

USING TIME LAPSE PHOTOGRAPHY TO DOCUMENT
TERRAIN PREFERENCES OF BACKCOUNTRY SKIERS

by

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ABSTRACT

Avalanches are one of the greatest hazards for those recreating in snow covered mountainous terrain. In the past 20 years an average of 13 people in Canada and 27 people in the US are killed in avalanches each winter. Meanwhile, uncontrolled backcountry avalanche terrain use has significantly increased demonstrated by increased demand for avalanche education and increased sales in backcountry equipment. Lift-accessed backcountry (LABC), or avalanche terrain easily accessed from the ski resort, has seen increased usage since resorts opened boundaries in the mid-1990s. This has led to increased research interest in how people are using backcountry avalanche terrain.

A simple method to reduce exposure to avalanche hazard is avoidance, however total avoidance is seldom practical. Professionals and recreational skiers alike mitigate avalanche hazard by managing exposure to terrain containing the avalanche hazard. Current research studies use GPS tracking to study the terrain metrics of backcountry skiers. This GPS research is limited to studying volunteers and professionals that willingly track and submit their trips. This approach ignores many users and thus presents a biased picture of use.

This paper develops a method to capture the terrain metrics of all skiers on an avalanche-prone backcountry slope. A remote time-lapse camera focused on a high skier-use backcountry slope, (Saddle Peak, in the Bridger Mountain Range of southwest Montana, USA) captured skiers descending Saddle Peak in ten-second increments. Skier locations were digitized from the photos, then transformed onto a geo-referenced digital elevation model (DEM) such that terrain metrics could be applied to each skier location.

Analysis of terrain metrics for each skier point compared slope, profile curvature (downslope), and plan curvature (cross slope) over days with different forecasted avalanche hazard. Terrain metrics on Considerable avalanche hazard days differed significantly from Moderate or Low avalanche hazard days (p -value < 0.001). Transformed data fell within a 49-m horizontal accuracy for all skier point locations with a 95% confidence interval. By capturing all skiers on a slope without their knowledge, the data collected provides a large and diverse data set of the terrain preferences of backcountry skiers under varying conditions.

INTRODUCTION

Background

Avalanches are one of the greatest hazards for those recreating in snow covered mountainous terrain. Between 1996-2016, an average of 13 people in Canada and 27 people in the US died in avalanches every winter season (Avalanche Canada, 2016; Colorado Avalanche Information Center, 2016). In 90% of avalanche accidents the avalanche is triggered by the party involved (McClung, 2014; McCammon and Haegeli, 2007). Over the same period, the rate of usage of backcountry avalanche terrain has drastically increased due to improved equipment, increased popularity and media attention, and many ski areas opening their boundaries (Birkeland et al., 2017; SIA, 2017). Notably, avalanche fatalities have remained relatively stable at 25-30 per year (in the US) since 1996. European data shows similar trends of stable avalanche fatalities in recent years (Birkeland et al., 2017). It is the hope that as more users enter avalanche terrain, they do so with a better knowledge base through avalanche education and forecasting.

This research captures how lift accessed backcountry skiers negotiate uncontrolled avalanche terrain under different avalanche hazards. Lift-access backcountry terrain is uncontrolled avalanche terrain accessed from a ski area. If we can understand why people choose to ski the terrain they do, we may be able to influence them to make safer decisions. Increased understanding about how backcountry skiers perceive the avalanche

problem may allow for improved education or increased awareness for this user group, which will hopefully save lives.

A time lapse camera focused on an avalanche prone slope (Saddle Peak, in the Bridger Mountain Range of southwest Montana, USA) captured skier locations every ten seconds as they descended. The skier locations were transformed from the photos onto a digital elevation model (DEM). From the DEM, terrain metrics (slope, down slope curvature, and cross slope curvature) were gathered and compared against days of different avalanche hazard (Low, Moderate, Considerable). By capturing all skiers on a slope without their knowledge, the data collected provides a large and diverse data set of recreational skiers in backcountry avalanche terrain.

Avalanche Terrain Management

There are two kinds of avalanche: loose-snow and slab. A loose-snow avalanche, or slough, is when loose, uncohesive snow originates from a single point, and falls down a slope. A slab avalanche occurs when a cohesive layer of snow (or slab) slides downslope over a bed surface. Slab avalanches are generally more hazardous than loose-snow avalanches and cause the most fatalities and property damage. Avalanche risk is forecasted on the Avalanche Danger Scale, a 5-level scale which rates public avalanche risk (1-Low, 2-Moderate, 3-Considerable, 4-High, 5-Extreme) (Statham et al., 2010). When rating avalanche hazard, forecasters consider the type of avalanche problem that exists, where it is located, how likely it is to trigger, and how big will it be if triggered (Statham et al., 2018). This places the avalanche problem within a spatial location on the slope (e.g. wind loaded features in the alpine or solar aspects during spring warming)

allowing for a backcountry traveler to avoid such terrain and reduce exposure to the forecasted hazard.

Careful selection of exposure to avalanche terrain is an essential risk management process which reduces avalanche risk. The overall aim of an avalanche forecast is that users adjust their terrain choices in response to the avalanche problem, thereby reducing their risk of avalanche involvement. If we assume that recreational backcountry skiers have read and understand the regional avalanche forecast, then by collecting data on the terrain choices skiers under different avalanche hazard may provide insight on how skiers adjust terrain according to the avalanche forecast.

In avalanche forecasting, slope is an important parameter in determining terrain conducive to avalanching. In avalanche terrain, slopes between 30-45 degrees are common angles of avalanche start zones. Downslope curvature indicates if the slope is concave or convex (supported vs. unsupported) and cross slope curvature indicates if the slope is a ridge or gully feature. When selecting avalanche terrain, less steep slopes and supported terrain is less conducive terrain to producing avalanches. As well, should an avalanche occur, ridgetops are generally safer places to be than gully features or other terrain traps that increase the destructive potential of the avalanche.

Lift – Access Backcountry Terrain

It is difficult to document how many people are in backcountry avalanche terrain, yet indirect indicators suggest a rapid increase in backcountry use in recent years. More avalanche skills courses are being offered and filled, more users are accessing avalanche bulletins and participating in observation networks, and retailers are reporting increased

sales in backcountry equipment (Birkeland et al., 2017; SIA, 2017; Avalanche Canada, 2016). As well, most North American ski resorts have changed area boundary policies to allow skiers (and snowboarders) to access uncontrolled avalanche terrain beyond the ski area boundary. Such backcountry avalanche terrain that is “lift-accessed” via the ski area can see higher use relative to other areas in a backcountry forecast region.

Between 1996 – 2016, the Colorado Avalanche Information Center reported 56 “Side-country rider” fatalities in a total of 556 recreational avalanche fatalities (Colorado Avalanche Information Center, 2016). This lift-accessed backcountry (LABC) avalanche terrain is not controlled for avalanche hazard, whereas the inbounds avalanche risk is mitigated by the area ski patrol. The ease of access in lift-access terrain allows for backcountry use by a user group with varying avalanche education including those who may not understand they have even left the resort boundary. In many cases, LABC terrain can be exclusively accessed by ski lifts; skins or other traditional modes of ascent are not needed. Intercept surveys suggest that lift-accessed backcountry users are less informed and less prepared than self-powered backcountry avalanche terrain users. Additionally, surveys of skiers on Saddle Peak reported 33% of skiers on Saddle Peak either did know or did not check the current avalanche forecast (Fitzgerald et al., 2016; Sykes, 2018). Due to the popularity of use and diverse user group, LABC can provide a novel data set to study the terrain metrics of recreational skiers in backcountry avalanche terrain.

Current Terrain Use Research

Current research on terrain metrics of backcountry skiers in avalanche terrain studies the GPS tracks of professional ski guides and recreational skier volunteers. GPS data is

used to study terrain choices based on avalanche hazard and other criteria. Recent results suggest professional ski guides opt for less hazardous avalanche terrain as avalanche hazard increases (e.g. Hendrikx and Johnson, 2016a; Thumlert and Haegeli, 2017;). These studies use who volunteers tend to be somewhat avalanche savvy (Hendrikx et al., 2014; Hendrikx et al., 2016; Hendrikx and Johnson, 2016c). Another method to capture avalanche terrain use information is by counting all skiers departing the ski area boundary through a gate. Such methods are partnered with subject surveys about their experience and acceptable levels of risk (Rubin and Camp, 2011; Sykes, 2018). The counters capture all users and the surveys provide insight on how those individuals utilize avalanche terrain.

Consistent and unbiased methods of observation are lacking in research about avalanche terrain choices of backcountry skiers. Time-lapse photography, taking a series of photos of skiers descending an avalanche prone slope, provides an opportunity to consider how all skiers move on a single slope, and allows us to compare the specific terrain metrics of recreational skiers under different avalanche conditions. Because the users are unaware of the camera and all skiers on a slope are captured, the data collected provides a larger and more diverse data set of skiers recreating in backcountry avalanche terrain.

Remote Sensing in Snow Science

Remote sensing is the acquisition of information about a natural object or phenomenon on the earth surface without direct physical contact with the object. Remote sensing can use space-born, airborne and ground-based sensors (Campbell and Wynne,

2011; Eckerstofer et al., 2016; Deems et al., 2013). In space-borne remote sensing, sensors mounted on space craft capture data on the earth's surface. Space-borne sensors have been used in snow research to study snow cover, depth and volume, snow water equivalent (SWE), and forecasting water resources in mountainous areas. However, the resolution scale at which data is acquired lacks the required precision to capture data at the mountain slope or snow crystal size processes. Airborne and ground-based remote sensing can provide high spatial resolution where space-borne platforms cannot, such as in capturing skiers descending a mountain slope (Hall et al., 2002; Koetz et al., 2008).

Airborne and ground based remote sensing generally occurs near the earth's surface. Airborne sensors are attached to aircraft or other aerial platforms. The major advantage of airborne sensors compared to satellites is the ability to acquire much higher resolution spatial data. Current methods of airborne and ground-based remote sensing in snow and avalanche research utilize laser scanners, synthetic aperture radar, and cameras (Luzi et al., 2009; Prokop et al., 2016; Eckerstofer et al., 2014, Buhler et al., 2016).

Photogrammetry is a science which utilizes photographs to make measurements, especially for determining the exact position of surface points relative to a coordinate system. Ground-based remote sensing utilizing photography and photogrammetry has been successfully used to map snow depth in high-alpine catchments, snow surface characteristics, avalanche start zones, and avalanche debris (Buhler et al., 2015; Buhler et al., 2009; Corripio, 2004; de Michele et al. 2016). In avalanche public safety, photography is used to document natural avalanches and avalanche control work, and in some cases to locate and track individuals. Successful thermal photography applications

utilized by avalanche control teams assess for skier-heat signatures prior to avalanche control work and monitor explosives avalanche control results (Saurer et al., 2016).

Photogrammetry research has developed accurate models of snow depth, mapped avalanche debris, and measured avalanche crowns, slab fracture lines, and created avalanche surface models (Buhler et al., 2016; Harder et al., 2016; Peitzsch et al., 2016, Eckerstofer et al., 2014; Eckerstofer et al., 2016).

Temporal studies using optical ground-based remote sensing (time-lapse photography.) are also common in snow and avalanche research. In remote sensing and snow mapping studies, time-lapse photography has been used to estimate snow depth, extent, and snow water equivalence, and to monitor snow dynamics and create temporal maps of snow cover (e.g. Kerr et al., 2013; Nolan et.al, 2015; Christiansen, 2001). Time-lapse photography has been used to monitor cornices and glide crack dynamics and aided efforts to link meteorological data and better understand wet snow avalanche characteristics (Vogel et al., 2010; van Herwinjnen et al., 2012; Peitzsch et al., 2012).

In other research, photographs acquired by the Extreme Ice Survey provided high enough spatial and temporal resolution samples to observe ice velocity and tidal effects on glaciers around the world (Ahn and Box, 2010). Time lapse photography has also successfully tracked the movements of animals in remote terrain, including Emperor penguins, and other birds and vertebrates in field studies (Richter et al., 2018; Cutler and Swann, 1999). Such research suggests time lapse photography may be a successful method in tracking skiers in backcountry avalanche terrain.

Especially in isolated and harsh environments, remote sensing techniques can provide data that cannot be acquired from field-based work. Where field-based research requires more exposure for personnel and introduces observational biases, remote sensing can safely eliminate data gaps that would otherwise occur (such as from weather events or inability to access research site). Remote sensing can also reduce researcher exposure to harsh or dangerous conditions.

Challenges in Remote Sensing

Remote sensing studies present common challenges due to power requirements, weather, isolation, and animals (including curious humans). When using cameras, any moisture is a concern. Precipitation during maintenance and installation can introduce humidity to the system. Snow cover can affect visibility either through icing of equipment or being buried in snow (solar power problems). Additionally, cold temperatures can quickly drain battery power. Clouds can obscure the view to the target and winds can cause excessive vibration of the camera. As well, snow is a difficult medium to photography and using automatic exposure may not completely compensate for the brightness of snow. Over time a fixed (non-snow covered or ground control point) feature may change which can be problematic in the feature identification process (Ahn and Box, 2010). However, despite these challenges, successful remote sensing studies are common. The projects above and many others have collected unique and impressive data sets utilizing remote sensing photographic equipment.

Study Area

To collect data about the terrain metrics of recreational backcountry skiers, a time-lapse camera photographed a popular backcountry avalanche-prone slope over two winter seasons. The camera was positioned to capture skiers on Saddle Peak, a popular backcountry slope adjacent to the Bridger Bowl Ski Area. The camera was programmed to capture one photo every ten seconds between 10:00 am and 4:00 pm.

Saddle Peak is in the Bridger Mountains in the Gallatin National Forest of southwest Montana, USA (Figure 1). This is a popular destination for backcountry skiers and 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. Due to these characteristics, and that access to Saddle Peak is almost exclusively obtained from the Bridger Bowl Ski Area (via riding the Schlasman's Lift, hiking along the ridge, and returning to the ski area), Saddle Peak is considered lift-accessed backcountry avalanche terrain. Saddle Peak is uncontrolled, backcountry avalanche terrain within a public avalanche forecast region (Gallatin National Forest Avalanche Center) with a consistent skier user group. Saddle Peak is skied often and under a variety of avalanche conditions and the slope has history of avalanche activity throughout the winter.

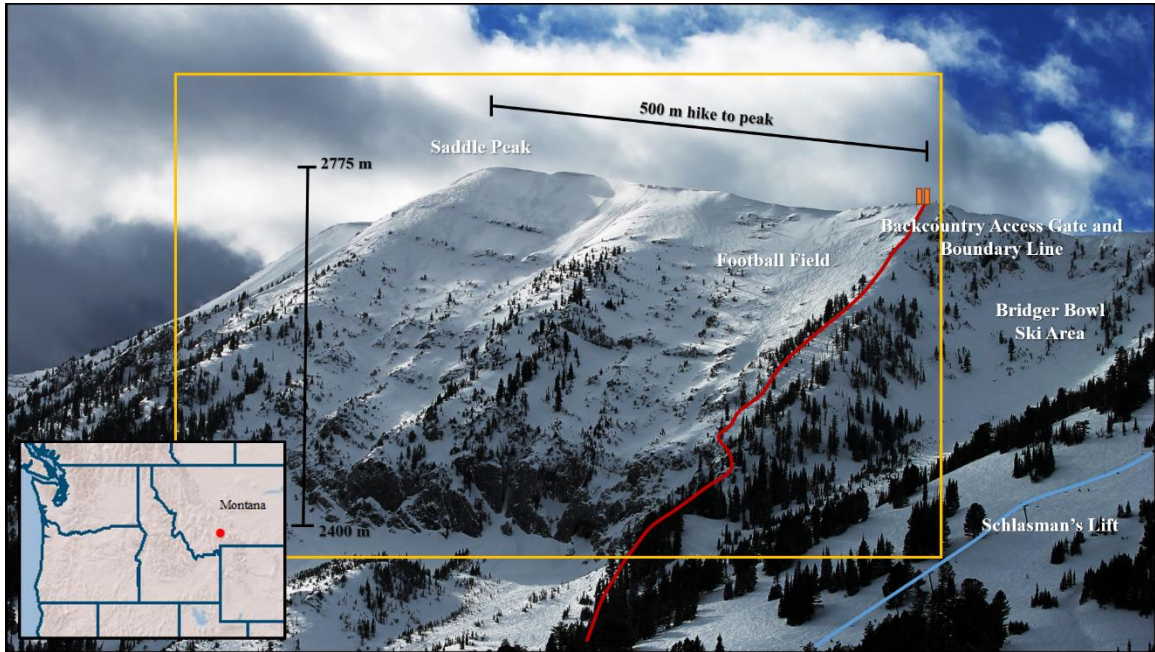


Figure 1. The east face of Saddle Peak located adjacent to the Bridger Bowl Ski Area as photographed from the time lapse camera, looking west. Saddle Peak is in the Bridger Mountains of southwest Montana. The slope is accessed by riding the Schlasman's Lift (blue line), exiting the boundary at the backcountry 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 gold box. Skiers are captured descending the east slopes of Saddle Peak. A trail back to the ski area is below the extent of the photo and leads back to the bottom of the Schlasman's Lift.

Research Questions

The aim of this work is to develop a method to capture skiers recreating in backcountry avalanche terrain. This data is used to investigate the relationship between avalanche conditions and terrain metrics of backcountry skiers. Overall, this work considers if whether backcountry skier terrain choices change with forecasted avalanche hazard.

The following specific research questions are addressed:

- 1) Do backcountry skiers have statistically different terrain metrics (slope, downslope curvature, and perpendicular curvature) when skiing days with different avalanche hazard (Low, Moderate, Considerable)?
- 2) Can a time lapse camera accurately record terrain use of backcountry skiers?

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USING TIME LAPSE PHOTOGRAPY TO DOCUMENT TERRAIN PREFERENCES
OF BACKCOUNTRY SKIERS

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Manuscript in Chapter 2

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Abstract

Careful selection of exposure to avalanche terrain is an essential risk management process which reduces avalanche risk. The overall aim of an avalanche forecast is that users adjust their terrain choices in response to the avalanche problem, thereby reducing their risk of avalanche involvement, little evidences exists if this occurs.

This paper develops a method to capture the terrain metrics of all skiers on an avalanche-prone backcountry slope. A remote time-lapse camera focused on a high skier-use backcountry slope, (Saddle Peak, in the Bridger Mountain Range of southwest Montana, USA) captured skiers descending Saddle Peak in ten-second increments. Skier locations were digitized from the photos, then transformed onto a geo-referenced digital elevation model (DEM) such that terrain metrics could be applied to each skier location.

Transformed data fell within a 49-m horizontal accuracy for all skier point locations with a 95% confidence interval. Analysis of terrain metrics for each skier point compared slope, profile curvature (downslope), and plan curvature (cross slope) over days with different forecasted avalanche hazard. Terrain metrics on Considerable avalanche hazard days differed significantly from Moderate or Low avalanche hazard days (p -value < 0.001). By capturing all skiers on a slope without their knowledge, the data collected provides a large and diverse data set of the terrain preferences of backcountry skiers under varying conditions.

Introduction

Avalanches are one of the greatest hazards for those recreating in snow covered mountainous terrain (McClung, 2014; McCammon and Haegeli, 2007). Every winter season over the past 20 years, an average of 13 people in Canada and 27 people in the US perished in avalanches (Avalanche Canada, 2016; Colorado Avalanche Information Center, 2016). In most cases, the avalanche was triggered by the party involved. Over the same time, rapid growth in backcountry skiing is evident in increased attendance in avalanche education courses, expanded media coverage, and significant growth in backcountry equipment sales (Birkeland et al., 2017; SIA, 2017). As well, many ski areas across North America have adjusted boundary policies that allow for skiers to utilize the ski area to access backcountry avalanche terrain in this period.

Between 1996 – 2016, the Colorado Avalanche Information Center (CAIC) reports 56 “Side-country rider” fatalities in a total of 556 U.S recreational avalanche fatalities (Colorado Avalanche Information Center, 2016). Additionally, 23% of recreational avalanche fatalities in Europe and North America between 2003/04 -2008/09 were reported in out-of-bounds terrain (Gunn, 2010). At most North American ski resorts adjacent to significant and hazardous avalanche terrain, the ski area will identify their operational boundary and allow access beyond that defined boundary area. Inbounds terrain within the ski area is mitigated for avalanche hazard, but the terrain beyond the boundary line is not.

Such backcountry avalanche terrain that is “lift-accessed” via the ski area often sees high use relative to other areas in a backcountry forecast region. This type of terrain has

also been termed “slack-” or “side-country;” we elect to call this lift-accessed backcountry terrain as to cause no confusion about the lack of avalanche control measures on the terrain. The ease of access in lift-access terrain allows for a user group with varying avalanche education including those who may not understand they have even left the resort boundary. Additionally, research on travel practices of lift-access backcountry skiers suggest a greater occurrence of solo skiers compared to self-powered backcountry terrain (Fitzgerald et al., 2016). 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 with the people one travels (Procter et al., 2014; Haegeli et al, 2012).

Avalanche terrain is managed by choosing terrain which limits exposure to the avalanche hazard. Thus, the avalanche forecast is a critical component to understanding how to mitigate the avalanche hazard. By collecting data on the terrain choices of recreational backcountry skiers on days of different avalanche hazard we can gain insight on how skiers adjust terrain choice according to the forecast. Current research on terrain metrics of backcountry skiers studies the GPS tracks of professional ski guides and recreational skier volunteers. Hand-held GPS units are used to record the tracks of ski guides in different avalanche conditions to study terrain metrics as a proxy to assess risk management. The GPS tracks capture real-time, terrain focused decision-making outcomes of the guide. Findings report that steeper, more open, and more convoluted slopes were skied in lower avalanche hazard conditions (Hendrikx and Johnson, 2016a; Hendrikx and Johnson, 2016b; Thumlert and Haegeli, 2017).

