REMOTE ANALYSIS OF AVALANCHE TERRAIN FEATURES: IDENTIFYING ROUTES, AVOIDING HAZARDS

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The threat of avalanches to winter recreationalists and mountain communities is well known. Geographic Information Systems (GIS) technology has been used to augment avalanche forecast and control programs in many parts of the United States and Europe. Successful GIS approaches combine terrain modeling, historical avalanche data and avalanche flow modeling to identify and predict avalanche probability and intensity for relatively small geographic areas (e.g., highway corridors, commercial ski areas and municipalities) (McCollister & Birkeland, 2006). However, little research has focused on the vast backcountry areas between such small, populated areas. With the advent of lighter, better equipment for both backcountry skiers and snowmobilers, recreationalists increasingly visit these areas and are at risk from avalanches. Thus, an effort to reevaluate and improve avalanche risk information available to winter recreationalists is warranted. This study developed and evaluated geoprocessing methods using readily available and inexpensive spatial data to identify two terrain features of particular importance in evaluating avalanche risk, depositional terrain traps and trigger points. Forest density layers for display and geoprocessing purposes were also created from several data sources. Avalanche terrain hazards were identified from slope curvature models where areas of aspect change were filtered out along with moderate and heavy forest and low angle slope areas. Field trials confirmed that such methods could improve decision making and route finding in winter backcountry areas.

CHAPTER ONE: INTRODUCTION

While skiing, snowshoeing and snowmobiling have long been popular winter recreational pursuits, the vast majority of past usage has been confined to relatively small areas. Skiers and snowshoers generally recreated at ski areas or winter parks. Snowmobilers were generally confined to valley bottoms and adjacent slopes due to equipment capabilities and few formalized avalanche awareness skills. In the last 10-15 years, advances in alpine touring and telemark ski equipment coupled with the wider availability of avalanche rescue equipment and awareness skills have led to a veritable explosion of newcomers to the winter backcountry (Haug, 2012). Snowmobiles have also evolved from heavy, unreliable machines with limited abilities to relatively lightweight, dependable, and powerful machines capable of climbing steep slopes in deep snow conditions. It is increasingly the norm for skiers to spend considerable time in either the backcountry or the sidecountry (e.g. unpatrolled areas adjacent to formal ski areas) (Welch, 2012). Even occasional snowmobilers no longer just putter along groomed trails but aggressively push into the high country seeking steep slopes and untracked powder to play in.

Avalanche conditions are a highly variable phenomenon that can change dramatically from day to day, week to week and no two winters being exactly the same. In response to this variability and the increased interest in the backcountry, avalanche forecast centers have been expanded in both scope and number. Avalanche forecast centers in the United States generally consist of several professionals who prepare daily or weekly avalanche forecasts for a region based on remotely and manually collected data and to limited extent anecdotal observations volunteered from backcountry users. Remote weather stations gather and transmit hourly temperature, wind speed and direction, relative humidity and dew point data while SNOwpack TELemetry (NRCS 2013) sites gather and transmit the same data as well as snow depth and snow water equivalent. Field data include a full or partial analysis of snowpack depth and layering as well as snow instability tests such as an extended column test (American Avalanche Association, 2009). Forecasts consist of a discussion on recent and expected weather, the condition of the snowpack highlighting dangerous layers or weaknesses, an evaluation of the most likely dangers (i.e. wind slab, storm snow or persistent weak layer) and a scaled evaluation of each danger's probability and potential (SNFAC, 2013).

In addition to the temporal variability of avalanche conditions there is a tremendous geographic variability that changes by aspect, elevation, mountain and range. Even slopes with similar aspects and elevations on adjacent mountains can produce radically different avalanche conditions (McCollister & Birkeland, 2006).

A conceptual visualization of some of this variability is expressed in the "danger rose", an avalanche risk matrix that divides terrain into eight aspects and three elevation zones, resulting in 24 aspect/elevation zones (Figure 1). Each zone is assigned a color corresponding to the avalanche danger scale as shown in Figure 2.

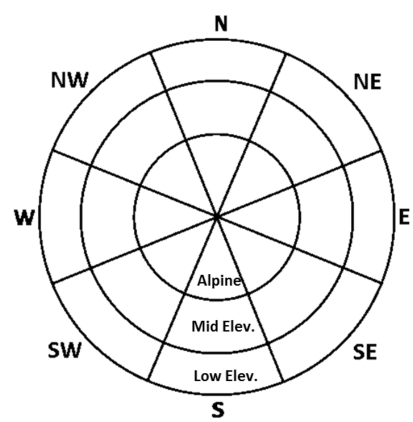


Figure 1: An avalanche danger rose in which topography is divided into three elevation bands and the eight cardinal and sub-cardinal aspects.

