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Using time lapse photography to document terrain preferences of backcountry skiers

Diana Saly[a,b,*], Jordy Hendrikx[b], Karl W. Birkeland[b,c], Stuart Challender[b], Jerry Johnson[b,d]

[a] Avalanche Canada, Revelstoke, British Columbia V0E2S0, Canada
[b] Snow and Avalanche Laboratory, Department of Earth Sciences, Montana State University, P.O. Box 173480, Bozeman, MT 59717-3480, USA
[c] USDA Forest Service National Avalanche Center, Bozeman, MT, USA
[d] Political Science Department, Montana State University, P.O. Box 173480, Bozeman, MT 59717-3480, USA

A B S T R A C T

Travel in avalanche terrain requires considered and careful selection of appropriate terrain to reduce exposure to avalanche danger. In many parts of the world, recreational backcountry skiers in avalanche terrain are aided by a regional avalanche forecast. The overall aim of an avalanche forecast is for users to adjust their terrain choices in response to the avalanche danger rating and avalanche problem, thereby reducing their risk of an avalanche involvement. In this paper we present a novel passive observation technique to assess how lift assisted backcountry skiers adjust their terrain use in response to the avalanche danger rating.

This paper develops and demonstrates a method to record the terrain metrics of all skiers on an avalanche-prone backcountry slope. Using a remote time-lapse camera focused on a high skier-use backcountry slope, we anonymously recorded the descent route of skiers in ten-second increments. Using 31,966 images over 13 days and 7499 skier point locations, skier locations were digitized from the images, then transformed onto a geo-referenced digital elevation model (DEM) such that terrain metrics could be extracted for each anonymous skier location.

When these location points are compared to simultaneous GPS measurements, the horizontal accuracy was estimated to be within a 49-m horizontal accuracy, with a 95% confidence interval. Analysis of the terrain metrics for each skier point compared slope, profile curvature (downslope), and plan curvature (cross slope) over days with different forecasted avalanche danger ratings. This statistical analysis was qualitatively supported by a review of the spatial patterns of the terrain choices on these days. Furthermore, we used this technique to estimate group size, and found a surprising number of solo skiers, even on Considerable avalanche danger days. By remotely photographing all skiers on a slope, the data collected provides a large and diverse data set of the terrain preferences of backcountry skiers under varying avalanche conditions, with limited bias. These results have implications for avalanche education by enhancing our understanding of specific terrain management skills by backcountry skiers.

1. Introduction

Avalanches are a recognized hazard for those recreating in snow covered mountainous terrain (McClung, 2014; McCammon and Haegeli, 2007). Over the last ten years, on average, 12 people in Canada and 27 people in the US perished in avalanches each winter season. (Avalanche Canada, 2018; Colorado Avalanche Information Center, 2018). Avalanche professionals manage avalanche risk by forecasting avalanche danger (through weather, snowpack, avalanche observations, and other collective data) and selecting terrain that limits exposure to the avalanche danger. Analysis on the GPS tracks of professional ski guides under different forecasted avalanche danger showed they skied steeper, more open, and more convoluted slopes as avalanche danger decreased, and chose more conservative terrain as avalanche danger increased (Hendrikx et al., 2016; Hendrikx and Johnson, 2016a; Hendrikx and Johnson, 2016b; Thumlert and Haegeli, 2018). Terrain management is considered to be a highly effective method of mitigating avalanche risk. As such, methods that can elucidate terrain use of backcountry skiers may indicate where and how terrain related accidents occur.

A public avalanche forecast aims to provide those recreating in backcountry avalanche terrain information on the forecasted avalanche danger. Users may then adjust their terrain use according to the avalanche problems in a similar method as avalanche professionals. Studies on the terrain choices of recreational skiers[1] have utilized GPS tracks and survey responses. Analysis of terrain choices from GPS tracks, skier surveys and post-accident reviews suggests most backcountry skiers alter avalanche terrain choices with changing avalanche danger (Hendrikx et al., 2014; Thumlert and Haegeli, 2018; Hendrikx and Johnson, 2016c). By collecting terrain preferences from an entire group of recreationalists on a backcountry avalanche prone slope, we may gain a more robust insight on how skiers adjust terrain choice according

* Corresponding author at: Avalanche Canada, Box 560, Revelstoke, British Columbia V0E2S0, Canada.
E-mail address: dsaly@avalanche.ca (D. Saly).

[1] In this paper we will use the term backcountry skier to describe all backcountry users in our study area (including skier, snowboarder or telemark skier).

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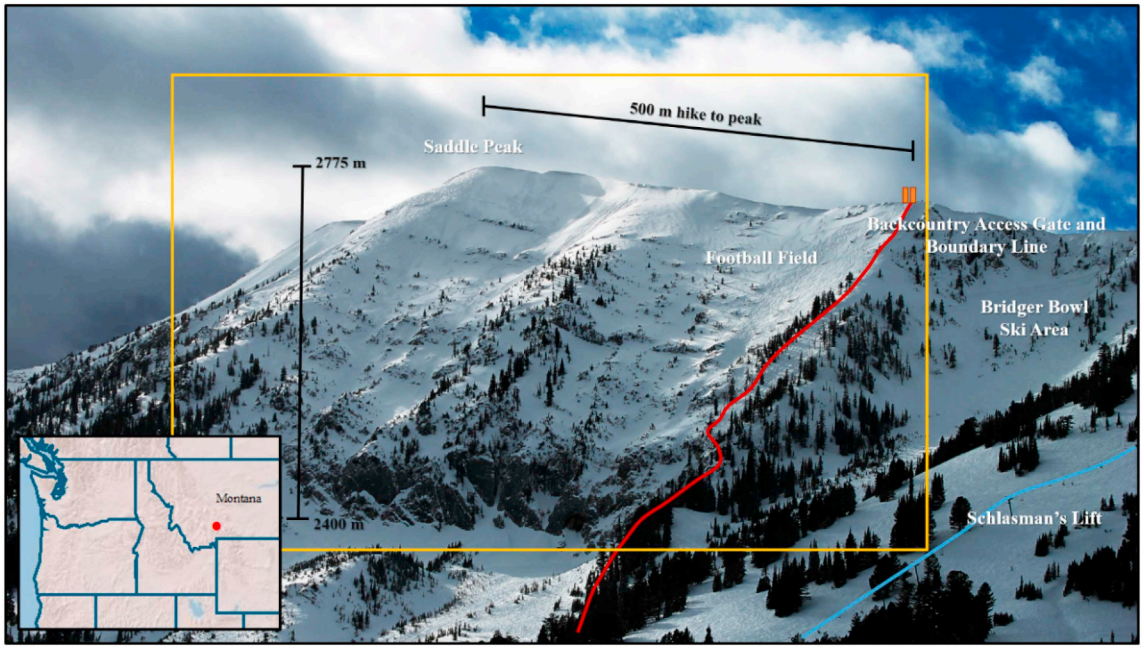


Fig. 1. The east face of Saddle Peak located adjacent to the Bridger Bowl Ski Area as photographed from the time lapse camera, looking west. The slope is accessed by riding the Schlasman's Lift (blue line), exiting the boundary at the backcountry access gate at ridgetop (gate and red line). Saddle Peak users can descend immediately into the Football Field or hike along the ridge, entering the slope at any point. The study area is outlined in the yellow box. Skiers are observed descending the east slopes of Saddle Peak. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to the forecast.

This research uses an oblique time lapse camera to record skier locations on an avalanche prone slope over multiple days. The skier locations in the images are geo-referenced and transformed onto a digital elevation model (DEM). Terrain metrics (slope, profile curvature, and plan curvature) from the DEM are referenced to each skier location and compared for days with different forecasted avalanche danger. By sampling all skiers on a slope, the data collected provides a snapshot of the terrain preferences of all backcountry skiers using this area under varying conditions as defined by the terrain metrics of slope, profile curvature, and plan curvature.