Along with GPS tracking, terrain choices of skiers are discussed using post-accident reviews or in developing decision making tools (Hendrikx et al., 2014; Hendrikx et al., 2016; Thumlert and Haegeli, 2017; Hendrikx and Johnson, 2016c). Studies of recreational skier terrain choices currently requires willing volunteers submitting GPS tracks and survey responses. These volunteers are typically knowledgeable about avalanche hazards and are aware they are being tracked (Hendrikx and Johnson, 2016; Fitzgerald et al., 2016; Sykes, 2018). GPS tracking is beneficial in capturing terrain metrics and other information such as experience levels from the skier. However, it presents a limitation to capture user groups who are not inclined to participate. Thus, the data collected may be biased towards users who are more avalanche savvy or experienced than the average backcountry skier.

This research uses a time lapse camera to capture skier locations every ten seconds on an avalanche prone slope. The skier locations are geo-referenced and transformed onto a digital elevation model. Terrain metrics (slope, downslope curvature, and cross slope curvature) from the DEM are attached to skier locations and compared against days of different forecasted avalanche hazard.

The time lapse photographs on Saddle Peak capture the terrain choices of all skiers on a slope over a day. By capturing all skiers on a slope, the data collected provides a snapshot of the terrain preferences of backcountry skiers under varying conditions as defined by the terrain metric of slope, downslope curvature, and cross slope curvature.

Study Area

Physical Setting

Saddle Peak (Figure 2) is in the Bridger Mountains in the Gallatin National Forest of southwest Montana, USA. The study area is the east face and heavily-skied slope of Saddle Peak, focusing on the steep slopes between the ridge and cliffs above the run out. Saddle Peak is 2792 m above sea level (asl). The peak is 500 m south from the backcountry access gate on Bridger Bowl's south boundary line at 2660 m asl. The slope is adjacent to the south boundary of the Bridger Bowl Ski Area and is highly visible from the Schlasman's lift within the ski area. The east face is divided in the middle by a sparsely treed ridge feature. The large complex start zones are frequently wind-loaded. The entire feature is broken mid-track by large cliffs up to of 60 m tall. Below the cliffs around 2400m asl, the avalanche run-out zone of Saddle Peak is low angle terrain that runs adjacent to the ski area. This is where debris collects from avalanches on Saddle Peak. A trail out 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 and 375 m vertical.

Saddle Peak is a popular destination for backcountry skiers and almost exclusively accessed through the ski area. 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. Due to these characteristics, and that access to Saddle Peak is almost exclusively obtained from the Bridger Bowl Ski Area (via riding the Schlasman's Lift, hiking along the ridge, and returning to the ski area), Saddle Peak is considered "lift-

accessed” backcountry avalanche (LABC) terrain. Saddle Peak is uncontrolled, backcountry avalanche terrain within a public avalanche forecast region (Gallatin National Forest Avalanche Center) with high-skier usage due to its proximity to Bridger Bowl Ski Area.

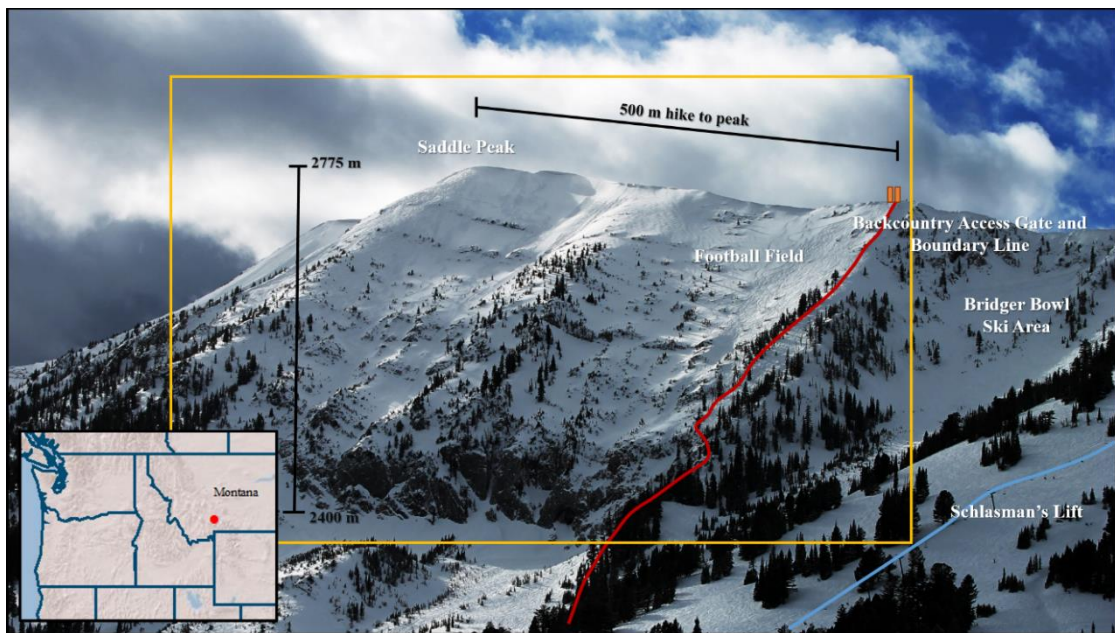


Figure 2. The east face of Saddle Peak located adjacent to the Bridger Bowl Ski Area as photographed from the time lapse camera, looking west. Saddle Peak is in the Bridger Mountains of southwest Montana. The slope is accessed by riding the Schlasman's Lift (blue line), exiting the boundary at the backcountry 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 gold box. Skiers are captured descending the east slopes of Saddle Peak. A trail back to the ski area is below the extent of the photo and leads back to the bottom of the Schlasman's Lift.

Avalanche History

Saddle Peak and the Bridger Range display an intermountain avalanche climate found in the Rocky Mountains in Montana. A typical winter snowpack in the Bridger

Range consists of basal facets and dense wind slab. It is common for a weak basal layer to plague the seasonal snowpack (Figure 3) (Mock and Birkeland, 2000).

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. Between 2010-2017, 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. Saddle's south bowl consistently produces natural avalanches every season (GNFAC, 2018).

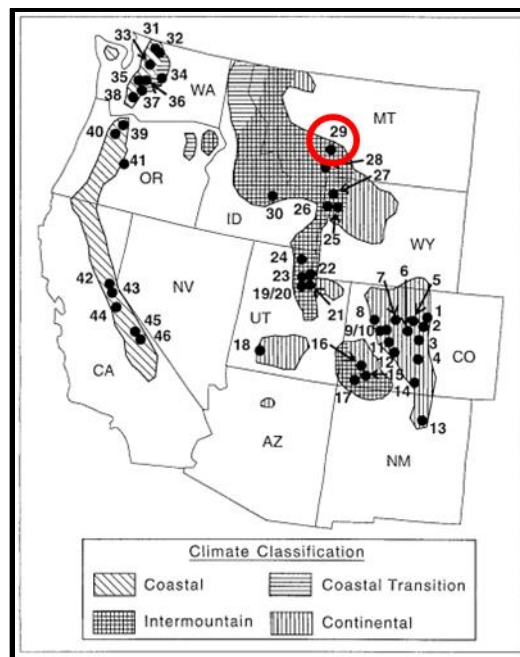


Figure 3. Classification of the avalanche climates of the western US from Mock and Birkeland (2000). Bridger Bowl and Saddle Peak are located at study site 29, circled in red.

A significant event occurred February 16, 2010 when a snowboarder on the ridge triggered a massive avalanche on Saddle Peak (HS-ACu-R4-D3.5). A storm the weekend prior to the avalanche deposited 75 cm of snow with strong westerly winds to the Bridger Range (Chabot et al., 2010). The avalanche hazard was rated Considerable by the GNFAC. The Schlasman's Lift had been closed for the storm and reopened Monday morning, February 16, 2010. Around 11:00 am a large section of cornice was accidentally triggered from the ridge of Saddle Peak. It rolled downslope approximately 30 m, where it initiated an avalanche approximately 300 m wide and 600 m long (Figure 4) (GNFAC, 2010). Reports estimated that 20-30 people were hiking the ridge at the time and several people had already skied the slope (Chabot et al., 2010). Many personal cameras captured the avalanche and immediately afterwards several skiers were on slope performing transceiver searches. Bridger Bowl Ski Patrol and Gallatin Country Search and Rescue responded with personnel and avalanche dog teams. No one was reported missing by 3:00 pm. Half of the face did not run, putting the runout zone at risk and new snow was rapidly re-loading the slope throughout the day. The search was called off; no one was involved or injured. The response utilized many responders in a high-risk environment (Chabot, et al., 2010).



Figure 4. Saddle Peak Avalanche February 16, 2010. A piece of cornice rolled down slope 30 meters (red circle) and initiated the large avalanche shown in the image. Several people were on slope or had just recently skied it at the time.

Following the 2010 incident, eleven other avalanche events around Saddle Peak had photographic records, including six events involving people (GNFAC, 2017). In February 2012, a skier triggered an avalanche in Saddle Peak south bowl (D3, R3). The skier was carried 600 m downslope and partially buried and injured. Two days later the north bowl of Saddle Peak avalanched naturally (D3, R3). The avalanche crown was 1 – 1.5 m deep and propagated 100 m across the slope. In December 2013 the Football Field was triggered by a skier on the ridge, failing deep in the snowpack (D2, R3). Then, in January 2014, the Football Field ran again; this time failing sympathetically with inbounds avalanche control operations (D2, R2). In December 2015 the Football Field was triggered by a skier (controlled, skier deliberately cutting cornice), running 30 m wide, 1.2 m deep, and failing on basal facets (D2, R2). Then, a month later in January 2016, the Football Field was remotely triggered by two skiers. The avalanche was 60 m

wide with a 60 cm crown and ran 500 m (D2, R3). It was a close call, but luckily there were no skiers directly involved. The event was captured by the time-lapse camera which was installed late December 2015 (Saly et al., 2016). These recorded events highlight both the use and complexity of this terrain and an opportunity to record terrain preferences by LABC skiers.

Methods

Field Data Collection

The time lapse camera was mounted to an abandoned concrete 75 mm recoilless rifle bunker platform within the Bridger Bowl Ski Area. The bunker is located at the top of a lower elevation hill at 2000 m above sea level (asl). From the camera location, the peak of Saddle Peak is about 2.5 km to the west and slightly south (110-120 degrees). The bunker was once used to fire explosives for avalanche control operations along Bridger Bowl's inbounds ridge terrain. It now serves as a storage area and vantage point for incidents around Saddle Peak. The camera captures an oblique view of the east face of Saddle Peak, both shooting from below and at an angle facing south-east to capture Saddle Peak (Figure 5).

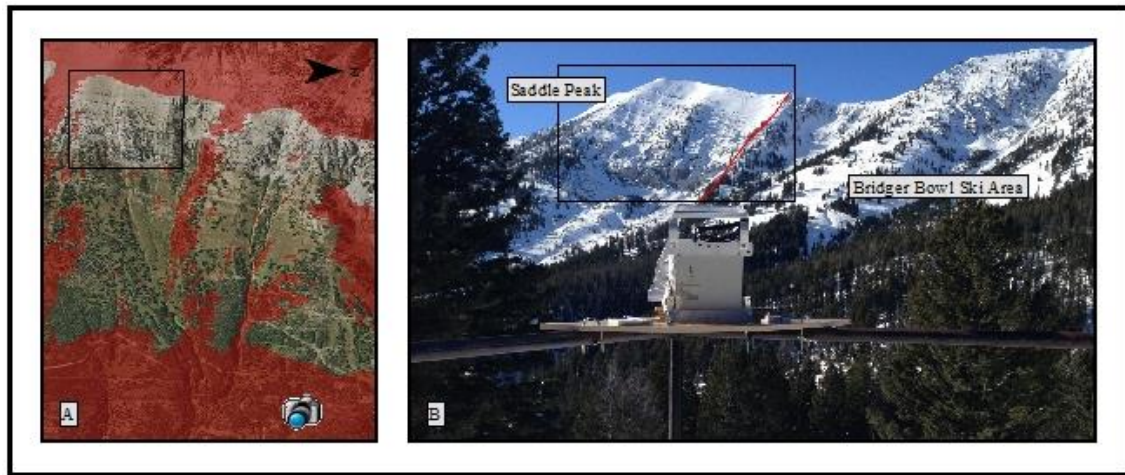


Figure 5. (A) The study area (in black box) as seen from the camera location (camera icon) and resulting viewshed (visible objects the camera location) calculated in ArcGIS using a 10 m DEM. The area covered in red is not seen by the camera due to the altitude and orientation of the slope relative to 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.

An off-the-shelf time-lapse product made by Harbortronics was used (<https://www.harbortronics.com/Products/TimeLapsePackage/>). The Harbortronics Time-Lapse Camera Package included a Canon Rebel T5 EOS Digital SLR camera in fiberglass housing with a glass window. The housing was attached to a plywood platform fastened to the railing on the top of the platform. A five-Watt Solar Panel on the top of the housing provided power to the camera and the Harbortronics DigiSnap time-lapse switch. The Harbortronics DigiSnap 2000 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 second interval between images was constant throughout the study. The camera captured

the east side of Saddle Peak from the ridgetop to the low angle slopes below the large cliffs. The resolution of the images made tracking and identifying individual skiers possible, but was not detailed enough to identify any distinguishing characteristics of skiers.

Infrequently, power and other technical issues resulted in inconsistent intervals between images or uncaptured skier-days. The main reasons for poor data collected were visibility of study area (snow and clouds), visibility of camera (platform and camera housing covered by snow), power (solar panel covered by snow), data processing (wind shake, contrast and brightness issues). As the gun platform was no longer used for avalanche control, wind was the primary cause for camera movement and image shifts during the study. The solar panel on the top of the camera housing acted like a sail and on wind days consecutive images capture by the camera did not align. This resulted in incorrect detection of pixel changes later in analysis.

The major issues following a properly installed, focused, programmed camera were power and data storage space. A 64 GB SD card could capture approximately five consecutive days of data, with 2880 images per day (8 hours at 10-second intervals). In the second field season, the card was upgraded to 128 GB. The 128 GB SD card extended data collection to ten consecutive days providing adequate power.

Data Preparation and Workflow

ESRI ArcGIS 10.3 was used to process the captured photographs and convert skier-locations in the photographs to digital points on a georeferenced digital model of Saddle Peak. A workflow utilizing ESRI ArcGIS was developed to digitize skier locations from

the oblique photos and project skier locations onto a digital elevation model (DEM) of Saddle Peak for analysis (Figures 6 and 7).

In the initial stages of the workflow, captured photos are visually assessed for quality and complete days of data. As well, the daily forecasted avalanche hazard was attached to each data set. Daily avalanche forecasts for Saddle Peak and the Bridger Range are published by the GNFAC which forecasts avalanche hazard on the five-point North American Public Avalanche Danger Scale. Data was collected on three different forecasted avalanche danger ratings (Low, Moderate, and Considerable), and no days High or Extreme avalanche danger were captured (Table 1) (Statham et al., 2018).

Table 1. North American Public Avalanche Danger Scale. This research compares days of Low, Moderate, and Considerable Hazard. High and Extreme forecasted avalanche days were not captured.

North American Public Avalanche Danger Scale				
Avalanche danger is determined by the likelihood, size and distribution of avalanches.				
Danger Level		Travel Advice	Likelihood of Avalanches	Avalanche Size and Distribution
5 Extreme		Avoid all avalanche terrain.	Natural and human-triggered avalanches certain.	Large to very large avalanches in many areas.
4 High		Very dangerous avalanche conditions. Travel in avalanche terrain not recommended.	Natural avalanches likely; human-triggered avalanches very likely.	Large avalanches in many areas; or very large avalanches in specific areas.
3 Considerable		Dangerous avalanche conditions. Careful snowpack evaluation, cautious route-finding and conservative decision-making essential.	Natural avalanches possible; human-triggered avalanches likely.	Small avalanches in many areas; or large avalanches in specific areas; or very large avalanches in isolated areas.
2 Moderate		Heightened avalanche conditions on specific terrain features. Evaluate snow and terrain carefully; identify features of concern.	Natural avalanches unlikely; human-triggered avalanches possible.	Small avalanches in specific areas; or large avalanches in isolated areas.
1 Low		Generally safe avalanche conditions. Watch for unstable snow on isolated terrain features.	Natural and human-triggered avalanches unlikely.	Small avalanches in isolated areas or extreme terrain.
Safe backcountry travel requires training and experience. You control your own risk by choosing where, when and how you travel.				

From the captured photography, skier locations were identified in each photo and digitized into a point-file. A script was developed within the ArcPy model to automate the process. The script analyzed each photograph by comparing an image against the previous image 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-files was performed manually. For every skier-location identified, a point-file was created. All skier-locations were merged into a single data file containing all skier points for a single day of study.

Next, skier-locations 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 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 (CP). The CPs are identified on both the DEM and the two-dimensional image of Saddle Peak for all thirteen days in this analysis.

The CPs 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. The smaller number of

CPs was a result 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.

The digitized skier-location points in the oblique photos were then projected and geo-referenced into a known coordinate system 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). Transformed skier locations were then analyzed with a terrain metrics acquired from a digital elevation model (DEM) of Saddle Peak.

From the DEM, terrain metrics of individual cells on the raster can be calculated. These values can be attached to a skier-location which occupies that cell. Terrain metrics assessed in this study are slope, profile curvature (downslope) and plan curvature (cross slope). Slope identifies the gradient of the raster surface value from each cell and is calculated for each cell (i.e. 10 m x 10 m). Curvature is calculated by the second derivative of the raster surface value, or the derivative of the slope. The downslope curvature and cross slope curvature of each cell is calculated in 3 x 3 cell neighborhood (i.e. 30 m x 30 m).

The DEM used in this study reported 10 m accuracy (U.S. Geological Survey, 2017). As this DEM is a representation of bare ground, the snow surface may be significantly different (smoothed) due to wind drift and loading. As well, in this study we establish a 49 m spatial accuracy resulting from the digitization and transformation of skier-location points. To account for less precision in the skier-location dataset, the 10 m DEM was

resampled to 30 m and terrain metrics were recalculated to skier points. This was done to better understand the accuracy of our data and to account for known precision error. A 30 m slope raster was recalculated and a 90 m downslope and cross slope curvature raster were extrapolated from the 30 m resampled DEM.

Terrain metrics are categorized according to groups as per Thumlert and Haegeli (2017). The profile curvature (down slope) 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).

Following the transformation of skier locations onto the DEM, terrain metrics were attached to each skier location. To determine the statistical significance of skier terrain metrics on days of different avalanche hazard, the Kolmogorov-Smirnov (K-S) test was used. Analysis of terrain metrics and forecasted hazard was performed in R (Figures 6 and 7). (R Core Team, 2015)

Table 2. Terrain parameter classes and corresponding values assessed in this research (as per Thumlert and Haegeli, 2017).

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				

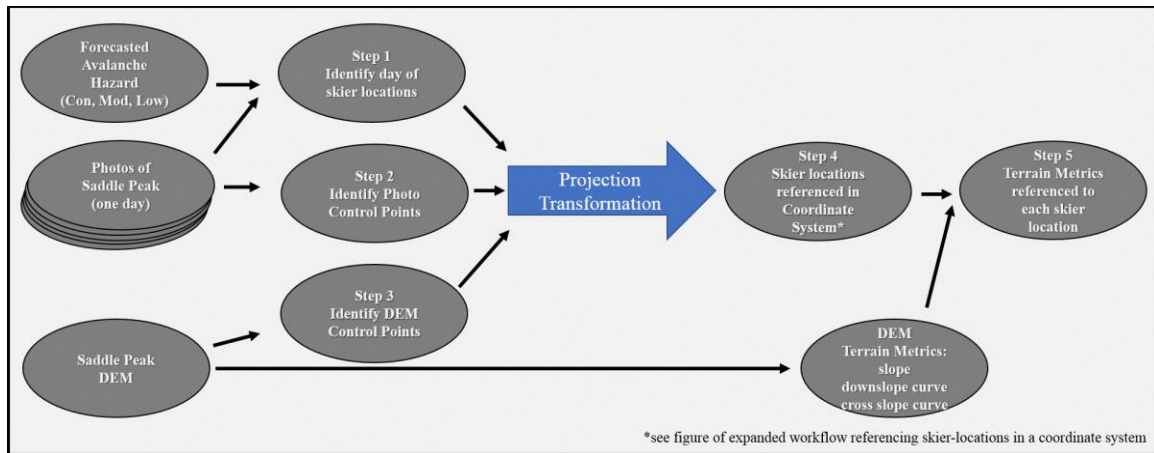


Figure 6. Data-flow diagram of workflow from image collection to analysis of terrain metrics in R. Step 1, from captured photographs skier locations on Saddle Peak are digitized and daily forecasted avalanche hazard is added to data set. Step 2, control points are identified in the photographs and Step 3, control points are identified on the digital elevation model of Saddle peak. Step 4, Skier location points are transformed into a coordinate system. An expanded workflow of Step 4 – skier locations referenced in a coordinate system is found in Figure 7. Step 5, Following skier-location transformation, terrain metrics were attached to skier locations. Then statistical analysis was performed in R testing the differences in terrain on days of different forecasted avalanche hazard.