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.			
No Rating	Insufficient information to establish avalanche danger rating. Check zone forecast for local information.		

Figure 2: The North American Public Avalanche Danger Scale (CAIC (Colorado Avalanche Institute Center), 2013).

All avalanche forecast centers stress that translation of conceptual danger models and forecast predictions to on the ground conditions is neither easy nor intuitive. It requires education, experience and skills available through avalanche awareness classes. There are several organizations that teach avalanche awareness and curriculum varies from organization to organization. However, all education focuses on recognizing signs of instability or recent avalanche activity, decision-making and safe travel protocol (AIARE, 2013). One important skill necessary for winter backcountry users is the ability to read a topographic map and make good route finding decisions based on them.

Avalanche risk is based on both snowpack instability and terrain. Although there are snowpack stability models (Kronholm & Birkeland, 2005), these models require data on local conditions that are difficult to track in the backcountry. The data on snowpack must be gathered in remote country, and may change dramatically over time. However, terrain (topography and forest cover) with the exception of forest fires or landslides, is relatively consistent over time. While the risk in many areas of the backcountry can fluctuate, i.e. with snowpack condition, there are areas that are always dangerous or that have lower risks relative to surrounding terrain, thus progress in incorporating terrain features may improve risk modeling even if the precision in space and time of snowpack data is limited (NRCS 2013a).

In the lexicon of avalanche terminology “terrain traps” is a catch all term describing terrain features that compound the risks of an avalanche. Rollovers are areas where a slope convexity increases tension in the snowpack increasing the likelihood of triggering an avalanche. Steeply sided gullies concentrate debris and increase burial depth, which increase rescue times reducing survival rates (Haegli, Falk, Brugger, Etter, & Boyd, 2011). In contrast to these traps other features such as ridges generally offer the path of least risk. Assuming the right data and methods are employed, a GIS may be able to identify and isolate these terrain features, and contribute to better modeling of avalanche risks in the winter backcountry.

1.1 Project Scope

This project tested the viability of identifying two hazardous terrain features common in avalanche country: depositional terrain traps (steep sided gullies) and trigger points (rollovers). Methods for identifying these features were produced and evaluated using bare-earth topographic data and land cover type data. Bare-earth topographic algorithms were developed and applied to 30 meter and 10 meter DEM datasets. As forest cover is a major component of avalanche activity because heavy timber inhibits avalanche initiation and propagation (Schaerer and McClung 2006, 93), various datasets that can be used to determine vegetation cover were compared. These datasets are: 1) publicly available land cover datasets, 2) forest cover datasets created from 1 meter resolution color Digital Orthophoto Quadrangles (DOQs), 3) a land cover dataset produced by the Sawtooth National Forest (SNF), and 4) Digital Raster Graphics (DRG) of 1:24000 USGS topographic maps. The objectives of this study were to develop a process creating two avalanche hazard layers depicting potential trigger points and depositional terrain traps, as well as create or use an existing vegetation cover datasets as a filter for trigger points and as a thematic display of forest display. Finally, this study sought to accomplish the first two objectives using data that is available to the public and is relatively inexpensive such that a similar study could be done in another area by others with few resources other than ArcGIS 10.2 software (ArcGISDesktop, Esri 2013, http://resources.arcgis.com/en/help/quick-start-guides/10.2/) and time.

All of the datasets have their own advantages and disadvantages. The 30 meter DEMs are widely available and easy to work with due to their relatively small size but have been found too coarse to identify micro-scale topography (McCollister & Birkeland, 2003). The 10 meter DEM datasets have a much higher level of detail but are not as widely available and can be cumbersome to work with given their large file size. The SNF Land Cover dataset covers the study area but the 30 meter resolution is coarser than the available terrain data and the accuracy of cover type coding is questionable (Figure 3).