2. Background

2.1. Study area

Saddle Peak is a popular destination for backcountry skiers in the Bridger Mountains of the Gallatin National Forest of southwest Montana, USA (Fig. 1). The east facing slope is adjacent to, but outside of, the south boundary of the Bridger Bowl Ski Area and almost exclusively accessed through the ski area. It is easily visible from the Schlasman's lift within the ski area. From the backcountry access gate on Bridger Bowl's south boundary line at 2660 m (above sea level), the peak rises to 2792 m, easily accessible by walking 500 m south ascending the ridge. The large avalanche start zones across the east face of Saddle Peak are frequently wind-loaded and corniced. The slope is broken mid-track by large cliffs up to 60 m tall. Below the cliffs around 2400 m, the avalanche run-out zone of Saddle Peak is low angle terrain adjacent to the ski area boundary. A trail at the bottom leads back to the ski area and to the bottom of the Schlasman's Lift. Skiers on the east face of Saddle Peak are rewarded with runs up to 700 m long with 375 m vertical drop. Bridger Bowl operates with an open boundary policy where skiers are free to depart the ski area in identified locations; the south boundary line is one such area.

A Canon Rebel T5 EOS Digital SLR camera triggered by Harbortronics DigiSnap 2000 time-lapse switch was installed to capture skiers on the east slope of Saddle Peak. The camera was positioned in a fiberglass housing with a glass window. A five-watt solar panel on the top of the housing provided power to the camera and time-lapse switch. The housing was mounted to a plywood platform fastened to the railing on the top of an abandoned concrete 75 mm recoilless rifle bunker platform once used for avalanche control operations within the Bridger Bowl Ski Area. The bunker is located at the top of a lower elevation hill at 2000 m and provided a good vantage point for the Saddle Peak study area. From the camera location, the peak of Saddle Peak is about 2.5 km to the west and slightly south (110–120 degrees). The camera captured an oblique view of the east face of Saddle Peak, both shooting from below and at an angle facing south-west to capture Saddle Peak (Fig. 2).

The time-lapse switch was programmed to take one photo every ten seconds between the hours of 10:00 am – 4:00 pm. The Schlasman's lift opens to skiing public around 10:00 am and closes at 2:30 pm daily (in late spring, the lift runs until 3:00 pm). The start/stop times were adjusted throughout the study, but the programmed 10 s interval between images was constant throughout the study. The resolution of the images made tracking and identifying individual skiers possible but was not detailed enough to identify any distinguishing characteristics of skiers, thereby providing anonymous positional data on the skiers in the area.

2.2. Avalanche history

The Bridger Range is a popular area for backcountry skiing and snowboarding and the Gallatin National Forest Avalanche Center (GNFAC) publishes a daily avalanche forecast for the area which includes Saddle Peak. The avalanche danger is rated on the five-level North American Public Avalanche Danger Scale (Statham et al., 2018). Between 2010 and 2017, the GNFAC database documented twelve avalanche events that occurred around Saddle Peak, either on the Football Field or the north and south bowls below the Peak (Fig. 1). Six of those events involved individuals, including an avalanche (size R3, D3) in February 2012, in which the skier was carried 600 m downslope, partially buried and injured (GNFAC, 2018). In January 2016, the first year the camera was installed, an avalanche (size R2, D2) was remotely triggered by two skiers and recorded by the camera (Saly et al., 2016). In April 2018, a solo skier was killed in an avalanche (size R3, D2) off

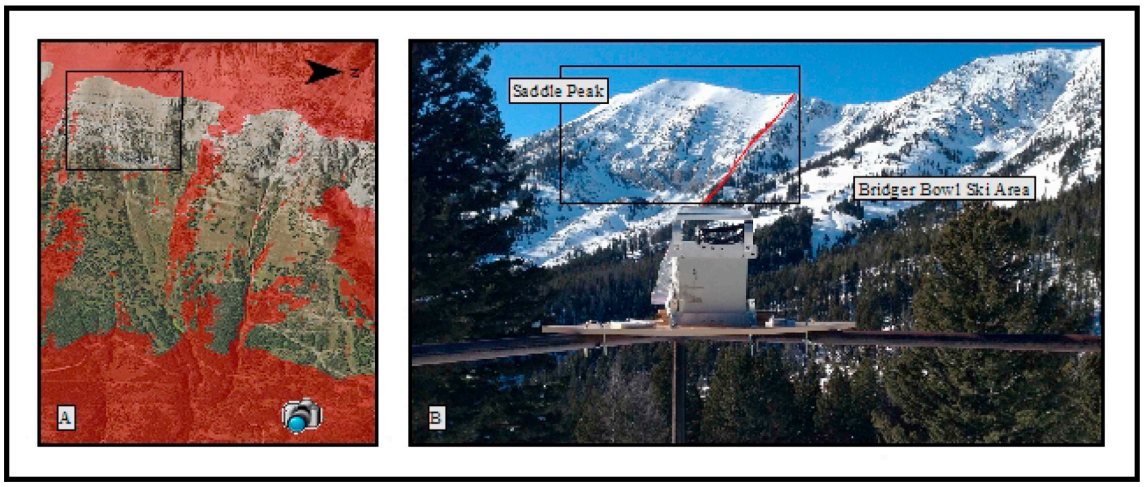


Fig. 2. (A) The study area (in black box) as seen from the camera location (camera icon) and resulting viewshed (visible objects the camera location) calculated in ArcGIS using a 10 m DEM. The area covered in red is out of the viewshed of the camera due to the altitude and orientation of the slope relative to the camera. (B) The camera and platform looking towards Saddle Peak. The red line identifies the division between the Bridger Bowl Ski Resort boundary and Saddle Peak and the backcountry. The study area is outlined by the black box in panel A and B. Refer to Fig. 1 for more details on the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Saddle Peak, carried 500 m and buried 40 cm below the surface (GNFAC, 2018). These recorded events highlight both the usage of, and complexity of, this terrain and the importance of careful terrain selection in the study area.

2.3. Related research on saddle peak

Fitzgerld et al. (2016) conducted surveys on the northern and southern boudaries of Bridger Bowl (where the southern boundary provides access to Saddle Peak), to document the level of preparadness of backcountry skiers. They noted that on average, skiers leaving these boundaries were less prepared with respect to rescue equipment and more poorly informed on avalanche danger level, compared to traditional backcountry skiers in the same region. Sykes, 2018 and Sykes et al. (2019), expanded on this work, and replicated the survey questions regarding preparedness and demographics, but also asked participants to carry a GPS so that terrain choices could be documented. While these approaches have improved our understanding of the population of users, and the terrain choices of a subset of these users, the studies utilize convenience samples, which are inherently biased towards more experienced participants (Hendrikx and Johnson, 2016a, 2016b, 2016c). This study aims to address the selection bias introduced by convenience samples documenting the terrain preferences by collecting data on all backcountry skiers on Saddle Peak on a given day(s) using a time lapse camera methodology.

3. Methods

3.1. Field data collection

A total of 121,388 images over 71 different days were collected over two winter seasons: January 1, 2016 – March 31, 2016 and January 7, 2017 – March 11, 2017 (Fig. 3). At ten second intervals, 360 images per hour were recorded with a successful six-hour data-day producing approximately 2160 images. Each image captured was 12 megapixels in size and had a vertical and horizonal resolution of 72 dpi (dots per inch). Files sizes were 3–5 MB and stored in JPEG format. Incomplete data affected 29 days of collected images, and, eight days of images were of insufficient quality for analysis (due to camera vibrations, etc.), leaving 34 potential days available for analysis. Of the 34 available days, a subset of 13 days, utilizing 31,966 images were processed and analyzed for this paper. The days were chosen to include similar weather, with visibility to the terrain, with a variety of avalanche danger forecasts.

Using this subset of 31,966 images over 13 days, we documented 525 skiers and 7499 skier-point locations. We recorded 182 skiers (1995 skier-points) on four days of Low avalanche danger, 175 skiers (4254 skier-points) on four days of Moderate avalanche danger, and 168 skiers (1250 skier-points) on five days of Considerable avalanche danger. No days of High or Extreme avalanche danger were sampled. On average, we documented fewer skiers under Considerable danger than Moderate or Low. However, the highest skier days recorded were 130 skiers under Low danger on March 27, 2016 followed closely by 129 skiers under Considerable danger on February 14, 2016 (Table 1 and Fig. 8).