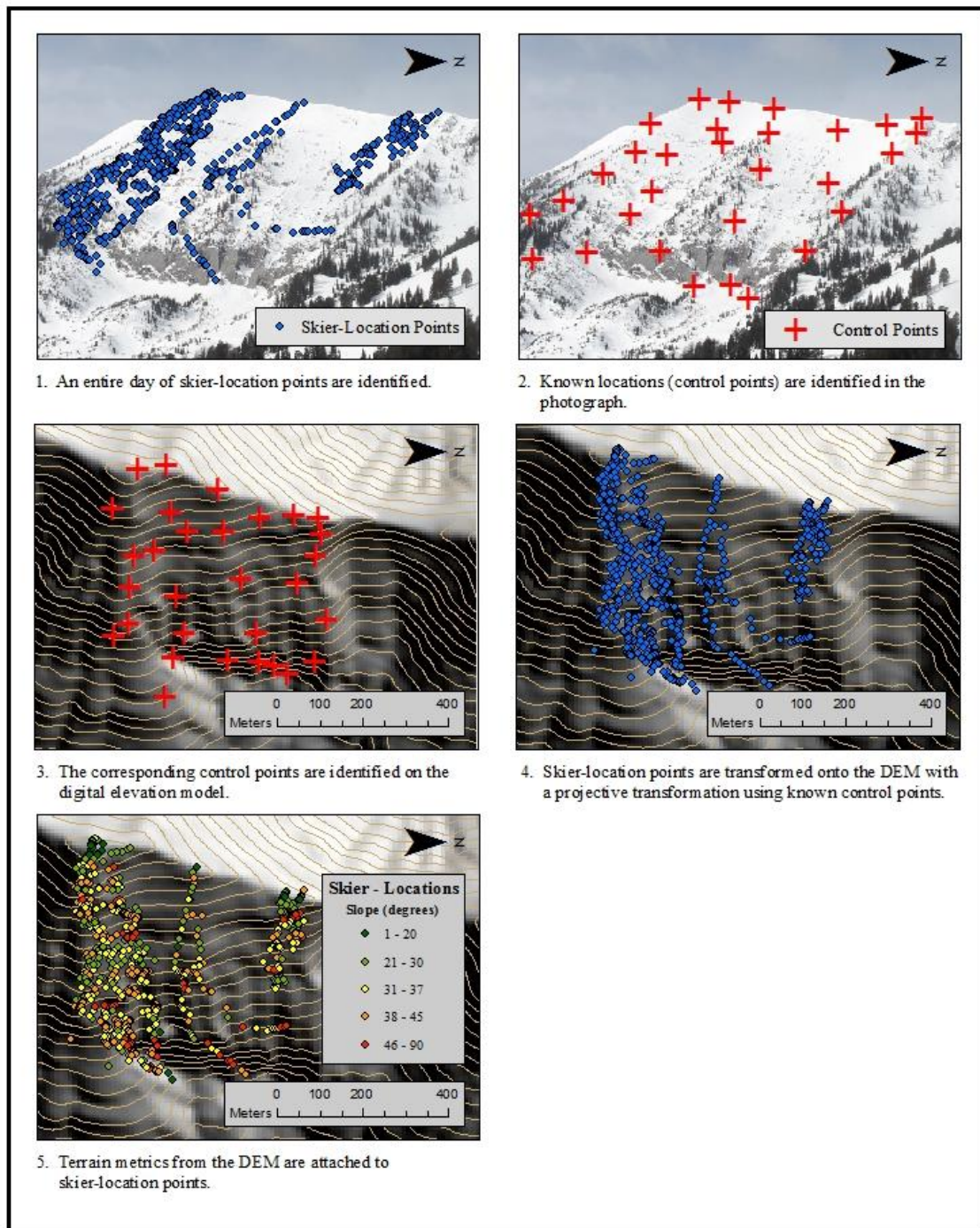


Figure 7. Expanded workflow of how skier-points are referenced in a coordinate system (Figure. 6, step 4). Following this process, the terrain metrics are analyzed in R.

Statistical Analysis

To determine if terrain metrics of skiers differed statistically on days of different avalanche hazard, statistical analysis was performed in R using the non-parametric Kolmogorov-Smirnov (K-S) two-sample test. The K-S test has been used in previous snow and avalanche research in similar areas testing the terrain metrics between different skier groups (e.g. Hendrikx et al., 2014). It hypothesizes two samples drawn from different populations will have the same median distribution (Wang et al., 2003). The K-S test does not require data be normally distributed and is used with ordinal or quantitative data, as is the case in our data set. The K-S test assesses the distance between the medians of the test variable against the data set. A large distance results in a small p-value, the smaller p-value providing more convincing evidence that the two values are statistically different.

This analysis considers the difference between these terrain metrics of skier-locations on days of different avalanche hazard (Considerable, Moderate, or Low). To account for positional accuracy determined in the skier location transformation process, the 10 m DEM was resampled to 30 m prior to identifying terrain metrics for each skier-location point. This study considers how skier terrain choices change under difference avalanche conditions. Wind, precipitation, and snow conditions may also govern terrain choice and but were not assessed in this project.

Positional Accuracy of Skier Location Points

The physical position of the camera naturally introduces error due the angle it views Saddle Peak and captures skiers because the camera is focused at an oblique angle.

Additionally, when the data is transformed onto the DEM, the positional accuracy of the transformed skier location data set is affected. To test the positional accuracy of the transformed skier-location points, spatial accuracy relative and accuracy are considered.

Spatial accuracy is an indicator of how points are accurately positioned with respect to true position in a referenced coordinate system. The transformation process applied to skier locations naturally introduces error in spatial accuracy as a two-dimensional oblique image location of a skier is transformed onto a three-dimensional elevation model (as per Figure 6, step 3). Spatial accuracy was assessed by considering the error values produced with the control point link tables used to transform skier locations onto the DEM. The 1998 National Standard for Spatial Data Accuracy requires positional accuracy reporting in ground distances such that 95% of error values are equal or less than the reported value (Federal Geographic Data Committee, 1998). This paper establishes a spatial accuracy of transformed data based on calculated error values used to link control points in the skier-point transformation process. Transformed skier location points tested 49 m horizontal accuracy for a 95% confidence interval. As we utilized a DEM with 10m accuracy, the DEM was resampled to a 30 m to align resolution between DEM and skier location data sets. Resampled 30 m DEM terrain metrics were used in analysis on skier locations because of established spatial accuracy from skier location transformation.

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. Volunteer skier tracks were captured with recreation Garmin eTrex GPS units as they descended Saddle Peak

on March 5, 2017 and were simultaneously captured by the camera (Sykes, 2018). 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). The skiers were simultaneously captured by the time lapse camera and accuracy measured distances between transformed skier locations to corresponding GPS track provided an assessment of relative accuracy.

Results

Data Collected

Photos were captured over two winter seasons: January 1, 2016 – March 31, 2016 and January 7, 2017 – March 11, 2017 (Figure 8). We collected 121,388 images over 71 different days. At ten second intervals, 360 images per hour were recorded. A successful six-hour data day produced approximately 2160 images. Each photo captured was 12 megapixels in size and had a vertical and horizontal 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. As well 8 days of images were too poor for analysis. Of the 71 days of collected images, 34 days were available for analysis. Of the 34 available days, a subset of thirteen days, utilizing 31,966 images are processed and analyzed in this paper. The days were chosen to include similar weather with a variety of avalanche hazard forecasts.

For analysis on the terrain metrics of backcountry skiers, we studied thirteen days on Saddle Peak over two winter seasons (2015-2016 and 2016-2017). We documented 525 skiers and 7499 skier-point locations. We recorded 182 skiers (1995 skier-points) on four

days of Low avalanche hazard, 175 skiers (4254 skier-points) on four days of Moderate avalanche hazard, and 168 skiers (1250 skier-points) on five days of Considerable avalanche hazard. We documented fewer skiers under Considerable hazard than Moderate or Low however, the highest skier days recorded were 130 skiers under Low hazard on March 27, 2016 and 129 skiers under Considerable hazard on February 14, 2016 (Table 3 and Figure 8).

Solo skiers on Saddle Peak were documented. Out of 525 skiers captured on Saddle Peak, 94 (18%) were not in a group. On days of Considerable hazard solo skiers represented 33 % (56 of 168) of skiers on Saddle Peak. Solo skiers represented 15% (26 of 175) on Moderate hazard and 7% (12 of 182) under Low hazard (Table 3).

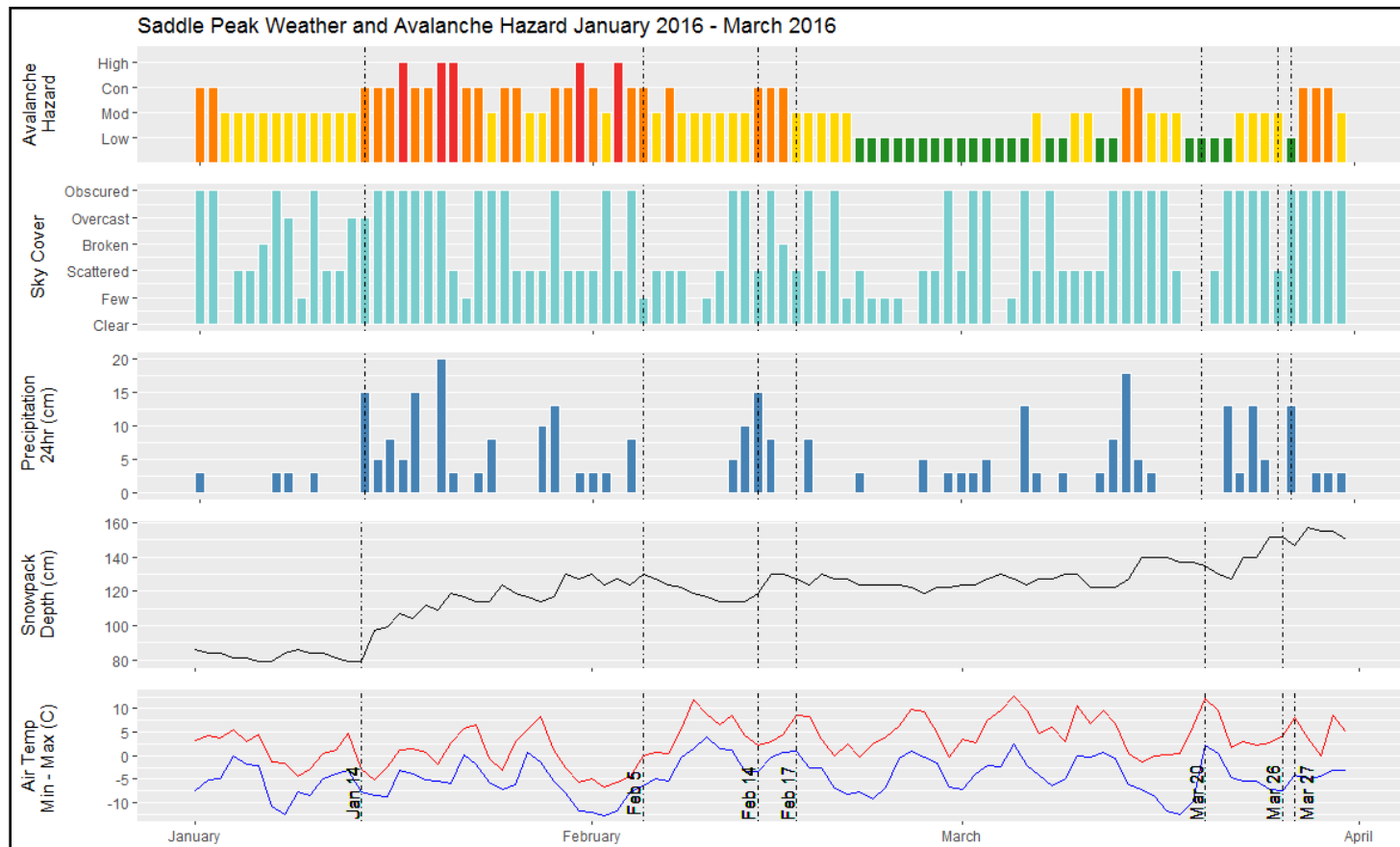


Figure 8. Weather and avalanche data for 2016 and 2017 study seasons (Jan - Mar). Avalanche Hazard: bar graph colors represent the forecasted avalanche hazard, Green – Low, Yellow – Moderate, Considerable – Orange, and Red - High. There were no days of Extreme Avalanche Hazard (GNFAC, 2018). Sky cover data is for Bozeman, MT (Weather Underground: Forecasts and Weather Underground, 2016; Weather Underground: Forecasts and Weather Underground, 2017). Precipitation, Snowpack, and Air Temp are acquired from Bridger Bowl Alpine Weather Station. For Air Temp, daily minimum is identified in blue, daily maximum is in red (Bridger Bowl, 2018). Doted vertical lines identifying days of study.

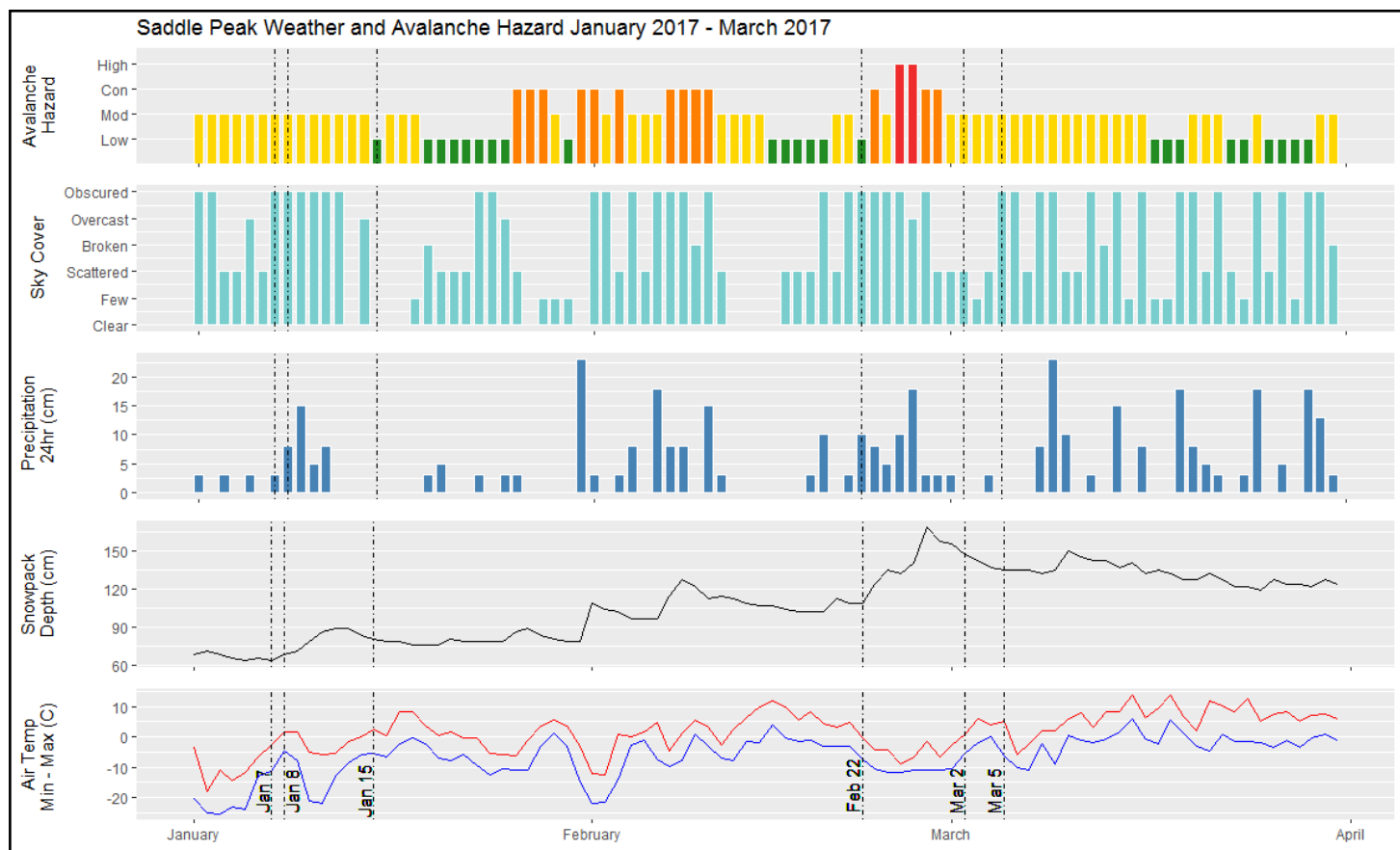


Figure 8 Continued.

Table 3. Table summarizing days of analysis. Row color corresponds to forecasted avalanche hazard (Red - Considerable, Yellow - Moderate, Green - Low).

Date	Day	Av Hx	Numbers of					Transform	
			Images	Points	Skiers	Solo skiers	Solo skier %	CPs	RMSE(m)
1/14/2016	Thur	Con	1802	109	18	4	22%	20	26.0
2/5/2016	Fri	Con	2879	20	1	1	100%	10	11.8
2/7/2016	Sun	Con	2879	92	18	3	17%	12	20.2
2/14/2016	Su	Con	2879	882	129	37	29%	30	23.4
3/20/2016	Sun	Low	2879	408	15	1	7%	30	20.8
3/26/2016	Sa	Mod	2879	2097	52	3	6%	30	23.2
3/27/2016	Su	Low	2789	1254	130	7	5%	30	23.2
1/7/2017	Fri	Mod	1980	185	13	1	8%	30	25.7
1/8/2017	Sun	Con	1853	147	21	11	52%	30	27.9
1/15/2017	Sun	Low	1782	286	34	4	12%	28	24.4
2/22/2017	Wed	Low	1691	47	3	0	0%	30	25.6
3/2/2017	Thur	Mod	3509	1152	76	17	22%	30	25.5
3/5/2017	Sun	Mod	2159	820	34	5	15%	30	28.1
Totals:			31960	7499	525	94	18%	Avg:	23.5

Skier – Location Point Analysis

Skier location points were visually assessed in GIS. Visually, skier line choices changed with different avalanche conditions. Under Considerable avalanche hazard, skiers chose either the ski area boundary line or the ridge descent from Saddle Peak. 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, most committing line. Under moderate hazard, line choice has more variance, but skiers still avoided the middle of large features. Under Low hazard skiers pushed deeper into terrain (Figure 9). 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. It was noted that the Football Field was more heavily

tracked on Low days, where-as on Moderate days skiers were more clustered toward the boundary line.

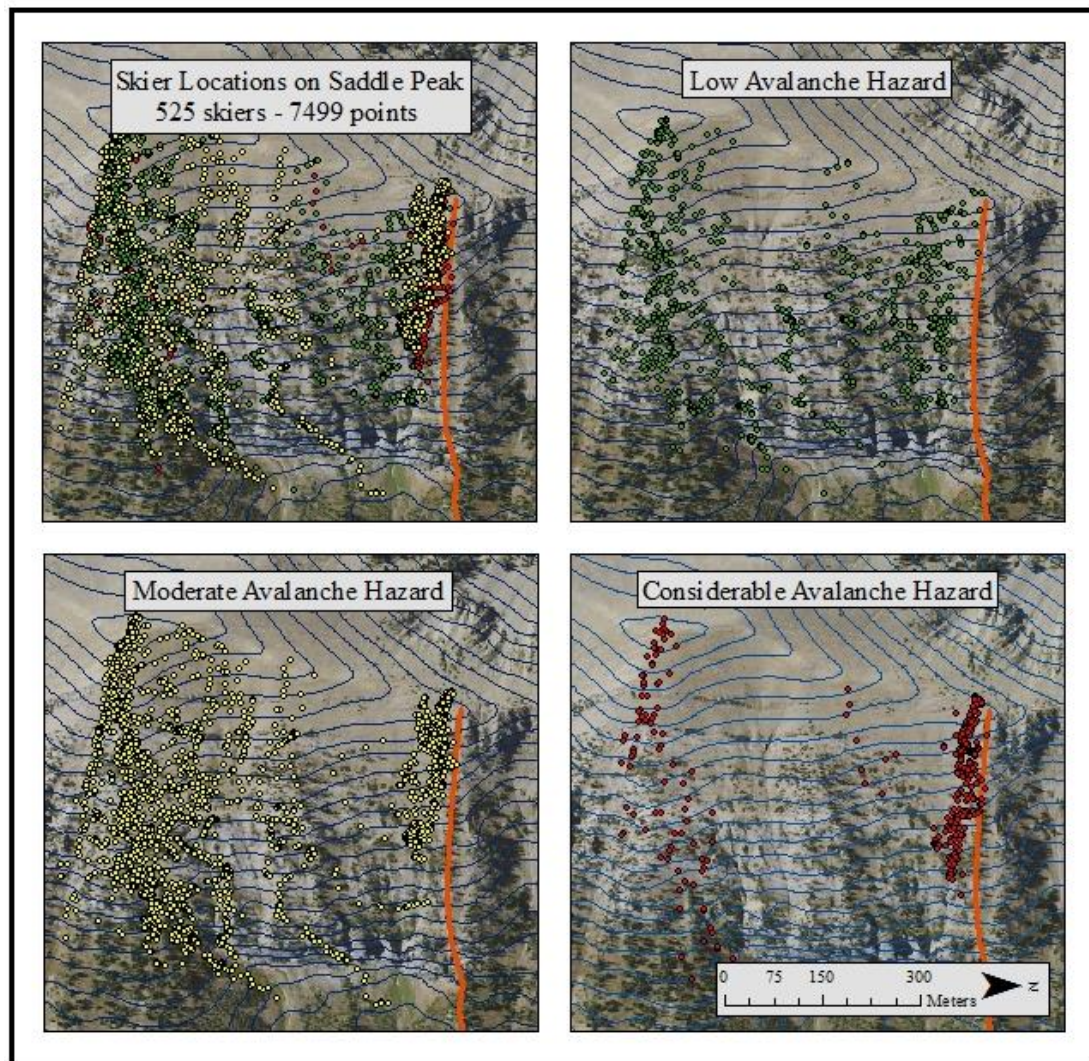


Figure 9. Skier-locations on Saddle Peak classified according to forecasted avalanche hazard. Red dots represent Considerable avalanche hazard skier locations, yellow represents Moderate hazard, and green dots represent low hazard skier locations. The Bridger Bowl Boundary line is identified in orange.