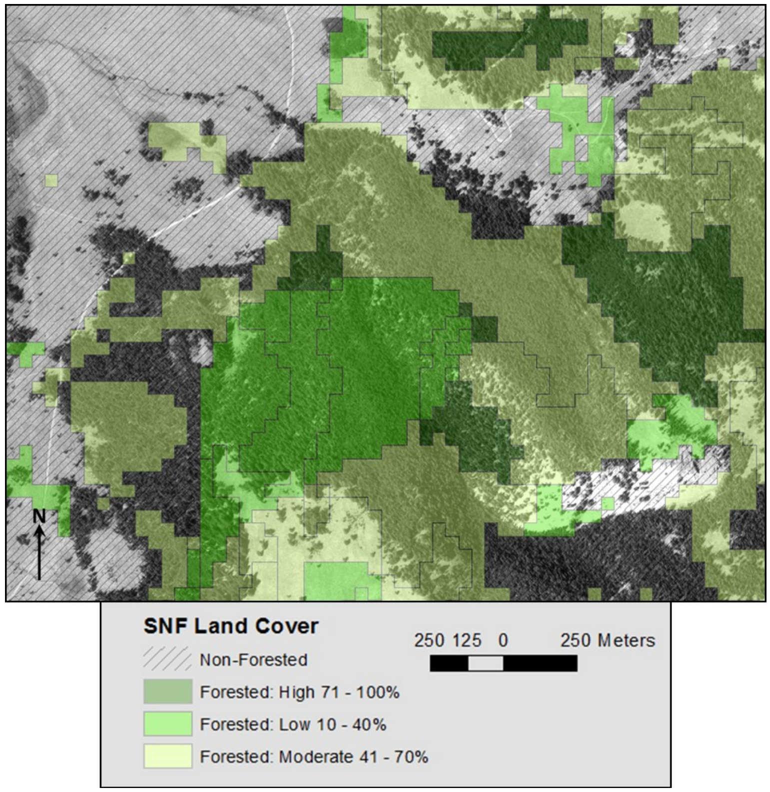


Figure 3: Example of SNF Land Cover dataset (2006) overlaying a DOQ (2011) at Galena Pass showing miscoded boundary regions of the SNF Land Cover compared to the underlying DOQ.

DOQs are far more precise (1 meter pixels) but deriving land cover type from them can be difficult and the large file sizes cause slow processing times. By developing terrain feature extraction algorithms, applying them to datasets with variable resolutions and using them in conjunction with different land cover dataset, this study showed that an optimal combination could be found that will remotely identify the terrain features in question with a minimum of uncertainty for large areas. Applied on a broader scale the development of this method will provide a foundation for GIS applications that assist winter recreationists in safer route finding by avoiding some avalanche hazards.

CHAPTER TWO: PREVIOUS RESEARCH

There are many examples of avalanche research utilizing GIS technology. Large scale topographic maps showing thematic layers like avalanche paths and hazards have been successfully made using DEMs with 5 to 10 meter pixels (Kriz, 2005). Ten meter DEMs are available for most of the United States although most of Alaska is still only available at 30 meter resolution. Avalanche path mapping studies have determined that 30 meter DEMs do not describe surface terrain adequately enough for avalanche path and hazard analyses (McCollister & Birkeland, 2006).

To assist land managers, McCollister and Birkeland (2003) developed a method of avalanche prediction using the Geographic Weather and Avalanche Explorer (GEOWAX) model. This model links historical avalanche activity with historical weather data (i.e. temperature, precipitation, wind speed and direction) such that near future avalanche activity can be predicted by comparing current weather conditions to similar weather conditions and avalanche activity (McCollister & Birkeland, 2003).

Spatially, snow cover is notoriously variable and large area snowpack models are often unreliable because the generally limited number of data points (i.e. weather stations or snow pit analyses) are too few to provide adequate interpolation (Schweizer, Kronholm, Jamieson, & Birkeland, 2008). While snowpack models are difficult to produce some success has been made in predicting avalanche propagation by using cellular automata to evaluate the spatial correlation of areas with strong internal structuring (Gutowitz, 1991; Kronholm and Birkeland 2005).

There are limits to the effectiveness of GIS technology in predicting or mapping avalanche hazards or activity. Some GIS applications have concentrated their efforts on spatially relating forecasting avalanche warning levels from remotely sensed weather data such as temperature and precipitation (Stoffel, Brabec and Stockli 2001). Some successful GIS applications in Europe (McCollister & Birkeland, 2006) have not worked as well in the United States because there are so many more avalanche prone areas. The extent of high resolution data and labor force required for some European avalanche programs make comparable programs in the United States unfeasible because of the high data costs and that the required labor force is too spread out (Scott, 2009).

Communicating avalanche hazards from GIS analysis to the public has also proved to be a difficult task (McCollister & Birkeland, 2006). It is easy enough to drape a danger rose over a digital elevation model dividing the topography into the different aspect/elevation zones to produce a map that shows corresponding danger rating colors. Unfortunately this approach produces a nice looking map, as shown in Figure 3, that does not reflect reality of the danger (McCollister & Birkeland, 2006). Such a map does not incorporate slope angle, tree cover or terrain traps (i.e. gullies or rollovers) into analysis and results in some low risk areas being coded as more dangerous than they are and some high risk areas being coded as low risk. Notice how the basin to the northeast of the peak near the center of Figure 3 changes between high and considerable danger. Such maps may result in bad decisions being made on poor information. Clearly, more accurate methods for the analysis of avalanche terrain are needed.