3.2. Data preparation and workflow

ESRI ArcGIS 10.4 was used to process the photographs and convert skier-point locations in the photographs (i.e. pixels) to digital points on a georeferenced DEM of Saddle Peak (Fig. 4). The DEM used in this study reported 10 m accuracy (U.S. Geological Survey, 2017), and was used to provide terrain metrics on each skier point. Visually assessing time-lapse images for quality and complete days of data initiates the workflow. The daily forecasted avalanche danger was attached to each data set (Table 1).

From each image, skier locations were identified and digitized into a point-file in pixel space relative to the image. A script was developed within the ArcPy model to automate the process. The script analyzed each photograph by comparing one image against the previous image (10 s prior) and identifying where pixel changes occurred. A pixel change represented where a skier had changed locations from the previous image as well as other changes such as clouds or the camera housing moving. For every pixel change a point-file was created. Isolating individual skier-locations from other pixel-change point detections (e.g. moving trees, etc.) was performed manually, resulting in a point-file that represented only skier locations at a given time stamp. All skier-locations for every time stamp were merged into a single data file containing all skier points for a single day of study (Fig. 4, Step 1).

Next, skier location point-files were geo-referenced to the DEM using a projective transformation. A projective transformation maps lines to lines without preserving parallelism (ArcMAP, 2017). These transformations are commonly used to understand and explain visual perspective and have been used in similar photography-based snow

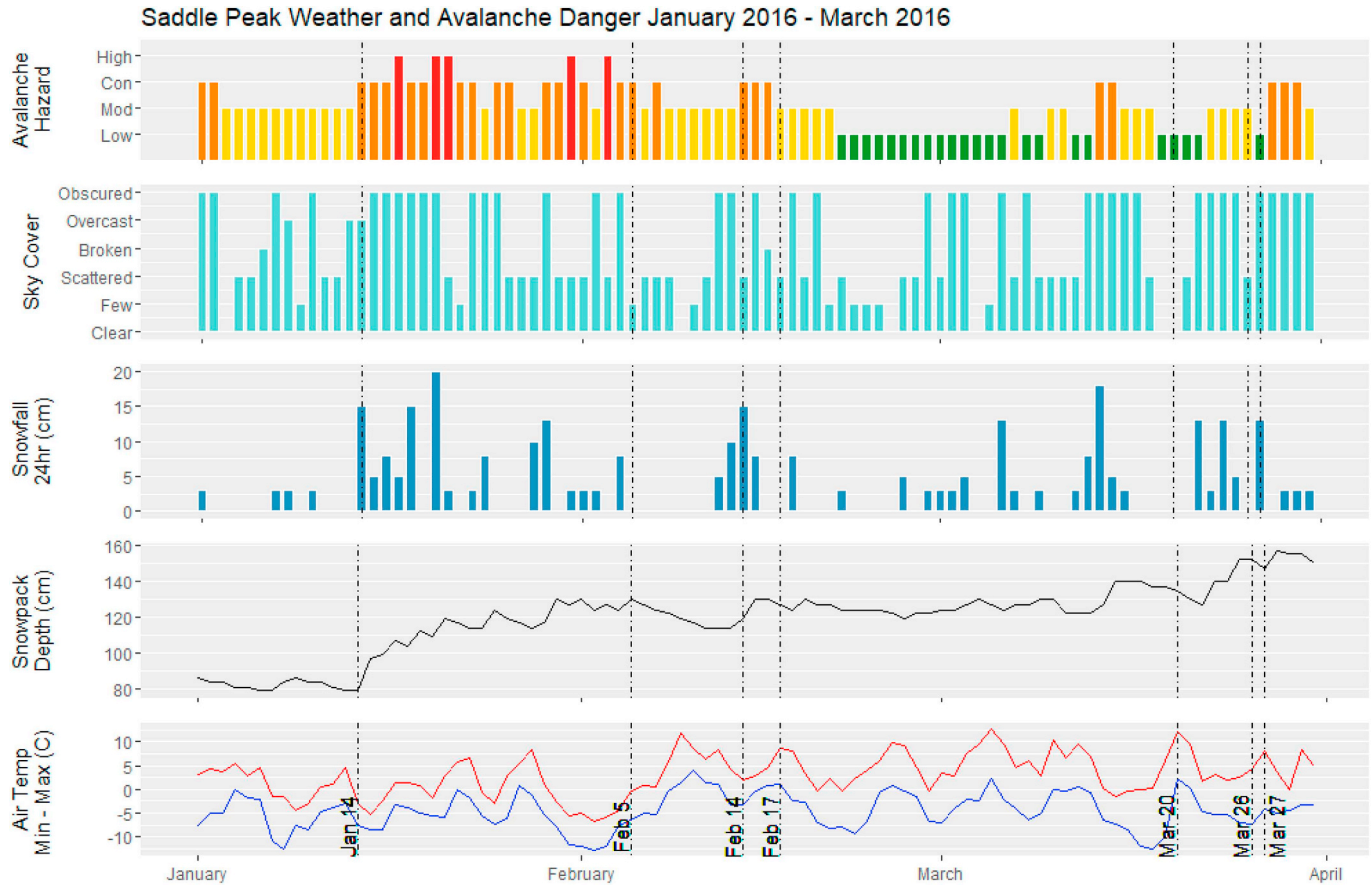


Fig. 3. Weather and avalanche data for 2016 and 2017 study seasons (January–March). (Bridger Bowl Raw Weather Data Tables, 2018; Weather Underground: Forecasts and Weather, 2016, 2017).

science research (e.g. Corripio, 2004). This ArcGIS projective transformation process requires a minimum of four displacement links. In this study, displacement links are identified as Control Points (CPs) on both captured two-dimensional image of Saddle Peak and DEM for all 13 days used in this analysis.

The CPs were stationary objects identified in the study area and remained the same on the DEM for every transformation and a subset of displacement links was created for every study day due to the small shifts that occurred to the camera which slightly changed each study day's image reference frame. We used 30 CPs for 9 days and 10, 12, 28, and 20 CPs in the other four days. When skier locations covered a large percentage of the study area, more control points provided better accuracy for individual skier locations. After more than 30 control points, there was a negligible reduction in overall image geo-referencing accuracy resulting in a maximum number of 30 CPs used. Smaller number of CPs were appropriate for days with of smaller number of skier points and more condensed and clustered points within a small geographic area. Adjusting the selection of CPs in relation to the area used resulted in improved accuracy for each given day (Fig. 4, Step 2 and 3).

The digitized skier-location points in the oblique images were then projected and geo-referenced into a known coordinate system, the North American Datum of 1983 (NAD 83) and the North America Vertical Datum of 1988 (NAV 88), so that elevation was documented in meters and slope in degrees (U.S. Geological Survey, 2017) (Fig. 4, Step 4).

3.3. Positional accuracy of skier location points

The oblique angle of the camera naturally introduces error due the angle it views Saddle Peak and records skier locations. Additional error is introduced in the transformation process as a two-dimensional oblique image is transformed onto a three-dimensional elevation model (as per Fig. 4). And as this DEM is a representation of bare ground, the snow surface could be significantly different (smoothed) due to wind drift and loading. To assess the positional accuracy of the transformed skier-location points, spatial accuracy and relative accuracy are considered.

Spatial accuracy is an indicator of how points are closely positioned with respect to true position in a referenced coordinate system. Spatial accuracy was measured by individual error associated with each CP in the projection transformation of skier-locations for each day. As each data-day had a unique subset of the CP links, every CP had unique error values. CP locations that presented a slope more perpendicular to the camera angle (i.e. steep, northeast aspect), had lower error values than locations that presented a slope more parallel (i.e. flat lower elevation, southeast aspect) to the camera. Slopes that were more parallel to the capture angle introduced more spatial error as small changes in location on the oblique image could result in large error values on the DEM (Fig. 5). In the projection transformation process, 10–30 CPs were used for each data-day CP link-file. For all thirteen data-days, in total 340 control points were identified. The maximum individual error for a single CP was 61.4 m (March 02, 2017), the minimum individual error was 0.4 m (January 17, 2017). The overall average error for all individual CP links was 21.8 m.