Statistical Analysis

Statistical analysis of terrain metrics analyzed slope angle, profile curvature (downslope), and plan curvature (cross slope). Spatial accuracy testes at 49 m from control point error in the transformation process. In the assessment of relative accuracy, we found most skier location points were within 30 m of the corresponding GPS track. To account for differences in accuracy between the DEM and skier location point, the 10m DEM was resampled to 30 m and terrain metrics from the resampled 30 m DEM of Saddle Peak are used for analysis. Terrain metrics of skier locations are compared against days of different forecasted avalanche hazard (Low, Moderate, Considerable). Summary statistics (e.g. minimum, maximum, median values) were plotted as box and whisker plots for terrain metrics by skier date (Figure 10).

Boxplot analysis suggested median slope angles skied were lowest under Considerable hazard. Under downslope curvature, there were less extremes skied and skiers posted more planar locations rather than either concave or convex under considerable hazard. Median values under cross slope curvature indicated skiers were on more ridge-like features under Considerable avalanche hazard (Table 4).

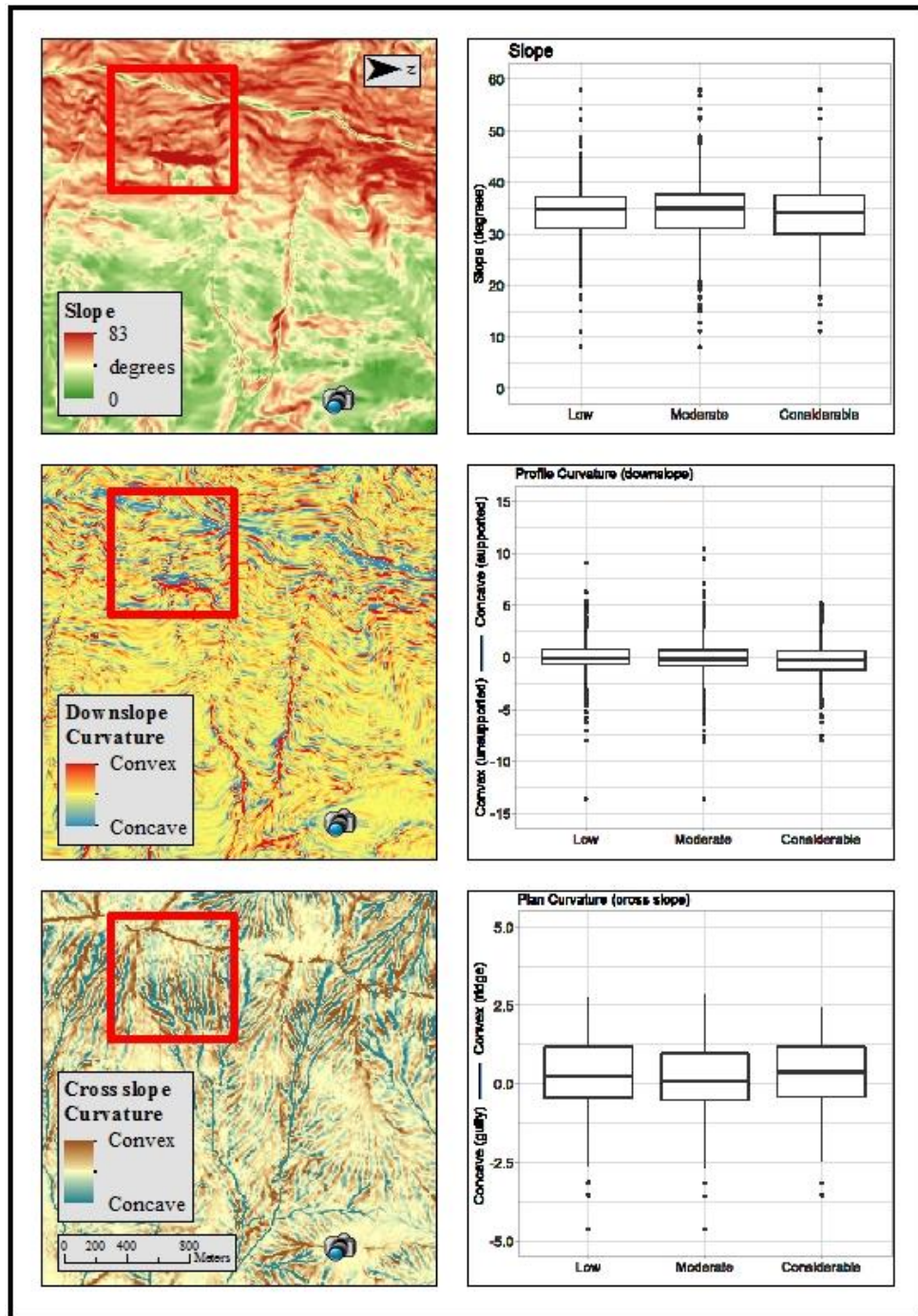


Figure 10. Box plots of terrain metrics by forecasted avalanche hazard, showing the median, 25% and 75% interquartile range, minimum, and maximum values.

For statistical analysis, the Kolmogorov-Smirnov non-parametric analysis assessed the statistical significance of slope, downslope curvature, and cross slope curvature terrain metrics for different avalanche hazard (Table 5). The K-S test quantifies a distance between the cumulative distribution function of both samples. The K-S test identifies if the median values from each set are statistically different and which median values are overall greater (or lesser). In the following tests we assess if the CDF of slopes skied under Considerable avalanche hazard are greater (smaller angles), the profile curve is greater (more supported), and the plan curvature is lesser (more ridge-top features).

The one-sided K-S calculated on the terrain metrics from the resampled 30 m DEM cell size found strong evidence ($p\text{-value} < 0.001$) that the terrain metrics (slope, downslope curvature, and perpendicular curvature) of Considerable hazard days are statistically different than Moderate or Low days (Table 5). Slope testing indicated a statistical significance between Considerable and Moderate and Considerable and Low hazard days. No statistical difference between slope on Moderate and Low days was identified. Down slope curvature testing indicated a statistical difference between all hazard days. Data suggested that skiers opted for more supported or convex terrain as hazard increased. Cross slope curvature testing indicated a statistical difference between Considerable and Moderate and Considerable and Low hazard days. Results suggest skier locations were on more ridge-like features as avalanche hazard increased. Additionally, a statistical difference between slope on Moderate and Low days was identified suggesting skier chose more gully-like features under Low avalanche hazard. This data suggests that

skiers choose more conservative terrain with increasing hazard aligns with previous research on terrain metrics of skiers in avalanche terrain.

Table 4. Median values by avalanche hazard for terrain metrics analyzed with resampled 30 m DEM.

Median Values by Avalanche Hazard	Considerable	Moderate	Low
Slope	34.14	34.95	34.82
Profile	-0.26	-0.14	-0.10
Plan	0.35	0.08	0.25
Number of skier location points	1250	4254	1995

Table 5. P-values associated with K-S tests on terrain metrics for 30m cell sizes.

Slope		CDF of x below (less) y	CDF of x is above (greater) y
Con	Mod	0.674	p < 0.001
Con	Low	0.031	p < 0.001
Mod	Low	0.004	0.121

Downslope Curve		CDF of x below (less) y	CDF of x is above (greater) y
Con	Mod	0.635	p < 0.001
Con	Low	0.850	p < 0.001
Mod	Low	0.888	p < 0.001

Cross Slope Curve		CDF of x below (less) y	CDF of x is above (greater) y
Con	Mod	p < 0.001	0.675
Con	Low	p < 0.001	0.421
Mod	Low	0.133	p < 0.001

Accuracy – Spatial Accuracy of Projective Transformation of Skier-Locations

Spatial accuracy was measured by individual error associated with each control point link in the link table 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. The viewshed at which the camera captures the east slope of Saddle Peak introduced systematic error due to the angle at which images were captured. The capture angle, or viewshed, of the camera was positioned at an oblique angle to the slope of Saddle Peak and at a lower elevation. This resulted in skier-location transformation errors on control points, particularly points that had a similar slope angle to the capture angle. CP locations that presented a slope more perpendicular to the camera angle (steep, northeast aspect), had lower error values than locations that presented a slope more parallel (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 photo could result in large error values in the DEM (Figure. 11).

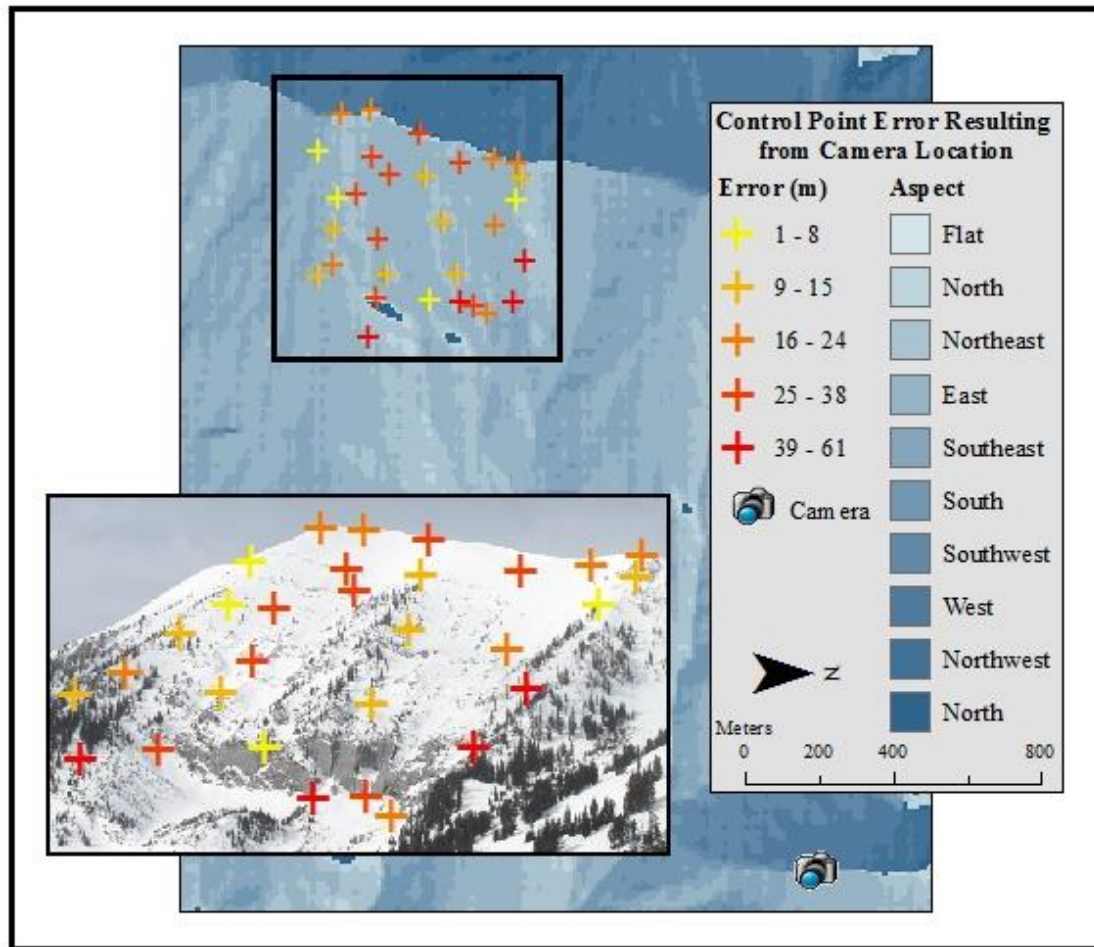


Figure 11. Control point error and camera location to identify the angle at which the camera capture skiers on Saddle Peak. Control points are colored by error values with warmer, more red colors identify areas of greater error. Orientation to the camera is one variable in control point error as represented by the aspect (blue colors).

In the projection transformation process, a maximum of 30 CPs were used per CP link file. When skier numbers were low or all skiers were condensed in a smaller area, less CPs were used as this lowered CP error. For all thirteen days, 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 (Jan 17, 2017). The overall average error for all individual CP links was 21.8 m (Table 3).

Error associated with individual control point lines was utilized to test the accuracy of the methodology of capturing skier locations using time-lapse photography. Individual control points tested 49 m horizontal accuracy at 95 % confidence level (Figure. 12). Due to the differences accuracy between 49 m skier locations and 10 m DEM, we resampled the DEM to 30 m to better align our data sets. We found our dataset accuracy to be acceptable for this study, however we make suggestions for improving data accuracy in the discussion.

Root Mean Squared Error (RMSE) was calculated for each day CP link file using the individual error values for each CP link.

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{j=1}^n (y_j - \hat{y}_j)^2}$$

The RMSE is based on the individual CP error values and provides an indication for the quality of a complete link file for the projective transform. Overall average RMSE for all transformation link files was 23.5 m. The largest RMSE was 28.1 m (March 5, 2017), the lowest RMSE was 11.8 m (for 10 control points, February 5, 2016) (Table 3). RSME tested 28 m horizontal accuracy at 95% confidence interval.

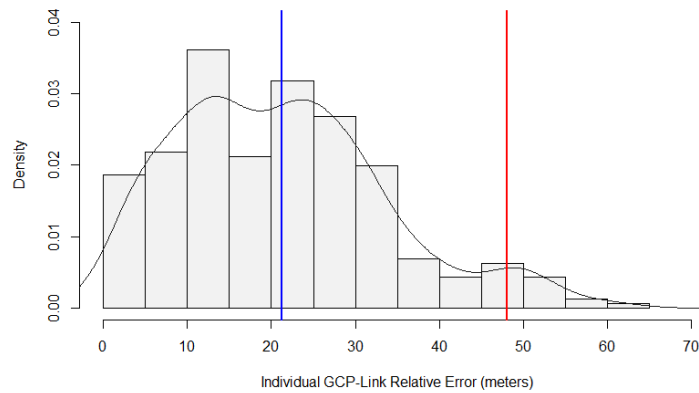


Figure 12. Histogram of the relative error values from all link-file tables as represented by the density of error values located within each bar. Individual control points tested 49 m horizontal accuracy at 95 % confidence level (red line). Median control point error is 21 m (blue line). With these results, we determine a positional accuracy of 49 m for our data set and evaluate corresponding terrain metrics. We found our dataset accuracy to be acceptable for this study, however we make suggestions for improving data accuracy in the discussion.

Accuracy – Relative Accuracy of Image Skier Locations to Recreational GPS Unit

On March 5, 2017, volunteer skiers on Saddle Peak recorded GPS tracks as they descended Saddle Peak. Fourteen GPS tracks were compared against the corresponding transformed skier locations points captured by the camera to assess relative accuracy transformed skier locations. On the same day, 36 skiers were captured by the time-lapse camera. Skier locations were identified in the photos, digitized and geo-referenced to the DEM and compared to corresponding GPS track. The fourteen GPS tracks were compared against the photos and identified; a 30 m buffer was applied to the track to visually assess skier-location distance from GPS track (Figure 13).

To measure skier-location relative accuracy against the GPS track, the nearest GPS point for every skier-location was identified and distance from track measured. 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 1.2 m, and the average distance between GPS track and skier-location point was 10 m (Table 6). Considering relative accuracy by distance between GPS track to skier location points. The maximum distances for each track/skier-location point line tested at 30 m horizontal accuracy at 95% confidence level.

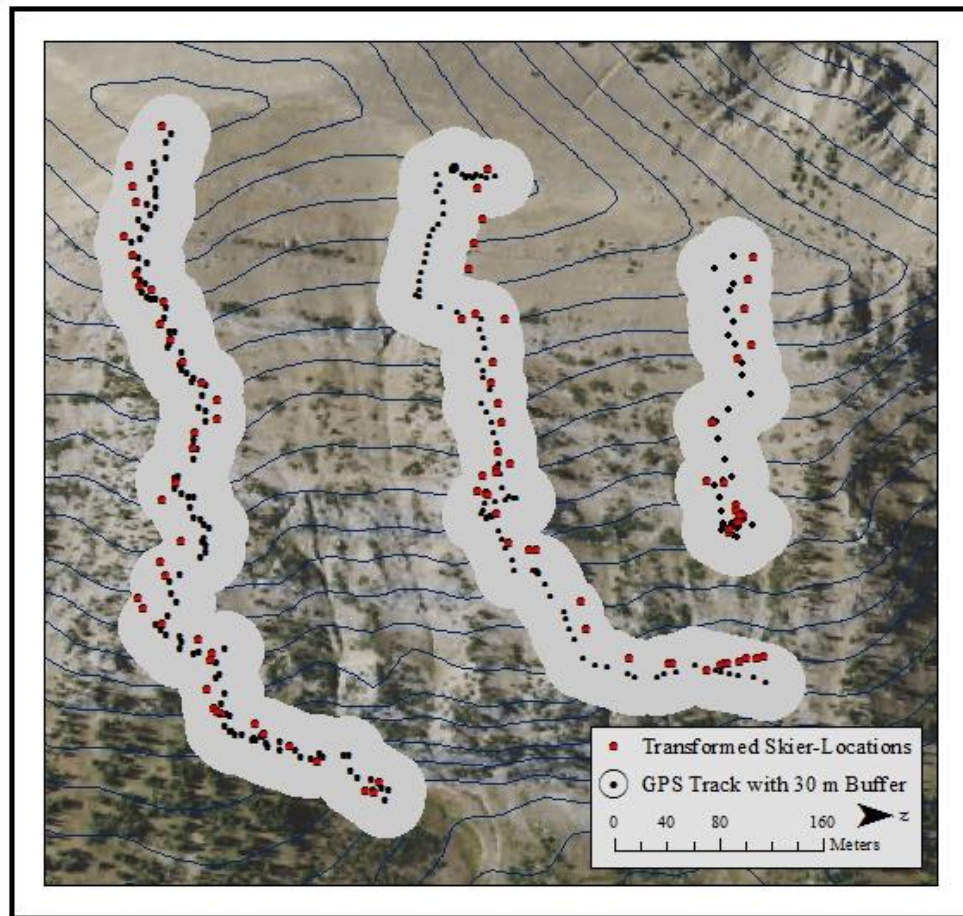


Figure 13. Three selected lines of transformed skier-location points (red dots) and corresponding GPS Tracks with 30 m Buffer (black dots) on March 5, 2017. 14 GPS tracks and skier location lines were assessed for relative accuracy, three tracks and transformed skier locations are displayed. The selected lines and GPS tracks with buffer provides a visual reference of the accuracy of transformed skier locations relative to corresponding GPS track. **Lines selected for visual display are identified in Table 6.

Table 6. Table displaying minimum, average, and maximum distances from each GPS track to corresponding skier-location points as captured by the time lapse camera. *We identified skiers in 14 separate groups throughout the day. In 2 situations (groups 10 and 14), there was more than one GPS unit per group of skiers. The maximum distances for each track/skier-location point line tested at 30 m horizontal accuracy at 95% confidence level. **In Figure 13, the tracks of the identified GPS and skier locations are displayed.

GPS File Name	Group*	Distance from GPS track (m)		
		Minimum	Average	Maximum
1807z_GPS7_1	1	1.4	8.8	25.9
1811z_GPS4_1	2	1.2	11.3	36.2
1832z_GPS8_1	3	0.2	12.4	33.8
1841z_GPS9_1	4	0.3	10.1	27.2
1847z_GPS6_1	5	1.7	11.6	24.9
1904z_GPS3_1	7	0.5	12.9	29.9
1917z_GPS5_1**	9	1	11.9	34.3
2005z_GPS3_1	10	3	10.2	30.8
2005z_GPS9_1**	10	0.2	9.2	28
2033z_GPS7_1	10	3	13.3	20
2016z_GPS4_1	12	3.4	11.1	18.9
2110z_GPS8_1**	13	0.2	7.8	25.7
2119z_GPS6_1	14	0.5	7.7	23.6
2120z_GPSJJ_1	14	0.4	6.3	24.1
Averages		1.2	10.3	27.4

Discussion

Terrain Use as a Function of Hazard

Analysis on terrain metrics of skier-point locations indicated that the terrain preferences on Considerable hazard days were statistically different than Moderate and Low days. Results suggest skiers choose more conservative terrain on days with more challenging forecasted avalanche conditions (Table 5). This is promising for avalanche education in that the terrain choices of recreational skiers can potentially be influenced by avalanche forecasts.

