1	0.5
		10%	0.6	0.6	0.0	0.1	0.6
		0%	1.1	1.2	0.1	0.1	1.3
	Yes	**100%**	0.6	0.6	0.1	0.1	0.7
		10%	0.9	0.9	0.2	0.1	1.0
		0%	1.5	1.5	0.2	0.2	1.8
Peaked Snowmelt	**No**	**100%**	0.4	0.4	0.0	0.1	0.4
		10%	0.5	0.5	0.0	0.1	0.5
		0%	1.1	1.1	0.1	0.2	1.3
	Yes	**100%**	0.6	0.6	0.1	0.1	0.8
		10%	0.8	0.8	0.2	0.1	1.0
		0%	1.4	1.4	0.2	0.2	1.8
2-Year Storm		**100%**	5.8	5.9	0.5	1	7.2

Table 4 Runoff volume due to snowmelt (average of winters 2007-2012, 1000 m^3) and the 2-year design storm

	Snow-making	Infiltration	Mainstem Gage	Grand Ave (MN-23)	Southern Ski Area	Southernmost Area	Tallas Island
Base Snowmelt	No	100%	47.7	48.9	1.2	3.8	54.8
		10%	47.6	49.0	1.4	3.8	55.1
		0%	47.6	50.5	2.4	6.7	61.5
	Yes	100%	172.2	173.3	24.9	5.2	204.1
		10%	173.8	175.1	26.3	5.2	208.1
		0%	193.7	196.6	41.9	9.9	252.7
Peaked Snowmelt	No	100%	55.3	56.6	1.2	4.5	63.2
		10%	55.1	56.6	1.4	4.5	63.5
		0%	55.0	58.1	2.4	8.0	70.5
	Yes	100%	182.4	183.6	32.2	6.9	223.3
		10%	185.7	187.1	34.5	6.9	229.0
		0%	207.1	210.2	54.1	13.3	279.0
2-Year Storm		100%	309.9	329.5	11.3	29.2	379.1

Table 5 Peak Snow Water Equivalent (SWE) (average of winters 2007-2012, mm of water).

	Snow-making	Main Ski Area	Southern Ski Area	Southernmost Area	Upland Watershed	Knowlton Watershed	Tallas Island
Base Snowmelt	No	6.2	0.5	3.0	7.7	6.7	5.9
	Yes	346.3	153.5	7.2	7.7	47.6	47.4
Peaked Snowmelt	No	8.4	0.8	5.9	9.7	8.6	7.9
	Yes	385.6	194.5	11.3	9.7	53.9	55.1

CONCLUSIONS

Snowmaking activities by SMRA have increased the peak flow in the mainstem of Knowlton Creek from the annual snowmelt event by up to one half, on average. Sediment transport is a non-linear function of the flow in a stream, meaning that the ability of the stream to move sediment has likely increased by even more than that amount during these events.

It is important, however, to view these increased snowmelt flows in the context of those resulting from less frequent storm events. This can be done by comparing the values in Table 3 with those in Table 6. The typical snowmelt event resulting from snowmaking activities over 2007-2012 had a peak flow that is less than one-fifth the flow from a 2-year design storm at the Mainstem Gage location. In a well-functioning forested watershed, it is often assumed that the flow most responsible for forming the shape of the stream channel, and the one that will carry the majority of sediment over long periods of time, occurs every one to two years (Leopold et al., 1964). Therefore, it can reasonably be hypothesized that the flow increase above the background

snowmelt caused by snowmaking would play only a minor role in the sediment transport and geomorphic adjustment of Knowlton Creek.

A literature search for studies of snowmaking impacts turned up very little work. Wemple et al. (2007) studied a ski area in Vermont that used water from within its watershed for snowmaking. They found that water yield increased by 18-36%, a much smaller increase than the snowmelt volume in the Knowlton Creek model. In the Vermont study, this resulted in a 2.5-fold increase in suspended sediment yield. The suspended sediment yield typically consists of silts and clays while larger material will move as bed load, except in extreme events. Unfortunately, no estimates of changes to bed load sediment transport or overall sediment yield were given by the Wemple et al. study.

It should also be noted that another significant hydrologic impact of the ski area has likely been the clearing of the ski runs themselves. Historically, the entire hillside of Spirit Mountain was completely covered by forest, which tends to reduce both overland flow and sediment yield. The effects of tree removal and other mechanical activity in the ski area, as well as the addition of impervious surface area across the watershed were not examined in this study.

It may be advisable to reduce the effects of runoff from the snowmelt events caused by artificial snowmaking, even though this impact is likely not large enough to drive the observed changes in the mainstem of the Knowlton Creek channel. If this reduction is done by the use of runoff control on and at the base of the ski slopes, it would also partially mitigate the effects of the land cleared of forest to create the ski area.

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