Accuracy of the methodology of capturing skier locations using time-lapse photography adheres to the 1998 National Standard for Spatial Data Accuracy guidelines. This tests the root mean squared error of the reported ground position of each individual control point link against the actual position, requiring that 95% of the dataset has reported error that is equal or smaller than the reported accuracy value

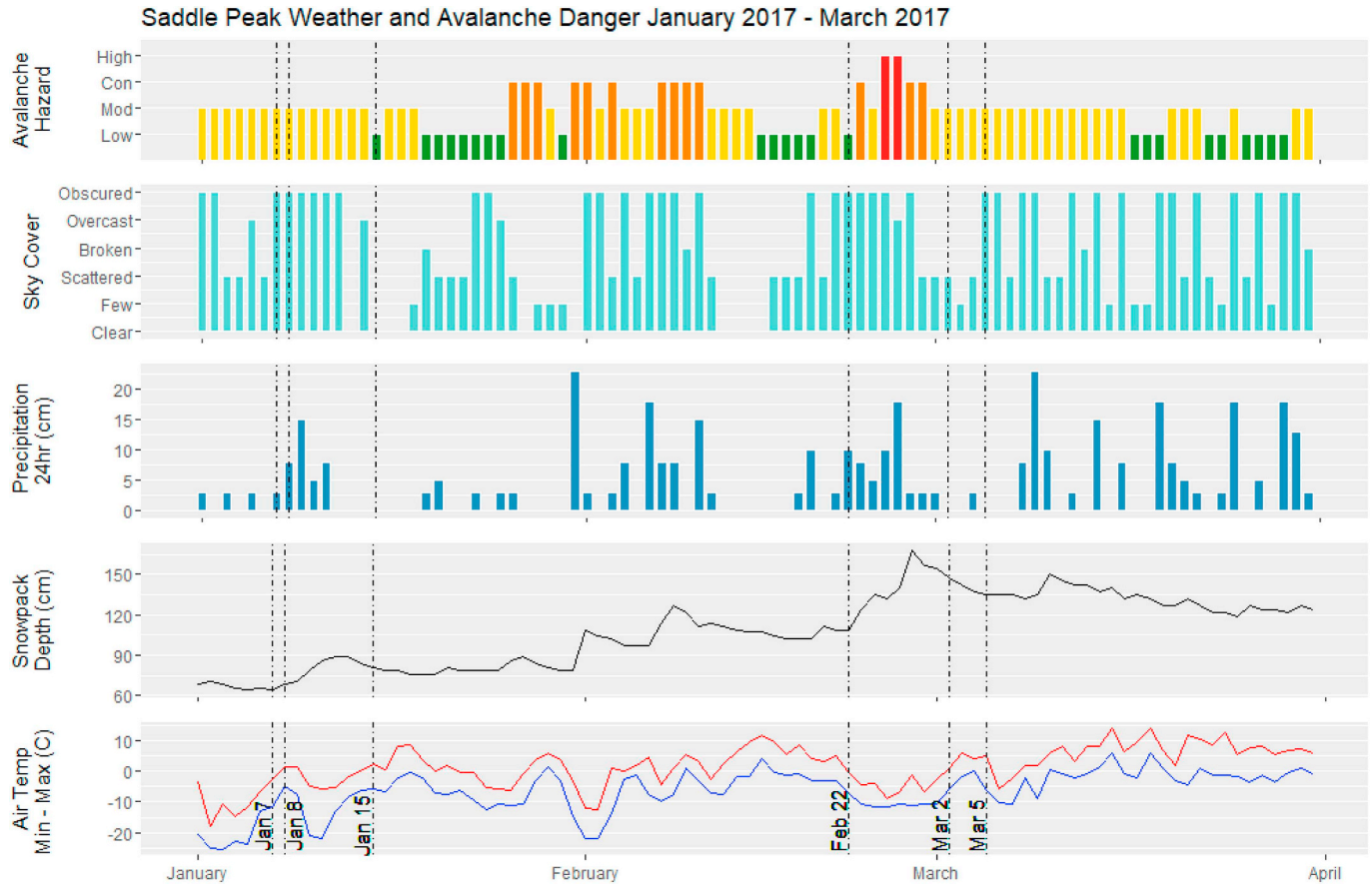


Fig. 3. (*continued*)

(Federal Geographic Data Committee, 1998). This paper establishes a spatial accuracy of transformed data based on calculated error values of each control points used in the skier-point transformation process. Transformed skier location points tested 49 m horizontal accuracy for a 95% confidence interval (Fig. 6).

A potential issue in our analysis was the difference in accuracy between transformed skier points (49 m) and the DEM (10 m). To align resolution between the DEM and skier location data sets, the 10 m DEM was resampled to 30 m resolution using a nearest neighbor assignment which averages the values of a 3 × 3 cell neighborhood (i.e. 30 m × 30 m). This was done to better understand the accuracy of our data and to account for the known precision error. However, resampling the DEM produces smoothing effect resulting in more homogeneous terrain with less accurate metrics. Our analysis utilized terrain

Table 1
Table summarizing days of analysis. Row colour corresponds to forecasted avalanche danger (Red - Considerable, Yellow - Moderate, Green - Low).

Date	Day	Av Danger	Numbers of Images	Points	Skiers	Solo skiers	Solo skier %	CPs
1/14/2016	Thur	Con	1802	109	18	4	22%	20
2/5/2016	Fri	Con	2879	20	1	1	100%	10
2/7/2016	Sun	Con	2879	92	18	3	17%	12
2/14/2016	Sun	Con	2879	882	129	37	29%	30
3/20/2016	Sun	Low	2879	408	15	1	7%	30
3/26/2016	Sa	Mod	2879	2097	52	3	6%	30
3/27/2016	Sun	Low	2789	1254	130	7	5%	30
1/7/2017	Fri	Mod	1980	185	13	1	8%	30
1/8/2017	Sun	Con	1853	147	21	11	52%	30
1/15/2017	Sun	Low	1782	286	34	4	12%	28
2/22/2017	Wed	Low	1691	47	3	0	0%	30
3/2/2017	Thur	Mod	3509	1152	76	17	22%	30
3/5/2017	Sun	Mod	2159	820	34	5	15%	30
Totals:			31960	7499	525	94	**Avg**: 18%	