In the case of slope, the overall differences in median slope angle values were small. The median slope angles on Considerable days was less than both Moderate and Low. K-S testing confirmed a statistical difference. Our data set suggests skiers were on lower angled terrain with days of more challenging forecasted avalanche conditions. Profile curvature analysis indicated a statistical divergence in the downslope curvature between Considerable and Moderate, Considerable and Low, and Moderate and Low testing. Results suggest that skiers were on more concave (supported) terrain with more challenging forecasted avalanche conditions. Additionally, the spread of data indicated less extreme convex or concave terrain overall under Considerable hazard, the terrain chosen was more planar. The analysis of profile curvature identified a statistically significant difference in all tests. Data indicates that skier locations were on more ridge-like features between Considerable and Moderate, and Considerable and Low analysis. Interestingly, analysis also found a statistical significance indicated skier locations were on more gully-like feature under Low hazard than Moderate Hazard. As well, Saddle

Peak presents limited variety of terrain choice options, which reflect the similarities between all days of study.

These results are positive and informative. They align with other studies of terrain metrics in that skiers generally opt for less hazardous terrain as avalanche hazard increases (Hendrikx and Johnson, 2016c; Thumlert and Haegeli, 2017; Sykes, 2018). Using the terrain parameters as a proxy, results suggests that recreational backcountry skiers on Saddle Peak are overall making more conservative terrain choices according to the forecasted avalanche hazard. In this assessment, we assume that all skiers knew the avalanche forecast, however other studies suggest that a large percentage of skiers on Saddle Peak may not know the current avalanche hazard (Fitzgerald et al., 2016).

Our data indicates that the tested terrain metrics of skier-locations are statistically different on days of Considerable avalanche hazard relative to Moderate and Low forecasted avalanche hazard days. However, there are many factors which contribute to a good day of skiing. Other confounding variables such as previous tracks, day of the week, and current weather, may also impact backcountry skiing and alter terrain metrics. Such confounding variables could be considered and tested for impact on terrain metrics in future research. Every attempt was made to reduce this potential, and days with similar conditions (but different forecasted avalanche hazard) were selected for our analysis (as per Figure 8).

As this research studies skier terrain use in relation to forecasted avalanche hazard, we assume that skiers know the avalanche hazard prior to skiing Saddle Peak. Other research and indirect evidence suggest that not all backcountry skiers are aware of the

forecasted avalanche hazard, particularly Saddle Peak users (Fitzgerald et al., 2016; Sykes, 2018) This fact is a major limitation when assessing terrain use as a function of forecasted avalanche hazard on Saddle Peak.

Solo Skiers

One notable observation was the large number of solo skiers on Saddle Peak. Out of 525 skiers captured on Saddle Peak, 94 (18%) were not in a group. Additionally, on days of Considerable hazard, 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 3). To determine if the percentage of solo skiers was statistically different between days of different forecasted avalanche hazard, the Wilcoxon signed rank test was used. The Wilcoxon signed-rank test is a non-parametric test that determines if the population means of two dependent samples differ. Statistical analysis reported suggestive evidence that percentage of solo skiers were significantly different when comparing Considerable – Moderate (p-value = 0.05) and Considerable – Low (p-value = 0.02). However, results suggested no difference in mean values of solo skiers between Moderate – Low (p-value = 0.2).

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 (Fitzgerald et al., 2016; Sykes, 2018). Unfortunately, a solo skier was killed in an avalanche on Saddle Peak on April 4, 2018. The skier was alone and responders reached the victim 75 minutes after the event; a hand was extending from the debris pile and resuscitation efforts were unsuccessful. (GNFAC, 2018).

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 with the people one travels (Procter et al., 2013; Haegeli et al, 2012). The number of solo skiers on Saddle Peak suggests an increased need to encourage traveling with a partner capable of self-rescue with skiing in avalanche terrain.

Lift - Accessed Backcountry Skiers with Transceivers

A unique characteristic of Saddle Peak is that riders on the Schlasman's Lift are required to wear avalanche transceivers, and thus, while skiing Saddle Peak. This is not a common requirement in lift-accessed backcountry avalanche terrain and survey research performed on skiers in lift-accessed avalanche terrain indicates LABC users generally have less avalanche knowledge than self-powered backcountry skiers (e.g. using skins). However, as these skiers are required to wear an avalanche transceiver, they require some avalanche knowledge in the acquisition on the device. Resultingly, Saddle Peak presents a subset of lift-accessed backcountry skiers, those that are wearing an avalanche transceiver.

Avalanche Events

In addition to documenting terrain choices, the time lapse camera also documented a near-miss avalanche event. On January 14, 2016, the camera captured an avalanche event in real time, and due to fortuitous timing, the images assisted Bridger Bowl Ski Patrol in the avalanche response. At approximately 11:39 am on January 14, 2016 a group of skiers remotely triggered an avalanche on the Football Field of Saddle Peak. The

avalanche and events prior were captured by the camera. The images of the event were viewed after the avalanche was triggered and assisted ski patrol in determining no involvement. The skiers who triggered the event were documented returning to the ski area as the avalanche released (Figure 14). Unlike the 2010 event, rescuers were not exposed to significant hazard in assessing for involvements. This case provides an example of the efficacy of using remote observation to monitor large geographic areas in a low cost/ low maintenance method for potential search and rescue scenarios (Saly et al., 2016).

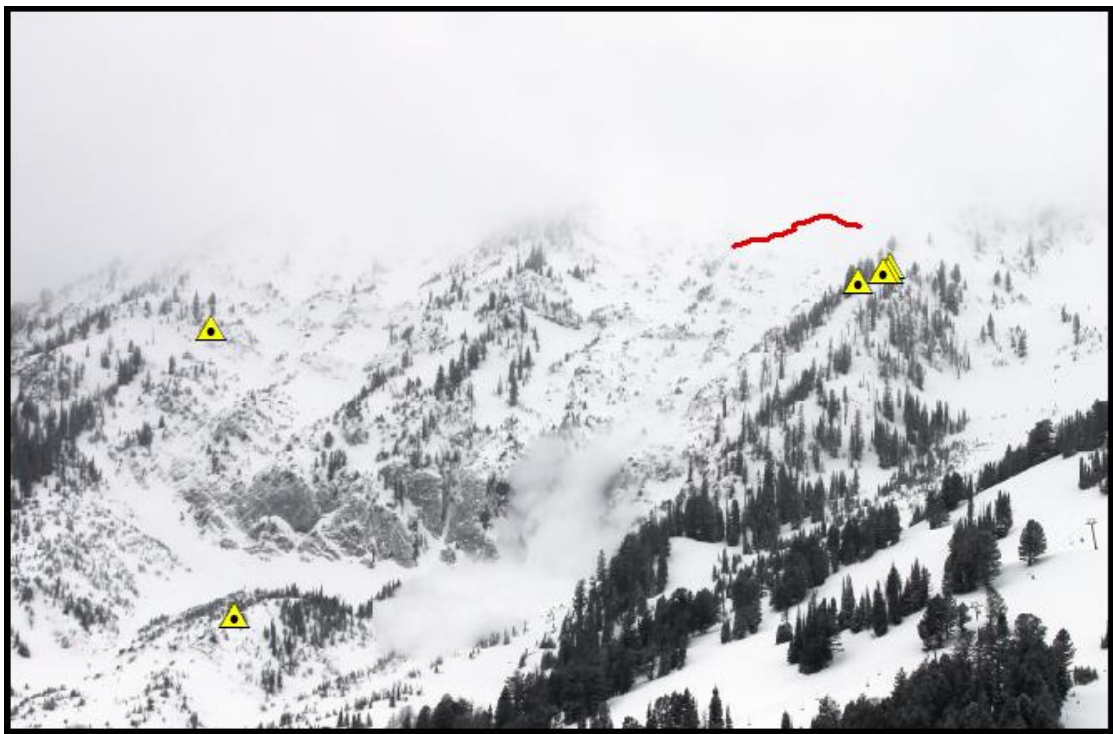


Figure 14. Football Field Avalanche January 14, 2016. A skier-remote triggered avalanche was captured by the time-lapse camera. The crown is identified in red with locations of 6 skiers (identified by yellow triangles) as the slab released. The group to the right of the crown were responsible for remote triggering the avalanche. The images captured by the camera assisted Ski Patrol with their response efforts.

Limitations

This was an observational study of the terrain choices (slope, profile curvature, and plan curvature) made by skiers descending a unique slope on thirteen days with varying avalanche hazard. A selection of study days was analyzed so that a variety of avalanche hazards (Low, Moderate, Considerable) were included in the data set. 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 skier on Saddle Peak (photographing skier locations). Resultingly, our data sets have selection biased for days of better visibility and may miss a user group of skiers on low visibility days. The results of this study are representative of a unique and specific slope at a certain moment in time. Inferences can be made about each study day, but inferences extended further (such as different location, user group, snowpack, season) should be made carefully.

The user group captured, unique subset of backcountry skiers, presents an area of limitation in this study. Skiers on Saddle Peak are in lift-accessed backcountry terrain and wearing an avalanche transceiver. As well, to assess the relationship between forecasted avalanche hazard this study assumes that all skiers on Saddle Peak know the avalanche hazard. However, other studies have found as many as 33% of users on Saddle Peak did not know the current avalanche forecast (Fitzgerald et al., 2016). Additionally, this study only captures skiers on the east face of Saddle Peak. On February 14, 2016, the time lapse camera captured a total of 145 skiers at the Bridger Bowl backcountry access gate (Figure 2). 82 skiers were captured within the study area, 16 skiers returned to the ski area and 47 skiers went beyond Saddle Peak. This indicates a large portion of Bridger

Bowl's lift-access backcountry user group is not captured by the camera. This study only captures skiers on the east slopes of Saddle Peak and does not extend to the entire group of "Bridger Bowl lift-accessed backcountry skiers."

A limitation in the analysis of terrain metrics was the difference in accuracy between transformed skier points (49 m) and the DEM (resampled 30 m). The 10 m Saddle Peak DEM was resampled to 30 m resolution using a nearest neighbor assignment which averages the values of a 3 x 3 cell group. While this is not a perfect match in resolution, we considered these values acceptable as a proof of concept in this study. Despite the limitations of the current study, we still gained valuable insight into the terrain selection of lift-accessed backcountry skiers.

Future Work

One area of interest and concern is the number of solo skiers on Saddle Peak. While this research did not consider group size when assessing terrain metrics, one suggestion is that solo skiers may be more experienced and regular users on Saddle Peak and have a premeditated plan to ski Saddle Peak, this may result in less terrain choice deviations under different hazard. Incorporating group size and testing if solo skiers (or other sized groups) alter terrain choices under different avalanche conditions may produce interesting results when compared with the overall terrain choices of skiers on Saddle Peak.

Incorporating the presence of skier tracks in the snow may provide an interesting angle to this research. While terrain properties may affect how people choose ski terrain based on avalanche hazard, the desire for fresh tracks may greatly influence skier decision. After a storm, when avalanche hazard is still high, skiers can access fresh tracks

close to the boundary line. But days later, when hazard is lower, the lack of fresh tracks influences skiers to push further into the Football Field in search of untouched snow. Additionally, future work should consider, adding time data when digitizing skier location points. This will add an additional level of information when considering the length of time a backcountry skier spends in uncontrolled avalanche terrain.

Another consideration for future work is to utilize a focal operation on the 10 m DEM raster to better align accuracy to the 49 m accuracy skier location points. The method differs from the local operation in that each cell value is surrounding 3 x 3 cell values, as opposed to a simple resample of 3 x 3 neighborhoods without overlap. This technique may produce better accuracy and a better generalization of terrain metrics attached to skier location points.

As well, relative accuracy suggested transformed skier location points were reasonably close to the corresponding GPS tracks. As this research required a fixed location for a ground-based camera, precision was lost in capturing skier locations from an oblique angle. As well the DEM is representative of bare ground, the snow surface may be very different due to snow drift and loading and may change considerably throughout the season. Creating digital surface models of the snowpack may also highlight more precise details in skier terrain preferences that we were not able to capture.

Future research could consider moving the camera location to a closer, more perpendicular angle, and higher elevation relative to the study area to improve the spatial accuracy of the skier locations. Continuing to improve accuracy and using data that is

compatible within accuracy constraints will improve precision. Adding a consistent power supply and large data storage will limit disruptions in capturing images. Furthermore, the ability to capture data in low visibility conditions, such as with infrared cameras, will increase data collection potential. Extending the study to different avalanche terrain will provide more insight into the terrain choices of backcountry skiers. Additionally, the workflow process created in this study requires a large amount of manual processing in identifying skiers represented by pixel changes. After pixel changes have been digitized, skier locations identified and selected from all points which are created from pixel changes between corresponding images. Adding scripting which automates the identification of skier locations over other pixel changes greatly improve workflow efficiency.

Conclusion

Photographs 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, we analyzed terrain metrics both with a 10 m DEM and a DEM resampled to 30 m, tested the impact of this in our terrain model.

This paper develops a technique to study recreational skiers in backcountry avalanche terrain and explore terrain preferences. Not only is it effective as a research method it also has value from an operational perspective. A time-lapse camera provides constant monitoring of terrain that can frequently avalanche or commonly has incidents.

As in the case of the January 14, 2016 avalanche on the Football Field of Saddle Peak, a camera can provide responders with another tool for risk analysis and lower the involvement risk of responders in an avalanche incident.

We found that terrain choices are statistically different with different avalanche hazard, even in terrain with limited options. In general, skiers chose more conservative terrain as avalanche hazard increased. 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 self-rescue.

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CONCLUSIONS

Summary

Avalanches are one of the greatest hazards for those recreating in snow covered mountainous terrain. Between 1996-2016, an average of 13 people in Canada and 27 people in the US died in avalanches every winter season (Avalanche Canada, 2016; Colorado Avalanche Information Center, 2016). In 90% of avalanche accidents the avalanche is triggered by the party involved (McClung, 2014; McCammon and Haegeli, 2007). Over the same period, the rate of usage of backcountry avalanche terrain has drastically increased due to improved equipment, increased popularity and media attention, and many ski areas opening their boundaries (Birkeland et al., 2017; SIA, 2017). Notably, avalanche fatalities have remained relatively stable at 25-30 per year (in the US) since 1996. European data shows similar trends of stable avalanche fatalities in recent years (Birkeland et al., 2017). It is the hope that as more users enter avalanche terrain, they do so with a better knowledge base through avalanche education and forecasting.

Careful selection of exposure to avalanche terrain is an essential risk management process which reduces avalanche risk. The overall aim of an avalanche forecast is that users adjust their terrain choices in response to the avalanche problem, thereby reducing their risk of avalanche involvement, little evidences exists if this occurs.

This paper develops a method to capture the terrain metrics of all skiers on an avalanche-prone backcountry slope. A remote time-lapse camera focused on a high skier-use backcountry slope, (Saddle Peak, in the Bridger Mountain Range of southwest

Montana, USA) captured skiers descending Saddle Peak in ten-second increments. Skier locations were digitized from the photos, then transformed onto a geo-referenced digital elevation model (DEM) such that terrain metrics could be applied to each skier location.

Transformed data fell within a 49-m horizontal accuracy for all skier point locations with a 95% confidence interval. Analysis of terrain metrics for each skier point compared slope, profile curvature (downslope), and plan curvature (cross slope) over days with different forecasted avalanche hazard. Terrain metrics on Considerable avalanche hazard days differed significantly from Moderate or Low avalanche hazard days ($p\text{-value} < 0.001$). By capturing all skiers on a slope without their knowledge, the data collected provides a large and diverse data set of the terrain preferences of backcountry skiers under varying conditions.

This study analyzes the terrain choices of a more diverse set of backcountry skiers than volunteer-based studies. Data collected capture all users on an avalanche prone slope, adding a larger and more diverse data set of backcountry skier terrain use. Study results were similar to volunteer-based studies, showing that skiers chose more conservative terrain on days with more challenging forecasted avalanche conditions. One notable observation was the large number of solo skier captured. Future studies should consider terrain choices by group size and avalanche hazard.

Methodology

We present an effective methodology to capture skiers in avalanche terrain and an unbiased method study the terrain metrics of backcountry skiers in different avalanche conditions. Appendix A contains the work flow used to process time-lapse photos,

Appendix B contains the Python script for image comparison and pixel change identification. GIS data information, source credits, and data dictionary for data created is in Appendix C. Appendix D contains the link tables for individual transformation unique to the day of study. Appendix E contains published papers related to this project.

Limitations and Opportunities for Future Work

Limitations of this study are presented as recommendations for future research to further understand the how backcountry skiers move through avalanche terrain.

This study assesses skier use on Saddle Peak and assumes users know the forecasted avalanche hazard, however other research suggests that many lift-accessed backcountry skiers do not know the avalanche forecast and thus are not making terrain choices based on information acquired from avalanche forecasts. A more robust study should consider studying a variety of slopes with different avalanche terrain. Extending beyond a single slope will provide more insight into the terrain choices of backcountry skiers as well as capture a different user group. Capturing self-powered backcountry skiers may present a more informed user group (in terms of the current avalanche hazard) and less solo skiers. Additionally, skiers on Saddle Peak are required to wear avalanche transceivers to ride the Bridger Bowl lifts. As a result, this is a sub-group of lift accessed backcountry skiers, not all lift access skiers have avalanche transceivers.

Weather and visibility were critical variables in capturing complete and uninterrupted day-data sets. Snow or ridgetop cloud (i.e. Bridger Cloud) would obstruct visibility of skiers, resultingly poor weather days may be underrepresented in the data set as a full day of data was required for skier locations to be processed. Saddle Peak use is

also dependent on the operation of the Schlasman's lift, and disruptions in service are commonly a result of bad weather, one potential confounding variable in this study.

The location, power, and storage capabilities of the camera unit could be improved. Positioning the camera in a better position (closer to subject and face-on, ideally overhead view of subject) would improve the accuracy of the skier-locations. Continuing to improve accuracy and using data that is compatible within accuracy constraints will improve data precision. As well, a smaller time interval/higher skier sampling rate would capture more skier locations producing a larger sample of skier locations. I suggest that with improved camera positioning and a higher sampling rate, this method is comparable to a GPS track produced by a skier. A consistent power supply and large data storage will increase the ease and limit disruptions in capturing images. This research utilized 64 MG and 128 MB memory cards which required filled after about 5 and 10 days of data. A larger storage device or remote-access could require less field-trips for data recovery. As well, the ability to capture data in low visibility conditions will increase data strength.

Creating a more automated workflow would greatly improve the efficiency of this method. Establishing a spatial reference early in the workflow is one option, however it was avoided in this study to accurately identify skiers in the photos which was more difficult following a transformation of the photo. A program that can identify skiers as images are captured could be of great value in avalanche rescue operations.

Despite these limitations and challenges, this approach has been shown to be effective in documenting terrain preferences of a cohort of LABC skiers on Saddle Peak, Montana.

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APPENDICES

APPENDIX A

ARC WORKFLOW

Workflow Development Narrative

All skier points were digitized to extract terrain information from skier locations in the images. Two methods were used. The first method manually identified skier locations through a series of photos, and the skier locations were recorded as tracks in Google Earth and resulting KML file. The KML track was then exported to ArcMap and terrain information was extracted. This was a tedious and inefficient process and encouraged further development of the skier location tracking using ArcMap.

The second method developed utilized a developed ARC toolbox. The Tool was designed to compare all the days photos against a single, selected photo. Any change in a pixel (the squares of color which make up the photo) represented a change from the original image. However, as the time a photo was taken became further away from the time of the original select image, all the pixels became slightly different. (There are several reasons this would happen, such as from wind shaking the camera or from changes in the focus. This limited processing to about 10 photos at a time, which did not improve efficiency. The toolbox was not an effective process and a more robust python script was written to compare each image against the image prior.

The python script was developed to compare successive images and identify pixels that had changed. The script creates a Point shapefile for every change it records. Following the identification of pixel changes by the Python script, skier points needed to be identified manually from other points that represented other pixel changes (trees moving, camera shift, etc.). With the assistance of the original images, all non-skier pixel change points were manually removed from each point shape file. At times, the script

would fail and stop before reaching the end of the day. The easiest way to solve this problem would be to identify which image number the script failed on, then repeat the process starting with the following image (skipping processing the image which caused the failure). As well, ensuring that the correct workspace was established and naming conventions were correct is a critical step in avoiding errors and successful processing with the python script.

The python script was a far more effective skier identification method. However, this process also required a high amount of manual processing, particularly in identifying which pixel changes were in fact skiers. The script is effective at identifying skiers and picks up minute shifts in pixels caused from natural processes (wind – trees and camera shake) or mechanical changes (lighting, focus) or non-skier movement (birds, planes). Manual identification of skier points was required. The python script produced the best results on calm, bright, clear days – days with high contrast and no shadows where the camera did not shake. In contrast shadows, particularly from clouds could be troublesome as were snowy and low contrast days where the script could not pick up the skiers in the clouds. On January 14, 2016 (the avalanche event) several skiers were not identified by the python script although they were identified in the photos.

Following the completion of the Python script, individual skier points were identified manually. Using the photos as aids, only point features that represented a skier were identified and selected. These selections were then exported as individual points such that for every image which contained a skier(s) a point file with the same image number was created with a point for every skier in the image. The Date and Image

number were added as attributes to each skier-point shapefile. All other identified point features not representing skier changes were removed. All images that did not contain a skier location point resulted in no points created for that image. The processes prior resulted in a File Geodatabase containing multiple feature classes corresponding to every image which contained at least one skier point. The NAME field, adding the original image number to each skier point, and Date fields were added.

Until this point, the whole process had occurred in an “Unknown” spatial reference of the two-dimensional image, the skier-points are unreferenced. After skier-location point files were created for every image on a field study, the points were then assigned a spatial reference.

Next, the points are transformed into a known coordinate system so that they can be associated with a DEM and corresponding terrain metrics. Ground-control points were established on the DEM and corresponding points were identified in the image creating a link file to use to spatially adjust the skier locations from the image reference frame onto a DEM with a known coordinate system. The link file was used in a projective transformation of the skier-location point features to the DEM.