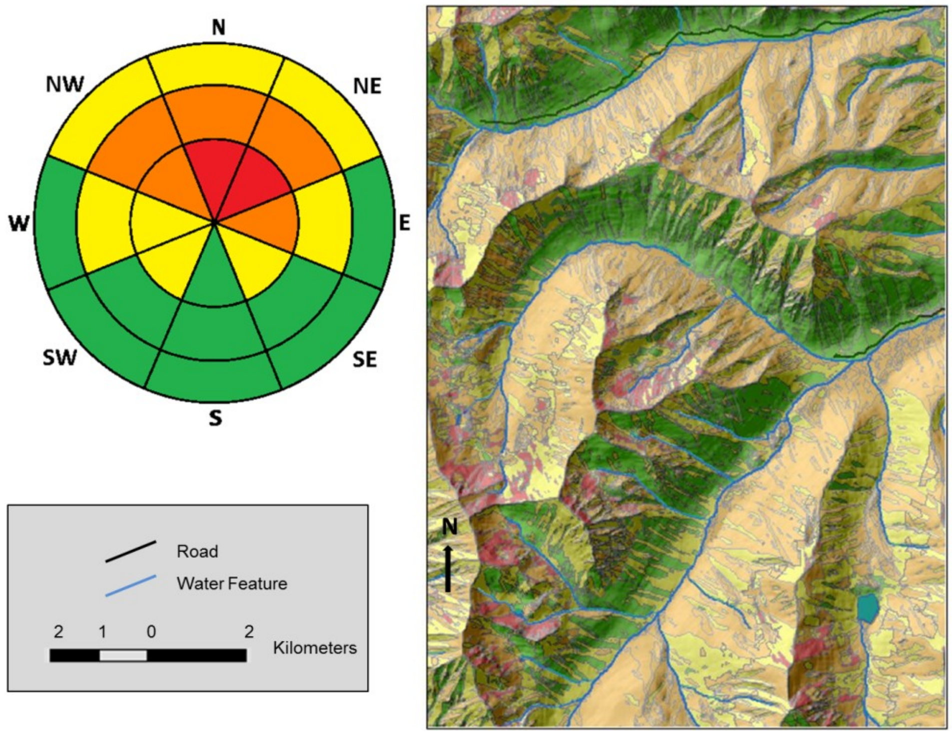


Figure 4: Example of an avalanche danger rose's (upper left) risk levels draped over a topographic surface. While attractive, the results do not accurately reflect on the ground risk.

There has been a significant amount of research into the extraction of geomorphic terrain features. Some research has focused on comparing the effectiveness of different surface feature (i.e. ridges, spires) extraction algorithms (Clarke & Archer, 2009). Other research has focused on comparing different datasets. Some features like ridges were more likely to be correctly identified from Triangular Irregular Network (TIN) elevation than from raster datasets like DEMs (Hu, Wang, & Shao, 2008). Although features whose size is near the resolution limit of elevation datasets are widely distributed, quite often these features cluster in patches of rough terrain. Patterns within DEM datasets can identify these areas, perhaps to be used as a matrix component of a hazard analysis (Berry, 2000). Despite their size, small cliffs are still dangerous to skiers and are hard to discern from topographic contours. In a gap analysis done by the U.S. military, remotely sensed data was able to identify small discontinuities like cliffs in the landscape that did not show up on regular topographic maps (Blundell, Gutherie, & Simental, 2004).

Land managers use vegetation cover databases to aid decision making in many natural resource fields like grazing allotments, fire management or timber extraction. Digital Orthophoto Quadrangles are often used as a visual check for these databases and also have been used as the primary data source for canopy cover models. A study in Arizona was able to create an acceptably accurate 20,000 km^2 layer of primary forest species and density at 10 meter resolution using black and white DOQs (Xu, Prather, Hampton, Aumack, Dickson, & Sisk, 2006).

CHAPTER THREE: STUDY AREA

The Sawtooth National Recreation Area (SNRA) in central Idaho comprises the northern part of the Sawtooth National Forest. The SNRA spans the western portion of Custer County and the northern part of Blaine County. The northern two thirds of the SNRA comprises the headwaters of the Salmon River bounded by the White Cloud Mountains to the east and the Sawtooth Mountains to the west. The southern third of the SNRA forms the headwaters of the Wood River bounded by the Smoky Range on the west and the Boulder Mountains to the east (Figure 4). Valley bottoms in the Sawtooth and Upper Wood River range from 6000’ to 7000’. There are more than 40 peaks over 10,000’ in the SNRA with Castle Peak in the White Cloud Range being the highest point in the SNRA at 11,815’.