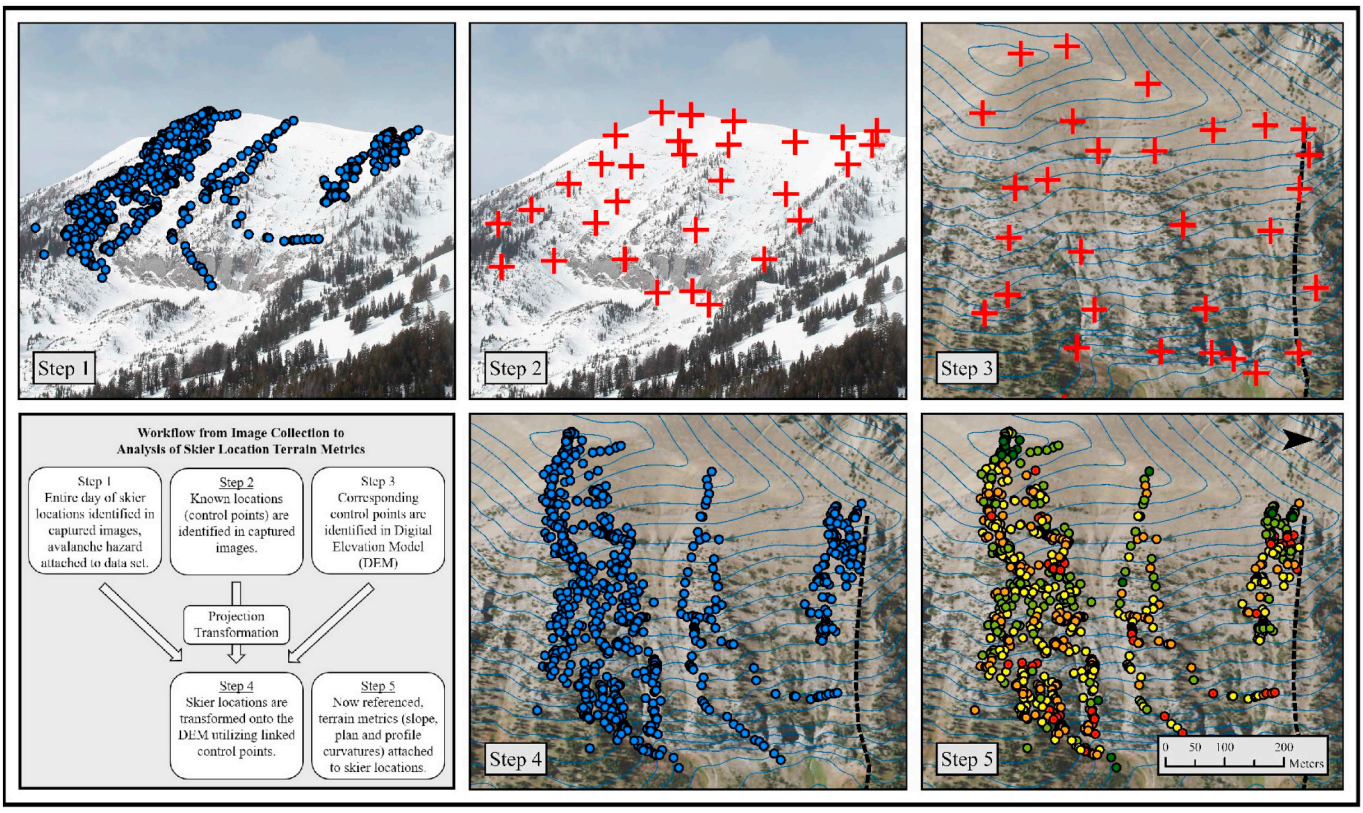


Fig. 4. Expanded workflow of how skier-points are referenced in a coordinate system. Following this process, the terrain metrics are analyzed in R (R Core Team, 2015). The dashed black line represents the Bridger Bowl Boundary.

metrics acquired from the resampled 30 m DEM to meet established spatial accuracy from skier location transformation. While this is not a perfect match in resolution, we considered these values acceptable as a proof of concept in this study.

Relative accuracy is the relationship between two points and the spatial characteristics of each. Relative accuracy was tested by assessing the distance of transformed skier location point to GPS tracks of the same skier. On March 5, 2017, GPS tracks of volunteer skiers were captured with recreational Garmen eTrex GPS units as they descended Saddle Peak (Sykes, 2018). The volunteer skiers were simultaneously recorded by the time-lapse camera. Over the day, 36 skiers were observed by the time-lapse camera and fourteen GPS tracks were recorded. Skier locations were identified in the photos, digitized and georeferenced to a DEM. These points were then compared to the corresponding GPS track. The fourteen GPS track point locations were compared against the photos and identified; a 30 m buffer was applied

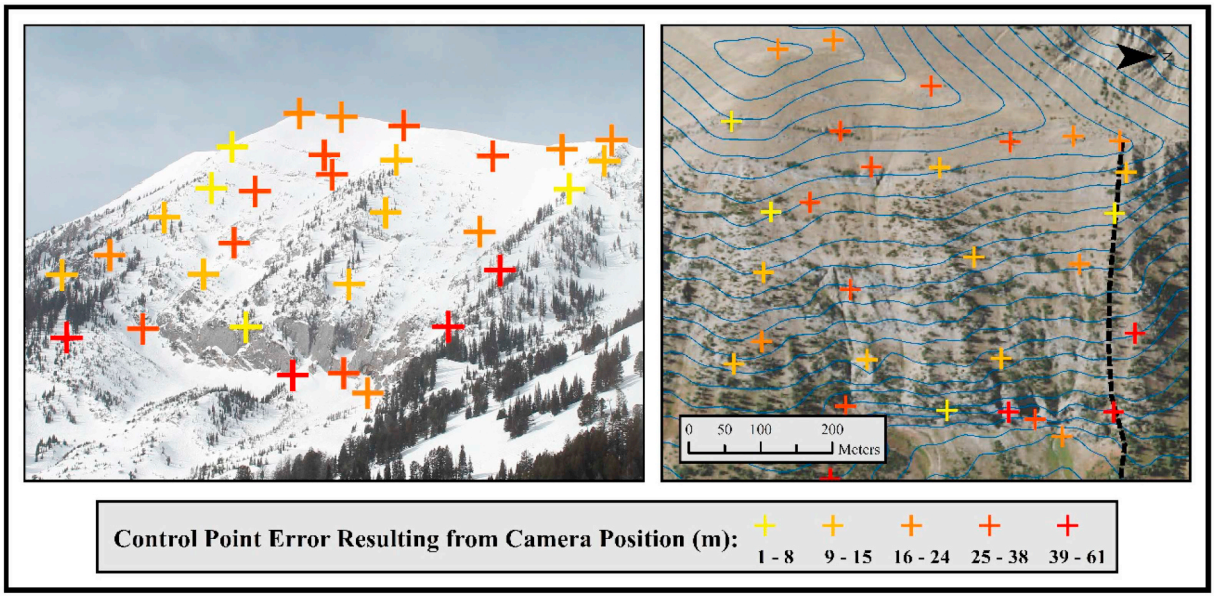


Fig. 5. Oblique and map view of the spatial locations of the control point error resulting from camera position. Colour codes provide the range of spatial error in meters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

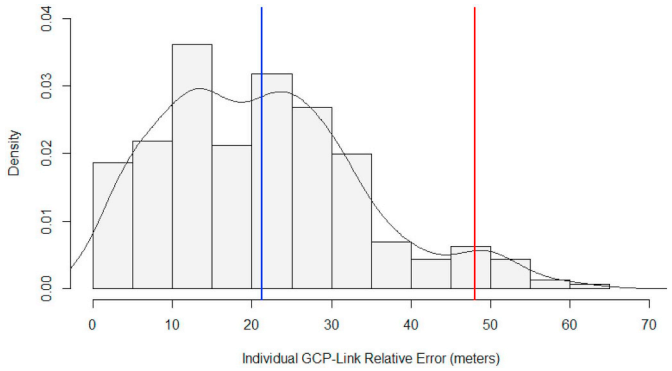


Fig. 6. Histogram of the relative error values from each control points links as represented by the density of error values located within each bar. Median control point error is 21 m (blue line). Individual control points tested at 49 m horizontal accuracy at 95% confidence level (red line) providing the spatial accuracy of our data set and corresponding terrain metrics. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to the track to visually assess skier-location distance from GPS track and provide an assessment of relative accuracy (Fig. 7). The GPS units had a much higher sampling rate than the ten-second images and Garmin ETrex are known to have accuracy of 5–7 m of error in open sky view terrain (representative of Saddle Peak) (Wing et al., 2005).

To measure skier-location relative accuracy against the GPS track, the shortest distance to the relative GPS track was measured for every skier-location. Overall, the maximum distance measured from a skier location as defined in the camera view to GPS track was 36 m, the minimum distance was 0.2 m, and the average distance between GPS track and skier-location point was 9.9 m. Considering relative accuracy by distance between GPS track to skier location points, the maximum distances for each track/skier-location point line tested at 22.9 m horizontal accuracy at 95% confidence level (Fig. 7).

3.4. Terrain metrics and statistical analysis

Terrain metrics are categorized according to groups as per Thumlert and Haegeli (2018). The profile curvature (downslope) is the direction of the maximum slope; an upwardly convex (unsupported) slope is indicated by a positive value and an upwardly concave (supported) slope is indicated by a negative value, zero indicates a flat surface. The plan curvature (cross slope) is perpendicular to the cross section of the slope. Similarly, a convex feature (ridge) is indicated by a positive value, a concave feature (gully) is indicated by a negative value, and zero indicates a flat surface (Table 2).