Terrain metrics were extracted using 10 m resolution elevation data (1/3 arc-second) that was obtained from the USGS via The National Map (grdn46w111_13). This data was published in 2013 in geographic coordinates in decimal degrees the North American Datum of 1983 (NAD 83). Elevation data is recorded in meters and referenced in the North America Vertical Datum of 1988 (NAV 88). From the geo-referenced skier points, terrain information was identified. The terrain metrics identified were location,

elevation, slope angle, aspect, and curvature (downslope average and perpendicular average).

Workflow Steps

Python Script

1. Within the Study Day folder (i.e. "\\SaddlePhotos_1617\2017MAR\05MAR"), create 2 new folders "images" and "output".
2. The first photo of the day, IMG_####.jpg, is also located within the Study Day (05MAR) folder. All other photos should be in the "images" folder.
3. Save Python script in the Study Day (05MAR) folder and make appropriate name changes to first image, input, and output commands.
4. Save and run script.

Manual Skier-ID Selection

1. In ArcMap, Create Geodatabase: Named by date: YYmonDD (17MAR02 – March 2, 2017)
2. Select individual skier points
 - a. Compare and identify ski points. Select and rename skier points for every image; rename point after image number (ex. s1138)
3. Select Point, Right Click, Data, Export Data...
 - a. Name: s [img#] (ex. s1138 – image number 1138)
 - b. Save in new Geodatabase
 - c. Complete Excel file to accompany image numbers, start and stop times, notable information, etc.

Name Skier Points and create feature class containing skier points for whole day

4. In ArcCatalog, Add Field to each point that contains the point-name (image number i.e. s1138)
 - a. AddFileName Tool
 - i. ArcGIS Tool developed by the US Fish and Wildlife Service
 - ii. Input: is all skier points in days feature dataset.
 - iii. Field Name: NAME
 - iv. Result – each point has a new field which contains the image number (s1138)
5. Merge all skier points from day into a single feature class labeled by date (ex. mar022017).
 - a. Data Management Tools: General, Merge.
6. Add Date field to attribute table
 - a. Add feature class to ArcMap Layers

- b. Open attribute table, in table of contents Add Field...
- c. Name: Date, Type: Text
- d. Highlight new field, right click, Field Calculator...
- e. DATE = "mmmddyyyy" (ex. "mar052017")

Move data to a Feature Class set with a larger extent (prep for transformation)

7. Create New Geodatabase, named by date (Mar02_17_ref.gdb)
8. Within new geodatabase, create a new Feature Dataset (named by date mar022017).
 - a. In Spatial References, choose "New" and select "Unknown".
9. Import all skier points into the new Feature Dataset (previously merged data).
 - a. Ensure that all points have corresponding image number information.
 - a. Right-click on the Feature dataset and select Import, Feature Class (multiple)...
 - i. Input: select the merge (mar022017 point-file) from original geodatabase (17MAR02.gdb).
 - ii. Output: set to the newly created feature dataset (mar022017). This puts all the points into a feature class with a large extent, but not yet in the correct location.
10. Save and close ArcMAP.
11. Open blank ArcMap and establish spatial reference.
 - a. Open blank document, add projected DEM* to establish spatial reference.
 - b. Or set spatial reference: Projected, NAD 1983 (2011) UTM Zone 12N
12. Add Feature Data set, Start Editing
 - a. Select Editor toolbar, More Editing Tools and turn on Spatial Adjustment.
 - b. Start Editing
 - c. In Spatial Adjustment toolbar
 - i. Select: Set Adjust Data
 - ii. Select: All features in these layers: Select All (not Selected Features).
 - iii. Select: Links
 1. Open Links File, View Links table, view RMS error
 - a. Adjust ground control points, save changes to links file (links_mar022017.txt)
 - iv. Adjustment Methods – Transformation - Projective
 - d. Adjust data. Save Edits. Stop Editing.

Apply Terrain Metrics

13. Acquire DEM*
 - a. grdn46w111_13 – US Geological Survey thematic map
 - i. USGS NED n46w111 1/3 arc-second 2013 1 x 1 degree Arc Grid
 - ii. GCS NAD 83 (decimal degrees) (Geodetic Reference System 80); elevation (meters) NAVD 88

- b. In the original DEM raster data, the x, y coordinates are recorded in decimal degrees. The coordinate system is projected to NAD 1983 2011 UTM Zone12N so that x, y values are in meters.
 - i. Data Management Tools: Projections and Transformations – Raster – Project Raster
 - c. From DEM raster, produce aspect, curvature (including downslope and perpendicular), and slope raster. Elevation values are extracted from the projected DEM.
 - i. Spatial Analyst Tool: Surface - Aspect, Curvature (including down and perpendicular curve), Slope
- 14. In ArcCatalog, apply Raster values to skier tracks data.
 - a. Spatial Analyst Tools: Extraction – Extract Multi values to Points.
 - i. Aspect, Elevation, Down curvature, Perpendicular Curvature, Slope)
- 15. Add X, Y Values to data.
 - a. Data Management Tools: Features - Add XY coordinates.
- 16. Export attribute table to Excel file for analysis.
 - a. Conversion Tools: Excel - Table to Excel

Error Analysis

- 1. In ArcMap, Analysis Tools: Proximity – Buffer: create buffer bubble around GPS point to identify maximum distance recorded for a skier point location on a line.
- 2. Analysis Tools: Proximity – Near: Calculate distance and additional proximity information between the input features and the closest feature in another layer or feature class.
- 3. Spatial Analyst Tools – Interpolation – IDW

APPENDIX B

PYTHON SCRIPT

Python Script

With Damian Spangrud, Director of Solutions at ESRI

Description: This model iterates over collected images and does an image difference
and detects movement (skiers).

```
# Import arcpy module
import arcpy
# GetExtension
arcpy.CheckOutExtension("Spatial")
```

```
# Set the environments
from arcpy import env
from arcpy.sa import *
arcpy.env.overwriteOutput = True
```

```
#Print in the run window
print "starting"
```

```
# Change the following variables (InputFolder, OutputFolder, startvalue)
```

```
# CHANGE: Folder where the test data is
InputFolder = "C:\\Users\\Owner\\Desktop\\WorkArea\\04MAR\\images"
```

```
# CHANGE: Folder where to put the output
OutputFolder = "C:\\Users\\Owner\\Desktop\\WorkArea\\04MAR\\output\\"
```

```
# CHANGE: Set the name of the initial raster to compare only the 1st image against
startvalue = "C:\\Users\\Owner\\Desktop\\WorkArea\\04MAR\\IMG_2161.jpg"
```

```
# =====
# The are no more changes to the code
# =====
```

```
# TEMP filename of the output polygons - overwritten for each image
OutputShpPoly = "outputpoly.shp"
```

```
# prefix for the output POINT shapefiles Thisname_Imagename.shp
OutputShpPt = "Skier_"
```

```
# TEMP Output of Raster Calculator
rastercalc01 = "rastercalc01"
```

```

# TEMP Output of the reclass
re_Value_ = "reValue"

# Temp Polygon output
skipoly_shp = OutputFolder+OutputShpPoly

# Set the workspace to iterate over containing the JPGs
# NOTE this workspace is where the temp working files will go as well
arcpy.env.workspace= InputFolder

# Set the Old raster to be the fixed value for the 1st run
Older_Image.txt = startvalue
Older_Image= Raster(Older_Image.txt)

# List all the JPG files for each raster in the list of rasters
for SkilImage in arcpy.ListRasters("*", "JPG"):
    print "Using Image "+ SkilImage
    # Final Skier Point output
    skier01__Value__shp = OutputFolder+OutputShpPt+SkilImage
    print "Doing Image Difference"+ SkilImage +" minus "+ Older_Image.txt
    rastercalc01 = SkilImage - Older_Image
    re_Value = Reclassify (rastercalc01, "Value", "-1000 -50 1;-50 50 NODATA;50 1000
NODATA")
    # Process: Raster to Polygon
    arcpy.RasterToPolygon_conversion(re_Value, skipoly_shp, "SIMPLIFY", "VALUE")
    # Process: Feature To Point
    arcpy.FeatureToPoint_management(skipoly_shp, skier01__Value__shp,
"CENTROID")
    Older_Image = Raster(SkilImage)
    Older_Image.txt = SkilImage
print "Cleanup"
arcpy.Delete_management(skipoly_shp)
print "Done"

```

APPENDIX C

DATA INFORMATION

Data DictionaryDigital Images: Saddle Peak, Bridger Range, Southwest Montana, USA

Name: March 05, 2017

Date Taken: December 2015 – April 2016, January 2016 – April 2017

Source: Diana Saly, Montana State University Snow and Avalanche Lab

Description: Digital Photos

Coordinate System: Undefined

Spatial Resolution: (pixel size in raster)

Temporal Resolution: 2017/03/05 10:00-16:00, 10 second interval

Scale: n/a

Skier-Location Points

Date Taken: December 2015 – April 2016, January 2016 – April 2017

Source: Diana Saly, Montana State University Snow and Avalanche Lab

Description: Point Feature Class

Coordinate System: Unknown –NAD 1983- 2011, UTM Zone 12N

Datum: NAD 1983 - 2011

Spatial Resolution: unknown

Temporal Resolution: 2017/03/05 10:00-16:00

Scale: n/a

3D Elevation Program – Bridger Range, southwest Montana, 2017

Source: U.S, Geological Survey

Description: USGS NED 1/3 arc-second n46w111 1 x 1-degree ArcGrid 2017

Data Type: File System Raster, grdn43w111_13

Coordinate System: GCS - North American 1983

Datum: North American Datum 1983

Spatial Resolution: 1/3 arc Second (10 m 31026 by 18189 pixels)

Scale: no scale range

Natural-Color Aerial Photos of Montana, 2013

Source: Montana Geographic Information Clearinghouse, Montana.gov

Description: Photo Image (3233.sid), 2013 NAIP

Coordinate System: Montana State Plane – NAD 83

Resolution: 1 m

Scale: no scale range

Typical Metadata for Skier Locations

Skier locations were captured by camera in 10 second increments and digitized. Points were transformed and referenced in NAD 1983- 2011, UTM Zone 12N. 10 – 30 control links were utilized to transform a day of data (one data set created per day of skiers). 49 m accuracy was calculated from spatial error between links.

Name: mar052017 - March 05, 2017 Skier-location points

Type: Point Feature Class

Dates

Publication Date: 2018

Start Date: 2015-12-24

End Date: 2017-04-30

File Modification Date: 2017-10-08 17:16:00

Citation

Saddle Peak Time-lapse skier point locations, 2017, Diana Saly, Montana State University Snow and Avalanche Lab

Summary

Contacts

Originator: Diana Saly, Montana State University Snow and Avalanche Lab

Metadata Contact: Diana Saly, Montana State University Snow and Avalanche

Lab

Publisher: Diana Saly, Montana State University Snow and Avalanche Lab

Distributor: Diana Saly, Montana State University Snow and Avalanche Lab

Purpose

Skier location points can be spatially analyzed such that terrain information can be acquired and used to assess skier terrain choices against metrics such as forecasted daily avalanche hazard.

Map

[Saddle Peak Location Map, see Figure in paper]

Tags

Theme: Avalanche Research, Backcountry Skiing, Digital Photography, Heuristics, Saddle Peak, Skiing, Terrain, Time-lapse

Place: Saddle Peak, Bridger Range, Montana, USA

APPENDIX D

CONTROL POINT LINK TABLES

Link Tables

Link Tables for transforming skier-locations from the Image to the DEM. DEMx and DEMy are consistent for the corresponding GCP number on each Date.

CP	Date	ImageX	ImageY	DEMx	DEMy	Error
13	22-Feb-17	2297.723	-1259.41	505099	5071365	4.251061
14	22-Feb-17	2239.515	-1431.39	505223.8	5071414	7.885371
19	22-Feb-17	1927.372	-1994.16	505457.4	5071449	32.73692
20	22-Feb-17	2109.935	-1685.39	505374	5071495	50.09835
21	22-Feb-17	2616.348	-1237.72	505063.3	5071464	22.41775
22	22-Feb-17	2857.649	-1213.11	505055.4	5071552	14.4918
23	22-Feb-17	3019.574	-1180.57	505062.1	5071617	23.71799
24	22-Feb-17	3002.905	-1255.18	505105.8	5071626	5.927988
25	22-Feb-17	2880.668	-1357.57	505162.9	5071610	16.27764
26	22-Feb-17	2571.105	-1498.86	505241.1	5071544	21.82991
27	22-Feb-17	2641.748	-1633.01	505345.9	5071617	27.53437
28	22-Feb-17	2099.616	-1998.13	505450	5071499	29.15202
29	22-Feb-17	2462.361	-1829.06	505439.9	5071609	37.99831
30	22-Feb-17	2176.61	-2060.84	505474.1	5071537	20.61095
1	5-Feb-16	2230.016	-757.478	504946	5071136	13.42962
2	5-Feb-16	2350.402	-933.426	505047.2	5071227	5.063298
3	5-Feb-16	1946.779	-901.941	505034.7	5071075	18.04705
4	5-Feb-16	2046.792	-1094.82	505147.7	5071185	15.73775
5	5-Feb-16	2386.517	-1021.8	505100.9	5071274	4.863348
6	5-Feb-16	1855.498	-1088.47	505160.9	5071130	4.175547
7	5-Feb-16	1647.932	-1205.95	505245.2	5071120	10.0303
8	5-Feb-16	1416.553	-1383.75	505341.7	5071118	8.050118
11	5-Feb-16	2438.905	-765.415	504929.3	5071208	12.89193
15	5-Feb-16	1966.887	-1258.6	505269.1	5071241	10.06638
13	7-Feb-16	2786.161	-1064.78	505143.1	5071414	4.210025
14	7-Feb-16	2633.276	-1188.48	505223.8	5071414	19.8624
20	7-Feb-16	2470.293	-1505.98	505362.1	5071452	17.38034
21	7-Feb-16	3107.763	-935.275	505062	5071464	13.20396
22	7-Feb-16	3417.327	-896.911	505055.4	5071553	9.104265
23	7-Feb-16	3626.877	-862.515	505071.8	5071620	23.64261
24	7-Feb-16	3602.402	-948.368	505106.6	5071626	4.363909

25	7-Feb-16	3446.298	-1084.63	505164.5	5071608	18.23241
26	7-Feb-16	3018.598	-1111.75	505158.5	5071490	21.53255
27	7-Feb-16	3142.865	-1431.28	505345.9	5071617	20.23945
28	7-Feb-16	2454.947	-1899.07	505450	5071499	39.61009
29	7-Feb-16	2916.381	-1687.4	505439.9	5071609	23.91346
1	7-Jan-17	1861.913	-894.661	504934.1	5071140	24.1901
2	7-Jan-17	1982.915	-1091.1	505047.2	5071227	25.03858
3	7-Jan-17	1536.207	-1055.08	505034.7	5071075	0.418472
4	7-Jan-17	1645.723	-1270.59	505147.7	5071185	28.13914
5	7-Jan-17	2037.043	-1184.87	505098.4	5071271	32.27329
6	7-Jan-17	1433.786	-1258.26	505160.9	5071130	1.793999
7	7-Jan-17	1198.439	-1385.58	505245.2	5071120	18.42313
8	7-Jan-17	935.9716	-1584.23	505341.7	5071118	17.76101
9	7-Jan-17	710.943	-1669.56	505373.1	5071079	7.481402
10	7-Jan-17	722.0556	-1983.88	505522.7	5071213	54.12763
11	7-Jan-17	2075.969	-911.654	504921.7	5071218	22.53438
12	7-Jan-17	2378.389	-956.897	504985.4	5071354	27.67009
13	7-Jan-17	2358.545	-1137.08	505099	5071365	11.08957
14	7-Jan-17	2287.927	-1381.63	505223.8	5071414	7.57507
15	7-Jan-17	1534.895	-1526.33	505269.1	5071241	27.66504
16	7-Jan-17	1389.639	-1678.42	505366.9	5071264	13.1763
17	7-Jan-17	1096.656	-1954.55	505431.6	5071235	40.82027
18	7-Jan-17	1602.629	-1932.42	505437.5	5071376	5.524133
19	7-Jan-17	1839.431	-2174.51	505457.4	5071449	37.15813
20	7-Jan-17	2104.015	-1730.01	505365.3	5071452	12.17161
21	7-Jan-17	2809.308	-1099.86	505063.3	5071464	26.17405
22	7-Jan-17	3154.678	-1068.29	505055.4	5071552	16.57104
23	7-Jan-17	3389.628	-1028.6	505062.1	5071617	20.874
24	7-Jan-17	3357.878	-1125.44	505105.8	5071626	14.07273
25	7-Jan-17	3184.84	-1273.08	505162.9	5071610	5.206311
26	7-Jan-17	2749.864	-1473.1	505241.1	5071544	9.69736
27	7-Jan-17	2846.702	-1660.43	505345.9	5071617	43.20675
28	7-Jan-17	2076.366	-2160.99	505450	5071499	30.69636
29	7-Jan-17	2589.527	-1940.62	505439.9	5071609	48.96344
30	7-Jan-17	2189.476	-2260.5	505474.1	5071537	25.46353
1	8-Jan-17	1872.143	-913.964	504934.1	5071140	25.16108
2	8-Jan-17	1991.206	-1112.4	505047.2	5071227	26.35182
3	8-Jan-17	1549.034	-1072.4	505034.7	5071075	2.076661
4	8-Jan-17	1660.115	-1284.15	505147.1	5071186	26.54906

5	8-Jan-17	2028.459	-1205.88	505097.1	5071236	59.2378
6	8-Jan-17	1450.388	-1270	505160.9	5071130	1.3159
7	8-Jan-17	1224.962	-1397	505245.2	5071120	18.4133
8	8-Jan-17	963.5535	-1590.67	505341.7	5071118	19.20743
9	8-Jan-17	744.4781	-1678.51	505373.1	5071079	6.081642
10	8-Jan-17	760.3531	-1994.96	505525.9	5071213	52.09581
11	8-Jan-17	2084.437	-933.869	504921.7	5071218	24.26041
12	8-Jan-17	2373.362	-976.732	504985.4	5071354	32.0531
13	8-Jan-17	2338.437	-1141.83	505099	5071365	13.76828
14	8-Jan-17	2284.991	-1392.13	505223.8	5071414	9.265591
15	8-Jan-17	1551.565	-1533.95	505269.1	5071241	25.33679
16	8-Jan-17	1410.092	-1685.26	505366.9	5071264	13.35428
17	8-Jan-17	1125.664	-1955.14	505431.6	5071235	40.17663
18	8-Jan-17	1615.144	-1930	505437.5	5071376	7.187486
19	8-Jan-17	1849.301	-2165.48	505457.4	5071451	34.21485
20	8-Jan-17	2104.624	-1736.85	505365.3	5071452	14.17908
21	8-Jan-17	2799.355	-1118.77	505063.3	5071464	22.68197
22	8-Jan-17	3134.407	-1087.72	505056.9	5071552	11.24326
23	8-Jan-17	3313.288	-1052.15	505058.2	5071589	20.86992
24	8-Jan-17	3337.127	-1147.47	505106	5071626	15.0853
25	8-Jan-17	3162.104	-1285.58	505163	5071609	9.950951
26	8-Jan-17	2807.518	-1324.85	505162.5	5071518	18.15271
27	8-Jan-17	2834.369	-1667.16	505345.9	5071617	46.42459
28	8-Jan-17	2075.542	-2171.99	505448.4	5071489	38.91315
29	8-Jan-17	2586.718	-1941.8	505439.9	5071609	50.76688
30	8-Jan-17	2189.842	-2257.71	505474.1	5071537	25.96524
1	14-Jan-16	3092.974	-753.819	505060	5071604	14.3212
6	14-Jan-16	1386.183	-975.527	505160.9	5071130	14.10607
7	14-Jan-16	1175.32	-1090.08	505245.2	5071120	14.51439
8	14-Jan-16	938.2692	-1271.46	505341.7	5071118	14.69949
9	14-Jan-16	737.1355	-1357.66	505373.1	5071079	0.701718
10	14-Jan-16	755.0939	-1648.58	505524.5	5071213	49.86046
15	14-Jan-16	1482.408	-1213.99	505269.1	5071241	29.70906
16	14-Jan-16	1353.108	-1357.66	505366.9	5071264	8.85476
17	14-Jan-16	1083.732	-1598.3	505431.6	5071235	37.55766
18	14-Jan-16	1552.445	-1580.34	505437.5	5071376	6.461748
21	14-Jan-16	2628.152	-826.091	505063.3	5071464	29.5532
22	14-Jan-16	2933.575	-794.579	505055.4	5071552	18.34039
23	14-Jan-16	3130.458	-751.487	505062.1	5071617	18.19409