To determine if terrain metrics of skiers differed statistically on days with different avalanche danger, an analysis was performed using the non-parametric Kolmogorov-Smirnov (K—S) two-sample test. The K—S test has been used in previous snow and avalanche research testing the terrain metrics between different skier groups (e.g. Hendrikx et al., 2016). The K—S test assesses the distance between the medians of the test variable against the data set, hypothesizing two samples drawn from different populations will have the same median distribution (Wang et al., 2003). The K—S test does not require the data be normally distributed and is used with ordinal and interval data, as is the case for our data set. In the following tests we utilize the K—S assess if median distribution of terrain skied under Considerable avalanche danger is greater (less steep), the profile curve is greater (more supported/concave), and the plan curvature is lesser (more ridge-top/planar features).

4. Results and discussion

4.1. Qualitative analysis of terrain choices

Using our time lapse camera methodology, we are able to examine both qualitative and quantitative trends in terrain preferences of skiers. At a qualitative level, visual examination of the images illustrated that skier line choices changed with different avalanche conditions. Under Considerable avalanche danger, most skiers chose either the ski area boundary line or the ridge descent from Saddle Peak – lines considered less exposed than other choices. While previous avalanche activity indicates these areas do produce avalanches, we suggest these areas may be considered safer lines by skiers as opposed to “center-punching” or skiing the middle line, more exposed to multiple hazards and the large cliff band below this slope. Under Moderate danger, line choice had more variance, but skiers still avoided the middle of Saddle Peak's large features. Under Low danger skiers pushed deeper into terrain (Fig. 8). These results are broadly consistent with the findings from Sykes, 2018 and Sykes et al. (under review) using GPS tracking of a more limited sample in the same area. Another consideration for line choice is that of previous tracks. As more skiers track the slope, the following skiers push deeper into terrain as they seek fresh lines. The Football Field was

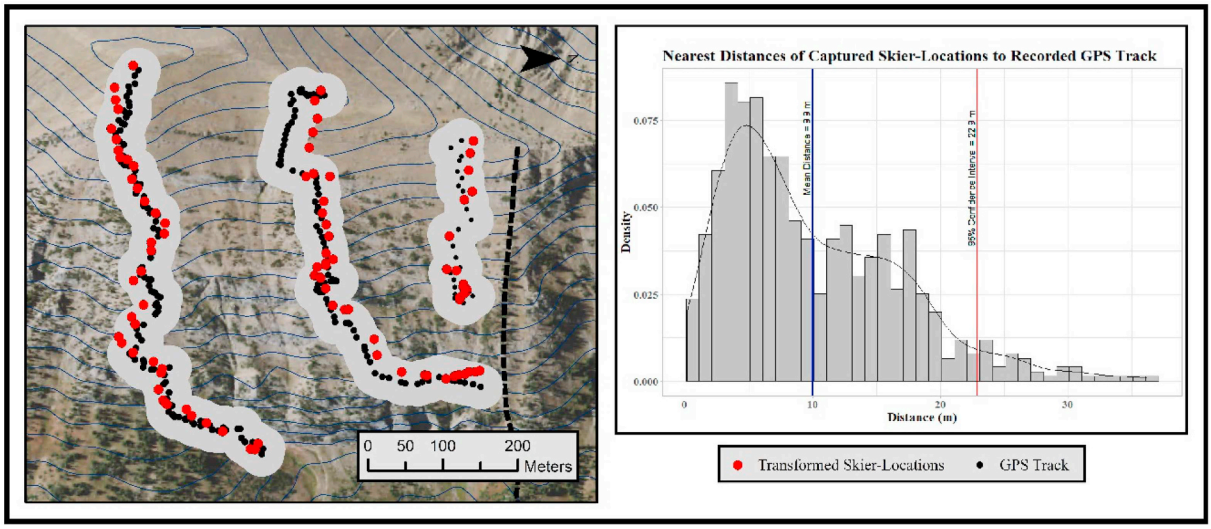


Fig. 7. Three selected lines of transformed skier-location points (red dots) and corresponding GPS tracks (black dots) on March 5, 2017. The grey 30 m buffer around the GPS tracks visually aids identifying the accuracy of transformed skier location points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Terrain parameter classes and corresponding values assessed in this research (as per Thumlert and Haegeli, 2018).

Slope (degrees)	Profile curvature	Value	Plan curvature	Value
0–15	Convex (supported)	< −0.1	Concave (gully)	< −0.1
15–25	Planar (flat)	−0.1 - 0.1	Planar (flat)	−0.1 - 0.1
25–35	Concave (unsupported)	> 0.1	Convex (ridge)	> 0.1
35–45				
> 45				

more heavily tracked on Low days, where-as on Moderate days skiers were more clustered towards the boundary line, where proximity to the boundary might provide a (false) sense of safety. A significant challenge to examining variation of terrain choices in this study area is the relatively homogeneous terrain on Saddle Peak. While the entire east ridge of Saddle Peak is avalanche terrain, some areas are more exposed and higher consequence than others. Evidence that users avoid certain areas is supported by a lack of data points in specific terrain in Fig. 8.

4.2. Statistical analysis of terrain metrics

Using the extracted terrain metrics from the time lapse camera workflow, the data indicated median slope angles skied were lowest under Considerable danger (Table 3 and Fig. 9). Under profile curvature, there were fewer extremes (very concave/convex) skied and skiers traveled over more planar areas, with less concave/convex characteristics under Considerable danger. Median values under plan curvature indicated skiers were on more ridge-like features under Considerable avalanche danger (Table 3).

We used a one-sided K−S test on the terrain metrics for different avalanche danger days, from the resampled 30 m cell size DEM. These tests found strong evidence (p-value <.001) that all tested terrain metrics (slope, profile curvature, and plan curvature) of Considerable danger days are statistically different than Moderate or Low days (Table 4).

The overall differences in median slope angle values were very small, reflecting the fairly homogenous terrain on Saddle Peak and a smoothing effect resulting from utilizing a 30-m resampled DEM (Table 3). However, the median slope angles on Considerable days were less than both Moderate and Low, with the K−S testing indicating a statistical significance (p-value <.001) between Considerable and Moderate and Considerable and Low danger days (Table 4). No statistical difference between slope angle on Moderate and Low days was identified. This statistical analysis supports the qualitative analysis and shows that skiers were on lower angled terrain with days of more challenging forecasted avalanche conditions.

Differences in profile curvature analysis were also small, but our analyses indicated a statistical significance (p-value <.001) in the profile curvature between Considerable and Moderate, Considerable and Low, and Moderate and Low (Table 4). Results suggest that skiers were on more concave (supported) terrain on days with elevated avalanche conditions. Additionally, the spread of data indicated skiers occupied less extreme convex or concave terrain overall under Considerable danger, and the terrain chosen was more planar (Fig. 9).

Table 3
Median values by avalanche danger for terrain metrics analyzed with resampled 30 m DEM.

Median values by avalanche danger	Low	Moderate	Considerable
Slope	34.82	34.95	34.14
Profile curvature	−0.10	−0.14	−0.26
Plan curvature	0.25	0.08	0.35
Number of skier location points	1995	4254	1250

Like slope angle and profile curvature, absolute plan curvature was small (Table 3) but statistical testing indicated a difference in all tests (Table 4). Between Considerable-Moderate, and Considerable-Low danger days, data indicates that skier locations were on more ridge-like features as avalanche danger increased. Additionally, a statistical significance (p-value <.001) between plan curvature on Moderate-Low days indicates skiers occupied more gully-like features under Low avalanche danger than Moderate danger.

These results are positive and informative. While using a vastly different method and workflow to obtain the skier location information, these results align with other studies of terrain metrics where backcountry skiers generally opt for more conservative terrain with increasing avalanche danger (Hendrikx and Johnson, 2016c; Thumlert and Haegeli, 2018; Sykes, 2018). These statistical results are also clearly consistent with the qualitative analysis of the images that illustrate skier terrain preferences. This methodology presents a novel passive observation technique to assess how lift assisted backcountry skiers adjust their terrain use in response to the avalanche danger rating.

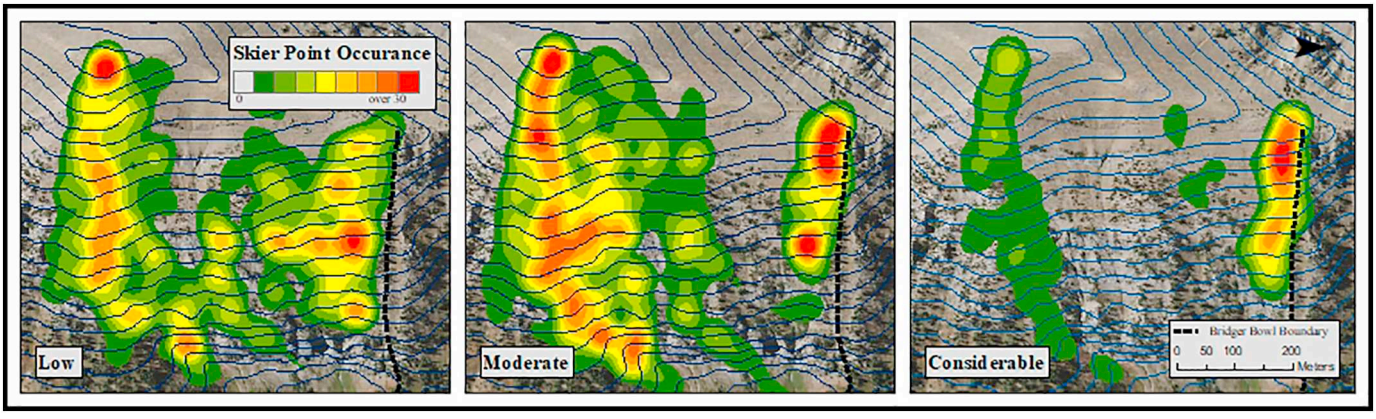


Fig. 8. Heat maps of skier-location by days of different forecasted avalanche danger. The dashed black line represents the Bridger Bowl Boundary.

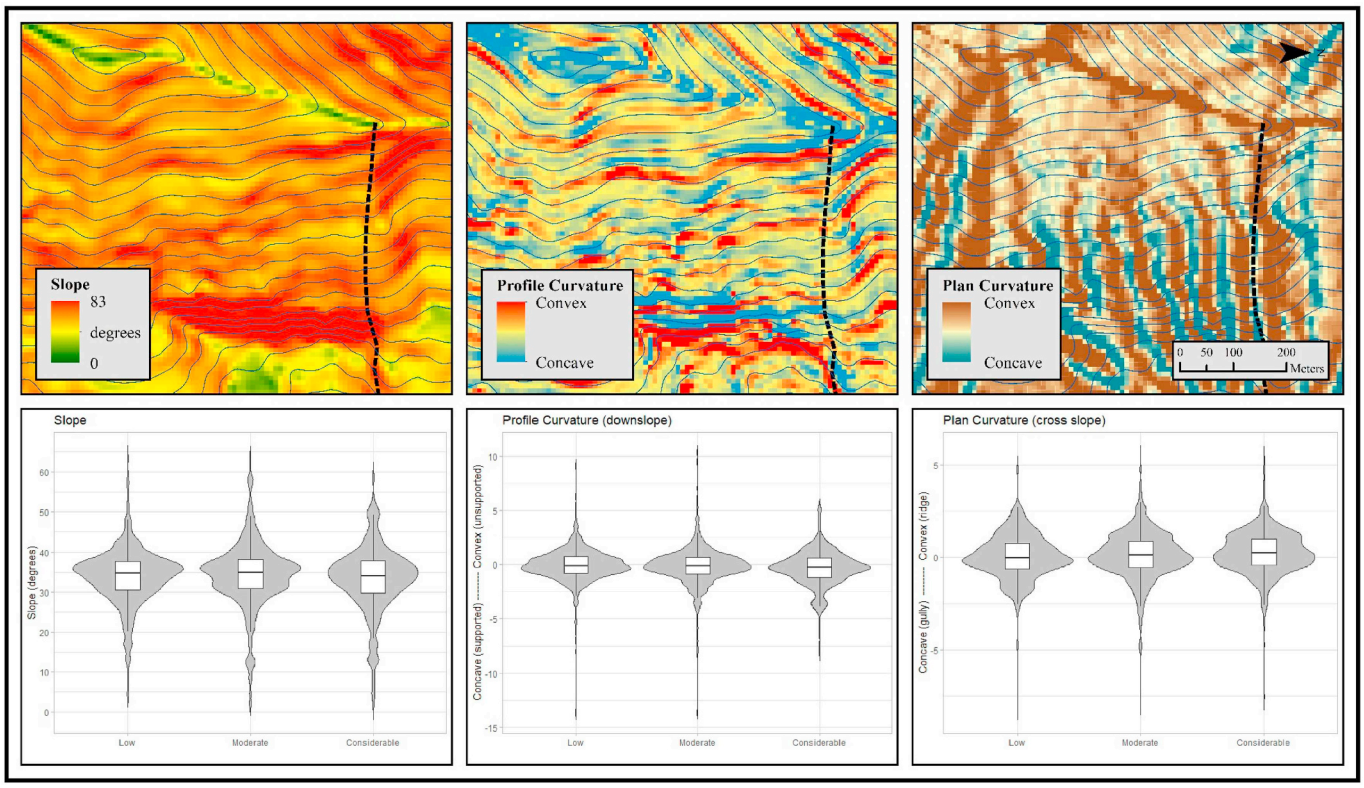


Fig. 9. Violin plots of terrain metrics (slope, profile curvature, and plan curvature) by forecasted avalanche danger.

Table 4
P-values associated with K–S tests on terrain metrics for 30 m cell sizes.

Slope		CDF of x below (less) y	CDF of x is above (greater) y
Con	Mod	0.674	***p* < .001**
Con	Low	0.031	**p < .001**
Mod	Low	0.004	0.121
Profile curvature		CDF of x below (less) y	CDF of x is above (greater) y
Con	Mod	0.635	**p < .001**
Con	Low	0.850	**p < .001**
Mod	Low	0.888	**p < .001**
Plan curvature		CDF of x below (less) y	CDF of x is above (greater) y
Con	Mod	**p < .001**	0.675
Con	Low	**p < .001**	0.421
Mod	Low	0.133	**p < .001**

A bold p-value indicates where the cumulative distributive function (CDF) produced statistically significant results.

4.3. Solo skiers

Good travel practices in backcountry avalanche terrain include having a partner. In the case of an avalanche, the best chance of survival lies within self-rescue and the members of your party (Procter et al., 2014; Haegeli et al., 2012). During visual processing of data, group size and solo skiers were identified with each day. One notable observation was the large number of solo skiers on Saddle Peak. Out of 525 skiers observed on Saddle Peak, 94 (18%) were not in a group. Additionally, on days of Considerable danger, 56 of 168 (33%) skiers on Saddle Peak were not in a group. Surprisingly, this is much higher than the overall average number of solo skiers 94 out of 525–18% (Table 1). Analysis utilizing the Wilcoxon signed-rank test revealed that solo skiers were significantly different when comparing Considerable – Moderate (p-value = .052) and Considerable – Low (p-value = .023). However, results suggested no difference in mean numbers of solo skiers between Moderate – Low (p-value = .243). These numbers of solo skiers in backcountry avalanche terrain are consistent with the intercept survey and GPS tracking results capturing backcountry skiers on Saddle Peak (Fitzgerld et al., 2016; Sykes, 2018). The number of solo skiers on Saddle Peak suggests an increased need to encourage traveling with a partner capable of companion-rescue when skiing in avalanche terrain.

4.4. Benefits and limitations

This research demonstrates how a time lapse camera can be used to collect an unbiased, non-convenience sample of backcountry travel terrain preferences. When compared directly to convenience-based, intercept studies, this method yields more data on sample days, as all backcountry users, rather than only those willing to participate in surveys are tracked. Specifically, for the case of March 5, 2017, this approach yielded more than twice as many tracks as the GPS intercept survey that was being conducted at the same time (Sykes, 2018; Sykes et al., 2019). The spatial accuracy of the time lapse camera method, while reduced in comparison to the GPS approach, still provides reliable data that clearly enables us to observe terrain preferences in response to avalanche danger at this scale and does so in a passive and efficient manner. While the time lapse camera approach and subsequent work flow yields robust results, it is dependent on good visibility, an issue that the GPS approach is not burdened by. Using this method of spatial data collection, this research expands on our understanding of skier terrain use and terrain metrics in relation to forecasted avalanche danger.