24	14-Jan-16	3119.303	-845.181	505105.8	5071626	7.64945
25	14-Jan-16	2961.969	-979.323	505164.5	5071608	3.340819
26	14-Jan-16	2577.868	-1160.12	505241.1	5071544	13.08976
27	14-Jan-16	2662.273	-1323.54	505345.9	5071617	38.65222
28	14-Jan-16	1976.263	-1790.46	505450	5071499	36.7263
29	14-Jan-16	2435.997	-1578.55	505439.9	5071609	42.41665
30	14-Jan-16	2067.851	-1876.66	505474.1	5071537	30.16154
1	15-Jan-17	1521.165	-946.526	504941.5	5071130	14.15682
2	15-Jan-17	1597.366	-1088.35	505047.2	5071227	29.21753
3	15-Jan-17	1275.632	-1060.83	505034.7	5071075	3.797129
4	15-Jan-17	1356.065	-1216.4	505147.1	5071186	24.3425
5	15-Jan-17	1631.894	-1152.68	505101	5071273	27.00088
6	15-Jan-17	1202.882	-1204.66	505160.9	5071130	7.723469
7	15-Jan-17	1038.311	-1303.09	505245.2	5071120	24.38997
8	15-Jan-17	845.1647	-1441.99	505341.7	5071118	33.9713
9	15-Jan-17	773.727	-1541.21	505373.1	5071079	33.48051
11	15-Jan-17	1670.155	-959.171	504932.3	5071255	40.14299
12	15-Jan-17	1894.787	-990.921	504985.4	5071354	13.50899
13	15-Jan-17	1865.418	-1116.33	505099	5071365	12.91771
14	15-Jan-17	1812.236	-1289.37	505223.8	5071414	12.97109
15	15-Jan-17	1280.939	-1398.7	505269.1	5071241	18.66498
16	15-Jan-17	1174.047	-1510.88	505366.9	5071264	21.4433
17	15-Jan-17	967.3363	-1705.4	505431.6	5071235	22.63851
18	15-Jan-17	1326.377	-1686.19	505437.5	5071376	20.96272
19	15-Jan-17	1496.239	-1843.36	505457.4	5071451	13.26654
20	15-Jan-17	1684.623	-1536.16	505365.3	5071452	26.93539
21	15-Jan-17	2186.274	-1092.72	505063.3	5071464	32.04941
22	15-Jan-17	2424.267	-1066.82	505056.9	5071552	18.5889
23	15-Jan-17	2592.454	-1046.12	505070	5071622	17.31392
24	15-Jan-17	2569.303	-1105.91	505106	5071626	12.19898
25	15-Jan-17	2447.286	-1210.77	505163	5071609	7.41936
26	15-Jan-17	2188.673	-1242.24	505162.5	5071518	19.58983
27	15-Jan-17	2211.507	-1484.42	505345.9	5071617	55.79614
28	15-Jan-17	1669.11	-1848.13	505450.1	5071499	15.13139
30	15-Jan-17	1767.27	-1979.54	505471.4	5071534	30.71245
1	2-Mar-17	1948.291	-1109.89	504934.1	5071140	24.27152
2	2-Mar-17	2043.599	-1254.97	505048.2	5071227	30.89352
3	2-Mar-17	1723.395	-1222.34	505034.7	5071075	1.974726
4	2-Mar-17	1804.093	-1378.44	505147.7	5071185	29.31767

5	2-Mar-17	2071.256	-1321.75	505098.4	5071271	34.26858
6	2-Mar-17	1651.362	-1369.38	505160.9	5071130	2.803249
7	2-Mar-17	1485.574	-1460.5	505245.2	5071120	18.27823
8	2-Mar-17	1297.19	-1602.32	505341.7	5071118	18.66634
9	2-Mar-17	1127.856	-1672.17	505373.1	5071079	5.541798
10	2-Mar-17	1145.848	-1891.24	505522.7	5071213	52.6952
11	2-Mar-17	2101.807	-1117.39	504921.7	5071218	21.65311
12	2-Mar-17	2324.057	-1154.43	504985.4	5071354	25.69466
13	2-Mar-17	2299.716	-1271.91	505099	5071365	13.81443
14	2-Mar-17	2260.557	-1455	505223.8	5071414	8.826222
15	2-Mar-17	1729.273	-1560.83	505269.1	5071241	29.67812
16	2-Mar-17	1626.614	-1670.9	505366.9	5071264	13.32512
17	2-Mar-17	1407.539	-1853.99	505431.6	5071235	32.12217
18	2-Mar-17	1769.49	-1851.87	505437.5	5071376	4.478023
19	2-Mar-17	1940.94	-2014.86	505457.4	5071449	34.47641
20	2-Mar-17	2130.382	-1705.82	505365.3	5071452	11.93359
21	2-Mar-17	2632.959	-1260.22	505063.3	5071464	30.49086
22	2-Mar-17	2877.732	-1233.63	505055.4	5071552	17.81067
23	2-Mar-17	3040.293	-1204.58	505062.1	5071617	19.63692
24	2-Mar-17	3021.243	-1271.25	505105.8	5071626	14.91929
25	2-Mar-17	2899.005	-1374.44	505162.9	5071610	6.470214
26	2-Mar-17	2589.442	-1520.49	505241.1	5071544	9.062296
27	2-Mar-17	2661.673	-1657.02	505345.9	5071617	41.51328
28	2-Mar-17	2116.101	-2015.26	505450	5071499	32.63206
29	2-Mar-17	2476.464	-1854.92	505439.9	5071609	48.45629
30	2-Mar-17	2198.651	-2083.53	505474.1	5071537	26.4828
1	5-Mar-17	1946.503	-1089.38	504934.1	5071140	23.38735
2	5-Mar-17	2033.286	-1233.84	505048.2	5071227	29.45064
3	5-Mar-17	1712.082	-1206.32	505034.7	5071075	1.82721
4	5-Mar-17	1791.457	-1360.84	505147.7	5071185	29.53776
5	5-Mar-17	2060.274	-1302.1	505098.4	5071271	34.34794
6	5-Mar-17	1640.115	-1349.73	505160.9	5071130	1.21136
7	5-Mar-17	1475.544	-1450.8	505245.2	5071120	11.25731
8	5-Mar-17	1285.572	-1583.09	505341.7	5071118	20.43704
9	5-Mar-17	1118.038	-1651.99	505373.1	5071079	10.09122
10	5-Mar-17	1134.971	-1871.06	505533.3	5071213	61.37665
11	5-Mar-17	2093.823	-1101.65	504921.7	5071218	23.65683
12	5-Mar-17	2310.782	-1132.34	504985.4	5071354	26.95016
13	5-Mar-17	2284.324	-1251.94	505099	5071366	14.89439

14	5-Mar-17	2247.282	-1435.03	505223.8	5071414	11.89323
15	5-Mar-17	1719.172	-1540.86	505269.1	5071241	28.68447
16	5-Mar-17	1612.281	-1649.87	505366.9	5071264	14.95102
17	5-Mar-17	1400.613	-1840.37	505431.6	5071235	37.87325
18	5-Mar-17	1759.389	-1834.02	505437.5	5071376	7.647433
19	5-Mar-17	1923.478	-2002.16	505439.9	5071462	48.2878
20	5-Mar-17	2119.422	-1684.6	505365.3	5071452	14.10097
21	5-Mar-17	2621.231	-1238.35	505063.3	5071464	30.76697
22	5-Mar-17	2862.532	-1214.54	505055.4	5071552	18.58971
23	5-Mar-17	3035.57	-1181.99	505062.1	5071617	21.83197
24	5-Mar-17	3010.17	-1255.02	505105.8	5071626	13.25465
25	5-Mar-17	2887.932	-1352.65	505162.9	5071610	7.507037
26	5-Mar-17	2575.194	-1501.88	505233.7	5071561	21.87212
27	5-Mar-17	2645.798	-1635.85	505330	5071638	51.39019
28	5-Mar-17	2101.236	-1994.31	505450	5071499	30.86176
29	5-Mar-17	2465.303	-1832.39	505439.9	5071609	49.08135
30	5-Mar-17	2184.844	-2064.16	505474.1	5071537	24.36389
1	20-Mar-16	1519.668	-691.909	504946.7	5071128	21.93601
2	20-Mar-16	1626.56	-871.826	505047.2	5071227	29.46104
3	20-Mar-16	1219.365	-832.138	505034.7	5071075	6.559508
4	20-Mar-16	1323.347	-1031.37	505147.7	5071185	29.63881
5	20-Mar-16	1670.216	-949.614	505100.9	5071274	26.24424
6	20-Mar-16	1130.465	-1021.05	505160.9	5071130	3.288451
7	20-Mar-16	920.9148	-1139.32	505245.2	5071120	15.13998
8	20-Mar-16	683.5831	-1321.88	505341.7	5071118	13.45718
9	20-Mar-16	590.7142	-1438.56	505409	5071137	24.9094
10	20-Mar-16	493.0827	-1685.42	505524.5	5071213	50.37808
11	20-Mar-16	1706.729	-703.815	504921.7	5071218	26.01155
12	20-Mar-16	2002.004	-738.74	504985.6	5071346	16.7965
13	20-Mar-16	1949.617	-894.316	505099	5071365	11.66392
14	20-Mar-16	1901.992	-1124.5	505223.8	5071414	7.338813
15	20-Mar-16	1233.653	-1267.38	505269.1	5071241	33.80771
16	20-Mar-16	1098.715	-1405.49	505366.9	5071264	9.562346
17	20-Mar-16	824.0771	-1629.33	505431.6	5071235	31.84165
18	20-Mar-16	1292.391	-1630.92	505437.5	5071376	4.361734
19	20-Mar-16	1504.273	-1832.27	505457.4	5071449	35.33735
20	20-Mar-16	1741.34	-1432.21	505362.6	5071453	13.16816
21	20-Mar-16	2370.785	-872.884	505063.3	5071464	27.0591
22	20-Mar-16	2676.644	-836.284	505055.4	5071552	13.21001

23	20-Mar-16	2877.286	-804.357	505067	5071617	25.13246
24	20-Mar-16	2856.12	-887.966	505105.8	5071626	16.11964
25	20-Mar-16	2698.428	-1021.32	505164.5	5071608	7.151439
26	20-Mar-16	2375.635	-1063.65	505160.9	5071519	23.84367
27	20-Mar-16	2407.386	-1368.45	505345.9	5071617	44.77229
28	20-Mar-16	1723.701	-1828.83	505450	5071499	32.0347
29	20-Mar-16	2183.018	-1625.63	505439.9	5071609	47.84098
30	20-Mar-16	1823.184	-1917.73	505474.1	5071537	26.34408

APPENDIX E

USING TIME LAPSE PHOTOGRAPHY TO MONITOR AVALANCHE TERRAIN

USING TIME-LAPSE PHOTOGRAPHY TO MONITOR AVALANCHE TERRAIN

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ABSTRACT: On January 14, 2016 an avalanche occurred on the Football Field of Saddle Peak in Southwest Montana. Saddle Peak is a backcountry slope, located immediately adjacent to the Bridger Bowl Ski Area boundary and accessed from the Bridger Bowl Schlassmans Lift. A time-lapse digital SLR camera mounted on an unused gun platform with a clear view of Saddle Peak captured the avalanche. Diana Saly (researcher) and Doug Richmond (Bridger Bowl Patrol Director) met at the gun platform where Richmond was initiating and coordinating the response. The team reviewed the images and assessed skier involvement within minutes of the event. Two skiers were photographed in close proximity to the avalanche during release and resulting avalanche. Both skiers were photographed returning to the ski area boundary following the avalanche and confirmed as not involved. A short video (2 min) was developed to document the January 2016 event and demonstrate the value of this technology for rescue and emergency situations. The data also provides an opportunity to document terrain use in different snowpack and avalanche conditions by travelers in easily accessed back country terrain.

KEY WORDS: time-lapse photography, backcountry, case study, terrain use

I. INTRODUCTION

Saddle Peak is located in southwest Montana, USA, in the Gallatin National Forest. Saddle Peak is directly south of the Bridger Bowl Ski Area which operates with an open boundary policy. The skiable slope below the ridge line to Saddle Peak is complex avalanche terrain with several start zones, mid-track cliffs, and frequent wind-loading. Saddle Peak is also easily accessed from the ski area and a compacted snowpack is common. With a favorable camera vantage point, Saddle Peak provides the opportunity to sample skier use of a backcountry environment.

On February 16, 2010 a large avalanche occurred on Saddle Peak. A storm the weekend prior to the avalanche brought 75 cm of snow with strong westerly winds to the Bridger Range. The avalanche hazard was rated Considerable by Gallatin National Forest Avalanche Center (GNFAC). The Schlassmans Lift had been closed for the storm and reopened Monday morning, February 16, 2010. Around 11:00 am a chunk of

cornice fell from the ridge of Saddle Peak onto the slope. It rolled downslope 30 m, where it initiated an avalanche approx. 300 m wide and 600 m long (Fig. 1). Reports estimated that 20-30 people were hiking the ridge at the time and several people had already skied the slope (Chabot, et al., 2010). Many personal cameras captured the avalanche. Several skiers were on slope performing transceiver searches immediately after the avalanche. Bridger Bowl Ski Patrol and Gallatin Country Search and Rescue responded with personnel and dog teams. No one was reported missing by 3:00 pm. Half of the feature did not run, putting the runout zone at risk. New snow was rapidly re-loading the slope throughout the day. The search was called off; no one was involved or injured. The response utilized a large number of responders in a high risk environment (Chabot, et al., 2010). Had the event been captured by a purpose specific camera, involvement could have been quickly determined and adding more people to the slope and subsequent search would have been deemed unnecessary. Search and rescue efforts could have been reduced and placing responders in hazardous terrain could have been avoided.

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Fig. 1: Picture of 2010 Saddle Peak Avalanche

Winter recreation in mountainous terrain has noticeably increased in recent years. Avalanches are one of the deadliest hazards threatening both recreationalists and professionals (Techel, et al., 2015). Backcountry terrain adjacent to ski area boundaries, referred to as sidecountry, provides easy access to complex avalanche terrain. From a snowpack perspective, there is little difference between sidecountry and backcountry; the most important factor is that neither is controlled avalanche terrain (Shockey, et al., 2014). Such areas can see high skier usage and avalanche occurrences. The adjacent resort is typically not obligated to respond to incidents which occur outside their boundaries. Placing personnel on slope can be hazardous and careful consideration is required when planning a rescue. Unwitnessed avalanches can be extremely hazardous as rescue efforts depend on fast response.

During the winter of 2015-2016, a time-lapse camera was installed at an unused gun platform to photograph skiers on Saddle Peak. A digital camera in weatherproof housing is a relatively low cost, low maintenance tool used to monitor high-use avalanche terrain. Once programmed and correctly mounted, the only limiting factors are power supply and image storage capacity, and visibility. This technology could be useful to first responders in avalanche emergencies in order to determine the number of people involved and their relative location with respect to an avalanche. Cameras could also be used to study terrain use by backcountry users, natural avalanche cycles in remote terrain, and start zones of frequent-flier avalanches to determine potential trigger spots.

2. STUDY AREA

Saddle Peak is located in the Bridger Range of Southwest Montana. The Bridger Range runs north-south; Bridger Bowl Ski Area (BB) utilizes the east side of the ridge. Saddle Peak is a short hike (approx. 30 min) up the ridge from the BB south boundary line. The Football Field is the northern (and closer) half of the east bowl of Saddle Peak, easily accessed from Bridger Bowl by riding the Schlassmans Lift and a shorter hike (10 min) along the ridge.

The east face of Saddle Peak is visible from the ski area; the face is divided in the middle by a sparsely treed rib feature. The large complex start zones are frequently wind-loaded. The entire feature is broken mid-track by large cliffs upwards of 60 m (Fig. 2). The run out features low angle terrain that runs adjacent to the ski area. A trail out leads back to the ski area.



Fig. 2: Annotated photo of Saddle Peak, February, 2016

Saddle Peak is an ideal slope to observe avalanche terrain usage. Accessible only via the ski area, use is dependent on when the BB Schlassmans Lift is open. Multiple groups hiking the ridge and skiers simultaneously on slope is common. The start zone slope angles (35-38 degrees) of Saddle Peak are stubborn to avalanche when steeper slopes are running. As well, constant wind-loading produces a notoriously a hard slab which further lowers the frequency of avalanching. The lack of frequent avalanching contributes to the lack of caution when skiing the terrain. The February 2010 avalanche incident highlighted the challenge of skiing avalanche terrain when there are numerous parties choosing to access the same area with limited regard for one another. Even with its complex start zones, constant wind loading, and close-out cliffs, Saddle

Peak is skied often and in a variety of snowpack conditions.

A gun platform, once used to control inbounds terrain along the ridge, provides a great view of Saddle Peak. A Canon Rebel EOS Digital SLR camera was installed on the gun platform in a weather-proof housing unit and programed to take one photo every 10 seconds between the hours of 10:00 am – 4:00 pm during the 2015-2016 winter season. An off-the-shelf time-lapse product made by Harbortronics was used (<https://www.harbortronics.com/Products/TimeLapsePackage/>). The camera captured a large portion of the east side of Saddle Peak from the ridgetop to the lowest traverse back into the boundary. The resolution of the images made tracking and identifying individual skiers possible, but was not detailed enough to pick up any distinguishing characteristics of skiers.

The easy access provided by Bridger Bowl allows users of varying ski/winter travel ability and avalanche knowledge to quickly find themselves in complex avalanche terrain with little effort. When an incident occurs on Saddle Peak, BB Ski Patrol are the first to be informed and closest response. However, as Saddle Peak is outside the ski area, the sheriff must first be informed and delegate ski patrol to become the Search and Rescue Team. Responder safety is a major concern in rescue response and efforts are made to minimize the number of people on slope.

Two unique case studies are presented where this time-lapse camera provided useful information for both operational safety and research applications.

3. CASE STUDY 1, OPERATIONAL

On January 14, 2016, the GNFAC reported 7-13 cm of new snow overnight with a forecasted 3-5 cm throughout the day. The GNFAC avalanche advisory rated all wind-loaded slopes at Considerable. A 15 cm basal depth hoar layer was topped by a 60-120 cm wind slab that had become increasingly harder to trigger in the days prior. The new snow did not produce a substantial load and was not forecasted to trigger a natural avalanche cycle. "New snow and wind overnight will make human triggered avalanches likely near ridgelines, and a poor snowpack structure make it possible to trigger a larger avalanche," wrote Alex Marienthal of the GNFAC January 14, 2016 (GNFAC, 2016).

The same morning Bridger Bowl Ski Patrol recorded 12 cm of new snow overnight (9% water content). Light south winds had resulted in small cornice growth and new snow was bonding well (Maleki, 2016).

At 11:39 am, skiers remotely triggered an avalanche on the Football Field of Saddle Peak. The time-lapse camera located at the BB gun platform photographed a pair of skiers skiing just outside the boundary appear to remotely trigger the avalanche from approx. 50 m away. It failed on a basal facet layer 15 cm above the ground, a layer that had previously run that season. The avalanche was 300-400 m wide with a crown depth of 30-60 cm. It flushed over the cliffs and left an impressive powder cloud over the valley (Fig. 3). The size 2.5 avalanche terminated far into the run out. Fortunately, the pair of skiers were not caught in the avalanche.

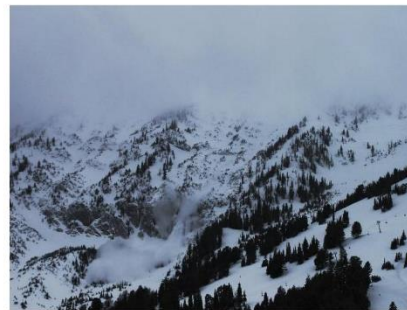


Fig. 3: Remotely triggered avalanche captured January 14, 2016.

However, the avalanche was not reported by the party triggered. The avalanche was observed by other members of the public and by the BB Ski Patrol, who then initiated their avalanche response plan. Ski Patrollers moved towards the south boundary line and top of the Football Field, the Schalassmans Lift was closed, and the GNFAC and search and rescue were alerted. Richmond (Bridger Bowl Ski Patrol) made his way to the gun platform to coordinate the response via radio. The gun platform provided an excellent view of Saddle Peak, the Football Field, and the run out. From his vantage point at the gun platform Richmond could see the crown line, but was unable to determine skier involvement.

Saly (Researcher) coincidentally arrived to perform camera maintenance and swap the data cards. Upon arrival, the memory card was pulled from the camera and the photos reviewed. Although clouds hid the crown line, the majority of the avalanche was still visible. The camera photographed a pair of skiers in close proximity to the fracture line prior to and during the avalanche initiation. As the avalanche released and moved past them, the pair of skiers were documented moving away from the Football Field and back to the ski area. Richmond and Saly were able to determine the avalanche had moved past the pair without involvement and that the pair had safely returned to the ski area.

With the information provided by the camera, BB Ski Patrol was able to reduce their level of avalanche rescue response. There was still significant hang-fire left in the Football Field and responder personnel were hesitant to enter the terrain without some level of avalanche mitigation.

A video of the avalanche can be viewed at <https://youtu.be/cipDJANpp-A>.

4. CASE STUDY 2, RESEARCH

In this second case study we review the terrain use of a group in the backcountry environment as captured with our camera. On Sunday, February 14, 2016 the GNFAC rated the avalanche hazard Considerable for slopes steeper than 35 degrees. In the 24 hours prior, 15-20 cm of snow had fallen in the Bridger Range. The snowfall overnight had a high moisture content (20 mm SWE) and was accompanied by moderate southerly winds. During the day, more snow was expected and winds forecasted to shift north-westerly. A dense and stubborn wind slab was the primary avalanche concern.

On February 14, 2016 several skiers were captured departing BB and hiking the ridge to Saddle Peak. A variety of lines were captured, two common areas were identified: (1) The BB boundary line and the skiers left of the Football Field, and (2) The east running ridgeline from Saddle Peak. Skiers also accessed the terrain by traversing low into the Football Field or skiing the low angle run out below the cliffs (Fig. 4).

Even under considerable hazard, solo skiers hiking and skiing Saddle Peak are common.

Groups act chaotically, with limited backcountry discipline and etiquette, initially skiing one at a time, then together stopping mid-slope. In large groups, the skiers at the back tend to drop on slope sooner than the initial skiers.