Our findings are contingent on our assumption that skiers know the avalanche danger prior to skiing Saddle Peak. However, other research and indirect evidence suggest that not all backcountry skiers are aware of the forecasted avalanche danger, particularly Saddle Peak users (Fitzgerld et al., 2016; Sykes, 2018; Sykes et al., 2019). It is possible some skiers simply follow the trail and ski tracks of others and have no specific knowledge of the area or the avalanche forecast. This fact is a limitation when assessing terrain use as a function of forecasted avalanche danger on Saddle Peak. Furthermore, since our research

observes a unique subset of backcountry skiers, specifically lift-accessed backcountry skiers, our findings may not be transferable and applicable in all other backcountry settings.

To demonstrate the time lapse methodology, a selection of study days was analyzed so that a variety of avalanche dangers (Low, Moderate, Considerable) were included in the data set, current weather, previous tracks or day of the week may also govern terrain choice and could be considered and tested for impact on terrain metrics in future research. Selected study days were more likely to have good weather as visibility was a critical factor in capturing data and may inadvertently introduce selection bias of skiers on Saddle Peak. As a result, our data sets have selection biased for days of better visibility and may miss a user group of skiers on low visibility/low popularity days.

5. Conclusion

Time lapse camera images of skier locations on a backcountry slope were digitized and referenced with a digital elevation model to study the terrain preferences of recreational backcountry skiers in backcountry avalanche terrain. The resulting error from digitization and transformation of skier points was a limitation in the extent of our study. To account for the established 49 m accuracy of skier location points, terrain metrics from a 10 m DEM resampled to 30 m, were tested against days of different forecasted avalanche danger. Our techniques using time lapse cameras to track backcountry skiers are novel and can be applied to studies in other similar locations with a fixed viewpoint and moving elements. Set up and collection costs are low and easily implemented.

Terrain choices were found to be statistically different under days of different forecasted avalanche danger, even in terrain with limited options. In general, skiers chose more conservative terrain as avalanche danger increased. This was supported by a qualitative review of terrain preferences. Surprisingly, we also noted a high percentage of solo skiers indicating a need for further research and education on backcountry group size and skiing with a partner competent in companion-rescue. Finally, our results demonstrate that a time-lapse camera can be an effective tool for determining terrain choices of backcountry skiers, or potentially other elements, moving in complex alpine terrain, and are not impacted by the inherent bias of convenience sampling.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.coldregions.2020.102994.

Declaration of Competing Interest

None.

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References

ArcMAP, 2017. About Spatial Adjustment Transformations, Transforming data… ArcMAP. http://desktop.arcgis.com/en/arcmap/10.3/manage-data/editing-existing-features/about-spatial-adjustment-transformations.htm#ESRI_SECTION1_EBB9C52B96934FE08A32CE852788EA02.

Avalanche Canada, 2018. 2017-2018 Annual Report. Avalanche Canada. October 24, 2018.

Bridger Bowl, Raw Weather Data Tables, 2018. Alpine Weather Station, Bridger Bowl. https://bridgerbowl.com/weather/history-tables.

Colorado Avalanche Information Center, 2018. Avalanche Accident Statistics. Colorado Avalanche Information Center. http://avalanche.state.co.us/accidents/statistics-and-reporting/.

Corripio, J.G., 2004. Snow surface albedo estimation using terrestrial photography. Int. J. Remote Sens. 25 (24), 5705–5729.

Federal Geographic Data Committee, 1998. Geospatial Positioning Accuracy Standards, Part 3: National Standardfor Spatial Data Accuracy. US Geolocigal Survey, Reston, Virginia.

Fitzgerld, K.R., Kay, J.M., Hendrikx, J., Johnson, J., 2016. Backcountry and sidecountry users: An intercept survey approach. In: Proceedings of the 2016 International Snow Science Workshop, Breckenridge, Colorado.

Gallatin National Forest Avalanche Center, 2018. Advisory Archive. https://www.mtavalanche.com/archive/advisory.

Geological Survey, U.S., 2017. File System Raster, grdn43w111_13, USGS NED 1/3 Ac-Second n46w111 1 x 1 Degree ArcGrid 2017. (The National Map).

Haegeli, P., Gunn, M., Haider, W., 2012. Identifying a high-risk cohort in a complex and dynamic risk enviroment: out-of-bounds skiing- an example from avalanche safety. Prev. Sci. 13 (6), 562–573 12 Dec.

Hendrikx, J., Johnson, J., 2016a. Heli-ski guide tracking for institutional memory and auditing. In: Proceedings of the 2016a International Snow Science Workshop, Breckenridge, Colorado.

Hendrikx, J., Johnson, J., 2016b. Tracking snowmobiliers to understand travel behaviour in avalanche terrain. In: Proceedings of the 2016b International Snow Science Workshop, Breckenridge, Colorado.

Hendrikx, J., Johnson, J., 2016c. Understandng global crowd sourcing data to examine travel behaviour in avalanche terrain. In: Proceedings of the 2016c International Snow Science Workshop, Breckenridge, Colorado.

Hendrikx, J., Shelly, C., Johnson, J., 2014. Tracking heli-ski guides to understand decision making in avalanche terrain. In: Proceedings of the 2014 International Snow Science Workshop, Banff, Canada.

Hendrikx, J., Johnson, J., Shelly, C., 2016. Using GPS tracking to explore terrain preferences of heli-ski guides. J. Outdoor Recreat. Tour. 13, 34–43 2016.

McCammon, I., Haegeli, P., 2007. An evaluation of rule-based decision tools for travel in avalanche terrain. Cold Reg. Sci. Technol. 47 (1–2), 193–206.

McClung, D.M., 2014. Risk analysis for dry snow slab avalanches released by skier triggering. Nat. Hazards 72, 1139–1158. https://doi.org/10.1007/s11069-014-10604.

Procter, E., Strapazzon, G., Dal Cappello, T., Castlunger, L., Staffler, H.P., Brugger, H., 2014. Adherence of backcountry winter recreationists to avalanche prevention and safety practces in northern Italy. Scand. J. Med. Sci. Sports 24 (5), 823–829.

R Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Saly, D., Hendrikx, J., Johnson, J., Richmond, D., 2016. Using time-lapse photography to monitor avalanche terrain. In: Proceedings of the 2016 International Snow Science Workshop, Breckenridge, Colorado.

Statham, G., Haegeli, P., Greene, E., Birkeland, K., Israleson, C., Tremper, B., Stethem, C., McMahon, B., White, B., Kelly, J., 2018. A conceptual model of avalanche hazard. Nat. Hazards 90 (2), 663–691.

Sykes, J., 2018. Travel Behavior and Decsion-Making Biases of Lift Access Backcountry Skiers on Saddle Peak, Bridger Mountains, Montana, USA, Master's Thesis. Department of Earth Science, Montana State University.

Sykes, J., Hendrikx, J., Johnson, J., Birkeland, K., 2019. (under review). Coupling GPS tracking and survey data to better understand travel behaviour of backcountry skiers. Appl. Geography 59–70 Submitted.

Thumlert, S., Haegeli, P., 2018. Describing the severity of avalanhe terrain numerically using the observed terrain seletion practices of professional guides. Nat. Hazards 91 (1), 89–115.

Wang, J., Tsang, W.W., Marsaglia, G., 2003. Evaluating Kolmogorov's distribution. J. Stat. Softw. 8 (18).

Weather Underground: Forecasts and Weather, 2016. Weather Underground: Forecasts, Interative Radar, and Weateather Alerts. https://www.wunderground.com/.

Weather Underground: Forecasts and Weather, 2017. Weather Underground: Forecasts, Interative Radar, and Weateather Alerts. https://www.wunderground.com/.

Wing, M., Eklund, A., Kellogg, L., 2005. Consumer-grade global posoning system (GPS) accuracy and reliaility. J. For. 103 (4), 169–173.