Fig. 4: The backcountry terrain immediately adjacent to Bridger Bowl, highlighting common terrain use above the cliffs: (1) the BB boundary line and Football field; and (2) the east running ridge line from Saddle Peak.

In particular, at 11:48 am on February 14, at least 15 skiers were captured along the Saddle Peak ridge. Two skiers were positioned atop Saddle Peak. Another skier was positioned directly above the middle of the Football Field and a group of five was positioned above the southernmost line still within BB Ski Area.

In this example, we observe as the first skier (BB1) on slope descends from the group above the in-bounds line. BB1 skis the gully feature and stops at the tree line still in bounds. The skier centered above the Football Field (FF1) follows. FF1 center-punches the bowl, skiing the center fast and aggressively. FF1 pauses above the cliffs then negotiates the edge of the cliffs along the BB boundary line and skis the runout below the Football Field (Fig. 5). The full line takes approx. 4 min. Shortly after FF1 drops into the Bowl, the large group on the in-bound line skis the terrain fast, meets up with BB1 and departs.

At the same time the first skier (SP1) from the pair on Saddle Peak drops in. SP1 skis the ridge line and stops at the tree line. SP2 skies a more exposed line towards the center of the bowl. The line is fast and aggressive line to the first set of rocks, SP2 then traverses right to meet SP1. The pair pauses mid-track, then moves together downslope through the rocks and trees and back to the ski hill (Fig. 5). Interestingly, FF1 drops in

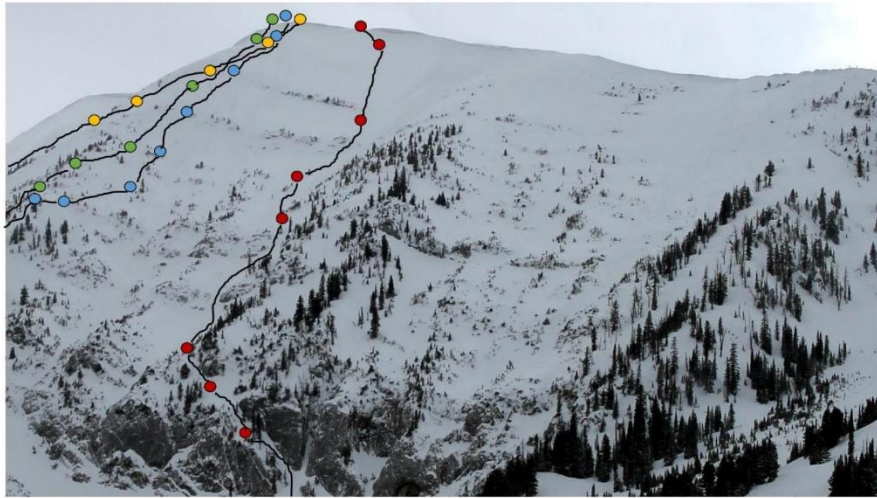


Fig. 5: The skier tracks of SP1 (blue), SP2 (orange), FF1 (green), BB1 (yellow). FF1 and SP1 ski the slope in unison.

almost exactly the same time as SP1, 450 m away; SP2 follows on slope 30 seconds later.

Approximately 12 minutes later as the skiers finish their lines, the camera captures more skiers on the ridge. A group of three (S1, S2, S3) positioned at the top of Saddle Peak; another skier (S4) approx. 100 m down the ridge next to the large cornice. The first skier (S1) drops from the peak and skis the southern ridge line stopping in some trees. The next skier (S2) descends from the peak and skis the first gully feature off the ridge line. As S2 and S1 regroup, both S3, positioned on the Peak, and S4, positioned down the ridge, drop in simultaneously. S3 follows the ridge, then skis right into the gully hidden from view away from S1 and S2 posted in the trees along the ridge. S4 skies an aggressive line down the center and out via the diagonal line through the middle of the cliff ban (Fig 6).

When S4 is still 100 m above the cliffs, another skier (S5) is captured descending from Saddle Peak. S1 and S2 are 300 m down slope of S5. S5 stops above the tree line and is then joined by another skier (S6) from Saddle Peak. The duo skis together into the gully which is hidden from the camera view. We note that simultaneous exposure

of multiple skiers to the same avalanche path is frequent from Saddle Peak.

Overall, 145 people were captured skiing Saddle Peak on Sunday, February 14, 2016. The camera captured 34 solo skiers, 25 pairs, 11 groups of three and 6 groups larger than three. 81 people skied the terrain off Saddle Peak, 21 people skied the Football Field and 34 skied along the boundary line.

5. DISCUSSION/CONCLUSION

Time-lapse photography is a simple and inexpensive method to document usage in avalanche terrain. It is a beneficial way to study the snowpack for three reasons: aiding in avalanche rescue response, documenting backcountry usage, and documenting avalanche occurrences. We propose that well placed time-lapse cameras like the one presented here would aid avalanche rescuers and researchers in other locations with similar backcountry challenges.

Time-lapse photography can be a powerful tool in avalanche rescue response. A camera can document avalanches occurring in heavily used avalanche terrain, such as slopes easily accessed from a ski area or highway. The images can assist

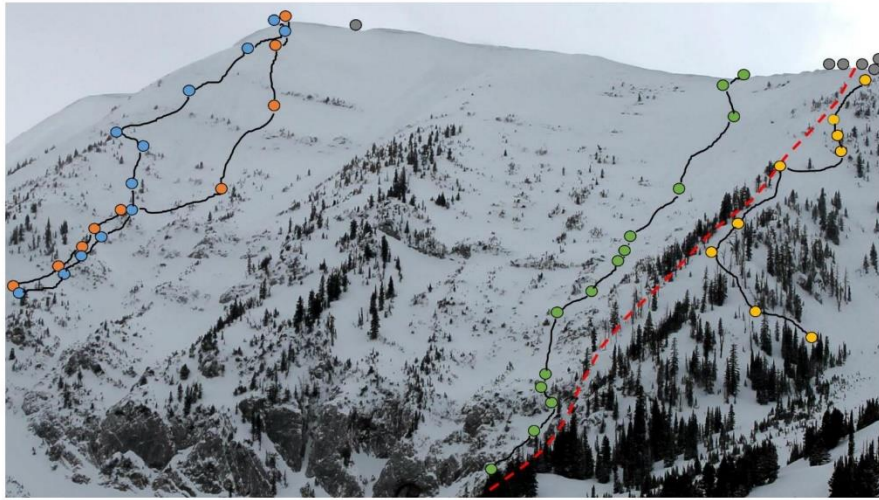


Fig. 6: The first four skier tracks of S1 (green), S2 (blue), S3 (red), and S4 (yellow). S1 and S2 act as a group, S3 and S4 ski the slope simultaneously following very different lines.

with determining the avalanche trigger and trigger location, the number of people involved and total group number, and provide a last seen point in the case of an avalanche involvement. Images can also provide a visual tool to determine residual hazards like hang fire. Well-placed cameras could assist in determining the amount of response needed in an avalanche event. This could be a critical factor when a rescue involves placing emergency responders in hazardous terrain. In heavily skied backcountry areas, a remotely accessed camera could quickly assist in rescue efforts. Cameras may also be helpful in the case of lost skiers.

A time-lapse camera monitoring avalanche terrain can also be beneficial outside of rescue efforts. From the gun platform, the Saddle Peak camera can document the total number of people who access Saddle Peak, what line they ski, and where they access the peak from (i.e. do they traverse on skis across South Bowl or hike the ridge to the peak?). Such information could provide insight into what factors affect a decision to leave a ski area boundary.

One concept of decision making by groups asserts the superiority of crowd averages over individual judgements (Surowiecki, 2004). However, this

“wisdom of the crowd” effect is largely contingent on the lack of social influence which undermines decisions (Lorenz, et al., 2011). This requires members make decision independently. The high number of Saddle Peak users suggests that independent decision making is not possible due to the high visibility of current skiers and previous tracks. In the case of Saddle Peak, do tracks result in a rise in skier traffic? Would less people ski Saddle Peak (and the Football Field) if the terrain was not visible from Bridger Bowl?

A camera provides visual documentation of an avalanche. Rather than documenting that an avalanche has occurred due to visual clues, the camera provides a full account of the event including anything that occurs prior to propagation such as weather events and impact by people. As such, this also can identify avalanche triggers and timing of the avalanche. The camera is limited by visibility issues, so terrain must be viewable from the camera location and the weather and light conditions must allow for a clear, or mostly clear view. An infrared camera could be considered for locations where inclement weather would regularly reduce visibility.

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APPENDIX F

THE EFFECTS OF COMPACTION METHODS ON SNOWPACK STABILITY

THE EFFECTS OF COMPACTION METHODS ON SNOWPACK STABILITY

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ABSTRACT: The interaction between snowpack layers determines the snowpack stability. It follows that disrupting layers may improve stability. Ski patrols and guiding operations employ mechanical compaction methods such as boot packing, ski compaction, and explosives aiming to increase snowpack stability. High-usage backcountry areas (but still uncontrolled avalanche terrain) may become compacted, developing a snowpack with different characteristics than in lower usage adjacent terrain. A challenge in avalanche forecasting is determining how this compaction alters snowpack stability, if at all.

Our results show that snow pack stability increases if compaction penetrates and impacts a weak layer, disrupts the failure plane, or affects slab cohesion. This is likely due to an increased probability of fracture arrest in a compacted snowpack from either slab or weak layer heterogeneity. While several compaction methods exist, specific research addressing different compaction techniques is lacking. This study compares the effects of different compaction methods on a snowpack. The snowpack for our case study consisted of an approx. 30 cm 1F wind slab over approx. 30 cm depth hoar. After applying mechanical compaction methods to nine slopes, we conducted ECTs and PSTs over six weeks to assess stability. We found ECTs more common in compaction-dense areas (boot packed) than in compaction-light (skied and compaction free) areas.

This research quantifies some of the effects of different compaction strategies, and provides preliminary guidance for avalanche practitioners on the most useful techniques for mitigating avalanche hazard.

KEYWORDS: compaction, snowpack stability, stability test, boot-packing, ski compaction

1. INTRODUCTION

Natural compaction occurs within a mountain snowpack due to snow metamorphism, wind, and settlement. Temperature, liquid water content, and layer depth are major factors which drive natural snow pack compaction. Compaction is a natural process of the winter snowpack; compaction over multiple seasons eventually produces glacier ice (Armstrong and Brun, 2008).

Mechanical compaction is the result of a non-natural settlement and impact to the snowpack – skiers, explosives, snow machines, etc. Mechanical compaction is a quicker, but more

localized process of snowpack compaction.

Mechanical compaction deforms the snowpack by disrupting snowpack layers. The resulting heterogeneous snow structure may increase snowpack strength and also may enhance fracture arrest (Kronholm and Birkeland, 2005). The resulting effect of mechanical compaction on snowpack stability is dependent on the depth of the compaction, the vertical position of weak layers within the snowpack, the amount of compaction, and the coverage of the compaction throughout an area.

Ski patrols and guiding operations employ mechanical compaction methods such as boot packing, skiing, and explosives aiming to increase snowpack stability. Compaction methods are intended to disrupt the shear plane of potential avalanches and decrease the cohesiveness of possible slab layers (Carvelli, 2008). Our research

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seeks to address how mechanical compaction may affect snowpack stability in uncontrolled avalanche terrain.

Compaction efforts such as boot packing, ski cutting, and explosives begin in controlled avalanche terrain as soon as the first snow falls. Aspen Highlands in Colorado has employed systematic mechanical compaction (bootpacking, explosives, etc.) in specific avalanche terrain for over 20 years effectively eliminating the occurrence of large avalanches in such terrain (Carvelli, 2008). Furthermore, preliminary work by Wieland et al. (2012) suggests that compaction can be successful in removing the instability from a basal weak layer as measured with an Extended Column Test (ECT). Their work suggested that effective boot packing can result in several weeks of difference between ECT N (arrest) and ECT P (propagation) results (9 weeks in their study). The end result of avalanche control methods (compaction by boot packing, skiers, and explosive testing) is to create a non-stratified snowpack by completely disrupting or destroying any potential sliding layer or interface, resulting in only surface instabilities created by new snow and wind (Carvelli, 2008).

With increased backcountry usage, the snowpack in popular skiing areas can quickly become compacted, though not nearly as heavily compacted as the snowpack within a ski area. Variable usage patterns, such as increased use on weekends or holidays, can produce a different snowpack than in the surrounding areas and regional avalanche forecast. A concern for some backcountry forecasters is the development of a false sense of avalanche knowledge and confidence in recreationalists who learn and progress in such high-usage backcountry areas. As users progress and explore, they eventually leave such high use areas and move into less-compacted terrain, where the regional avalanche forecast is more representative and the snowpack more variable. A major challenge presented to avalanche forecasters is how to communicate avalanche hazard in a region that has both areas with minimal usage and compaction and areas that have extremely high usage and a heavily disturbed snowpack. To date, there is little

research focusing on the effects of different methods of mechanical compaction on snowpack stability. This research examines the effect of three different methods of compaction (bootpacking, ski compaction, and skiing) on snowpack stability. Our aim is to provide preliminary guidance for avalanche practitioners on methods for assessing snowpack stability in compacted terrain.

2. STUDY AREA AND METHODS

The study area is a summer road within the boundaries of the Yellowstone Club in SW Montana, USA. The site is a planar slope with an average slope angle of 10 degrees below tree line at an elevation of 2690 m on the west side of the ski area. The access to the site was restricted and no unaccounted tracks were recorded. Along the road 13 plots (1 - 10 m x 10 m study plot and 12 - 5 m x 5 m test plots) were isolated and marked with rope (Fig. 1).



Fig 1: The study area at the Yellowstone Club. 5 m x 5 m study plots are identified by color: Ski – red; Compaction Free – yellow; Ski Compaction – green, Boot Pack – blue. The 10 m x 10 m study plot is outline in black. Aspect is W-SW; slope angle varies from 8-15 degrees.

Test plots were divided into three groups of four. Each group contained three different compaction method plots (Boot Pack, Ski Compaction, Ski) and one plot with no compaction (Compaction Free). The Boot Pack test plots were compacted so that footprints were spaced no more than 20 cm from each other. The Ski test plot was skied through 5-6 times with two turns such that it would be considered 'tracked out' in a back country

setting. Ski Compaction test plots were side-stepped so that the entire surface had been compacted by a ski. Mechanical compaction was performed by three individuals 68-77 kg, on skis 108-120 mm underfoot.

Each compaction method was used in three plots (a total of nine compaction plots). At this time, the 1 m deep snowpack structure consisted of basal facets and depth hoar buried under a denser mid-pack and low-density surface snow. A layer of interest was identified approximately 30 cm above the ground where a 1F wind slab sat on basal facets and depth hoar. Following the one-day compaction event, access was restricted to the entire area. Figure 2 displays a Compaction Free and Ski plot.

Over the course of six weeks (January 7 - February 17, 2016), nine field days occurred. A field day consisted of a full profile in the undisturbed study plot and four test profiles in one group of plots (three different compaction method plots and one compaction free plot). A single observer conducted every test for consistency and followed the standard procedure for Extended Column Tests (ECT), Propagation Saw Tests (PST), and Compression Tests (CT) (ORGS 2014, SWAG 2010). A test profile included layer identification and hardness, 10 cm snow density measurements, one CT, two ECTs, and one PST. Including the study plot, 90 ECTs, 45 CTs, and 35 PSTs were collected over nine field days.



Fig. 2: Compaction Free and Ski 5 m x 5 m plots. January 7, 2016

3. RESULTS

For this paper, we focus on the overall ECT and PST results and the danger rating provided by the Gallatin National Forest Avalanche Center (GNFAC). In an effort to provide relevance to current practices only a sample of our results will be presented with a more complete analysis to be presented later. One specific area of interest is the effectiveness of boot packing against skier compaction and the duration of time for which one is more effective than the other.

On all field days, the GNFAC rated the hazard in the Madison range either Moderate or Considerable (GNFAC, 2016). A weak basal facet layer below a dense slab was a constant concern. We found this layer 24-38 cm above the ground in the Study Plot. All ECTs and PSTs tested this layer.

Our results suggest that compaction dense methods (e.g. boot pack, ski compaction) are more effective than compaction-light methods (e.g. skiing) for this particular snowpack structure. We used ECT and PST results to index snowpack stability and interpret results (Ross and Jamieson, 2008) (Gauthier and Jamieson, 2008).

3.1 *Extended Column Test Results*

Ten ECTs were performed across five plots daily (Study Plot, Compaction Free, Ski, Ski Compaction, and Boot Pack). Over the nine field days, a total of 90 ECTs were performed. Overall, Boot Pack plots had the most ECTXs (13 of 18 – 72%), suggesting the lowest chance of propagation on a given day. The Compaction Free and Ski plots had the most ECTPs (both with 10 of 18 – 56%) and the Compaction Free had the fewest ECTXs (3 of 18 – 17%) (Fig. 3).

Total depth of the snowpack (HS) increased from approximately 95 cm at the top in the Study Plot to an average of 118 cm in the test plots at the bottom of the study area at the beginning of the study (Fig. 1). A large difference in overall ECT scores was observed between the Study Plot (compaction free) and the Compaction Free test plots (Fig. 3), with a larger proportion of propagating ECTs in the test plots. We propose

that this is due to the spatial variability of HS along the length of the study area – with much shallower snow at the study plot, and relatively deeper snowpack test plots at the bottom of the study area. ECT results indicating poor stability were observed in compaction-free and compaction-light (Ski, Ski Compaction) plots.

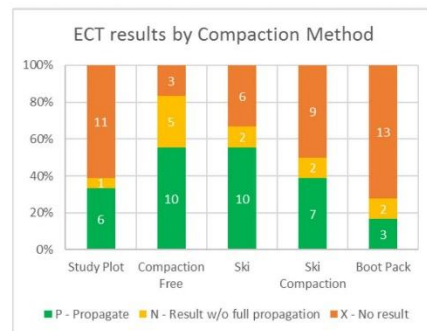


Fig. 3: ECT Results for the Study Plot and Test Plots as a function of the compaction methods.

3.2 Propagation Saw Test Results

A total of 35 PSTs were performed on the identified layer of interest (approx. 30 cm above the ground). Every PST resulted in propagation to the end of the column (PST End). For all compaction methods, 45 cm was the average PST cut length (Fig. 4). The Boot Pack plots had the longest average cut length of 59 cm.

The Compaction Free plot recorded the second longest average cut length of 48 cm. In contrast, the Study Plot produced the shortest average cut length of 36 cm. In contrast, the Study Plot ECT scores indicated a more stable snowpack than the Compaction Free plots.

4. DISCUSSION

Our study shows three methods of compaction had notably different impacts on stability, as indexed with the ECT and PST results. ECTX results increased as compaction methods became more penetrative, with boot packed plots having the greatest proportion of ECTXs. Most striking is the large difference in ECT scores between Boot Pack and the Compaction Free plots.

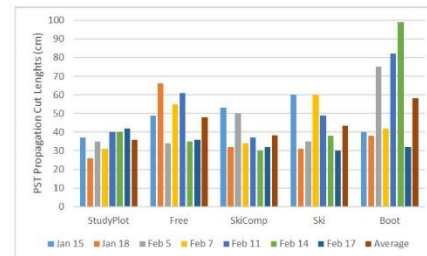


Fig. 4: PST Propagation cut lengths by compaction method

A similar study found a notable increase in ECT scores and poor fracture character in boot packed terrain compared in compaction-free terrain (Wieland, et. al, 2012). In their study, ECTs in compaction-free terrain propagated a full nine weeks longer than in the boot packed terrain. Our study produced more mixed results. Boot Pack plots were less reactive compared to other plots. However, our compaction methods did not completely eliminate the weak layer.

In some cases, ECT results in Boot Pack and Ski Compacted plots resulted in breaks within the compacted layer. These breaks sometimes resembled a boot print or ski track. Such breaks were also documented by the Aspen Highlands bootpacking program (Heineken, 2004). In our study, at times boot packing and ski compaction methods appeared to produce higher density and more cohesive blocks of snow. These results, along with the lack of similar results in the Ski plots, suggest that the concentration and density of the disruption are also important in compaction.

Compaction methods at Aspen Highlands stress that shear plane disruption is the primary goal of compaction measures (Carvelli, 2008). In order to achieve this, compaction measures begin early in the season. In our study, compaction methods were applied in January to an approximately 1 m deep snowpack with a weak layer buried by 70 cm of snow. We also noted a gradual increase in HS downslope through the study area. Compaction methods were less effective downslope in the relatively deeper snowpack. Shear plane disruption was not always achieved as compaction

methods did not penetrate deep enough into the snowpack. In some compacted plots (Ski Compaction), we increased the density and cohesion of the slab above the layer of concern, while not impacting the weak layer. In other compacted plots (Boot Pack), we had more success with compaction penetrating to the weak layer and resulting in more ECTXs.

5. CONCLUSION

This study assessed the impact of different compaction methods on a particular weak layer. We conducted ECTs and PSTs in areas with varying amounts of compaction and compared those results to danger ratings in regional avalanche advisories. Overall, tests in heavily compacted terrain (Boot Pack) indicated a more stable snowpack than compaction-free terrain. Terrain we skied and ski compacted had more intermediate and variable ECT scores.

Determining snowpack stability in compacted terrain is dependent on many factors including the type of compaction (skier, explosives, boot packed, etc.) and the density of the compaction (i.e. a single skier track versus a heavily-used snowmobile compacted slope). As well, snowpack stability tests have been validated in compaction-free terrain. Determining the effectiveness of snowpack stability tests in compacted terrain is suggested as an area for future study.

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