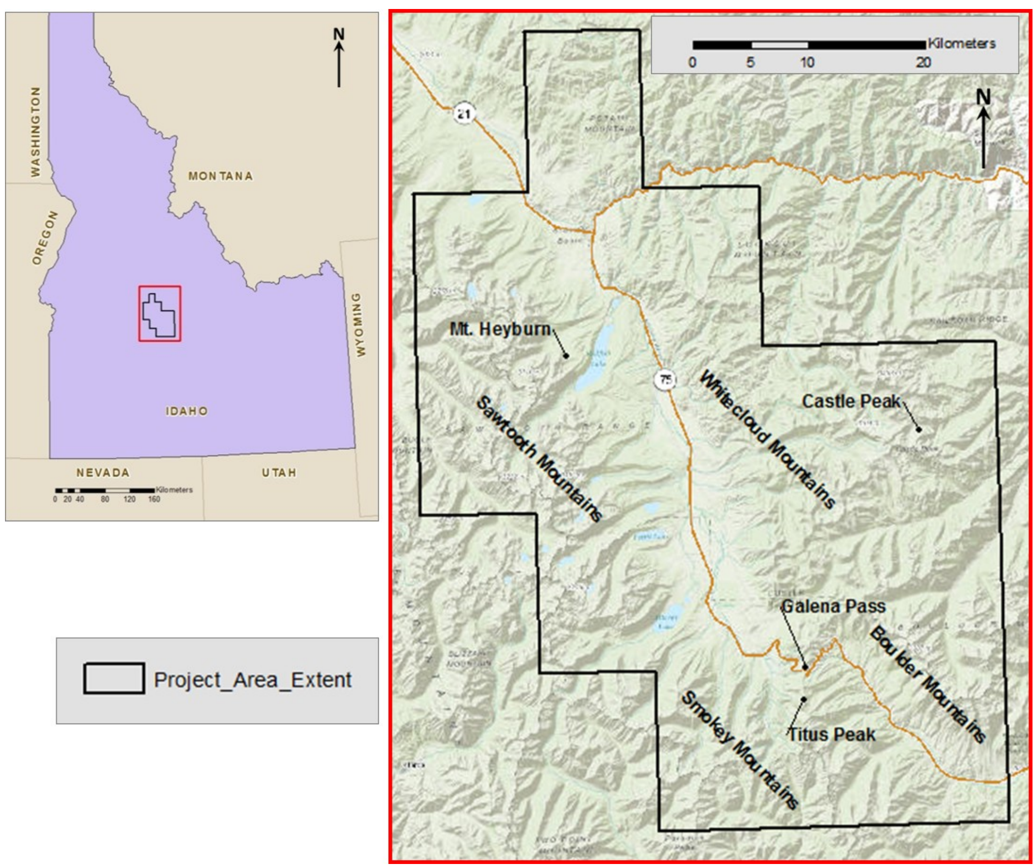


Figure 5: Project area location in state of Idaho (left map) and detail of project area (right map). Several locations noted in the study are marked (i.e. Galena Pass and Mt. Heyburn).

Valleys are predominantly sagebrush with willows and grass riparian areas. Lower slopes of the mountains are mostly Lodgepole Pine and Aspen fading to Douglas Fir at the mid elevations and Whitebark Pines at the higher elevations although few trees survive much above 10,000'.

The region is fairly arid, receiving an average of 43" (low: 35", high: 53") of precipitation in the last ten years (NRCS 2013b). Much of that precipitation falls as snow with 3'-5' of accumulation in the valleys and 8'-11' in the high country. Winter temperatures average lows just below 0°F and average highs around 30°F. Cold snaps are not uncommon with lows at -20° to -35° (NRCS 2013b). Due to the low relative humidity daily temperature swings of 30°-50° are common and aid medium to strong diurnal winds. Winter weather cycles vary from year to year but generally the area receives several big precipitation events separated by weeks of cold, dry, sunny weather. Cold, clear nights create pockets of hoar frost that can become persistent weak layers when new snow is added and frequent winds scour some areas of snow completely while forming massive cornices and pillows on the lee side of mountains.

Despite its chilly temperatures and variable snowpack, the area is a popular winter recreation destination. Both valleys have miles of groomed cross country ski trails, snowshoe trails and groomed snowmobile routes. Backcountry skiers attracted to the deep dry powder frequent the 8780' Galena Pass along State Highway 75 that divides the Sawtooth and Wood River for day trips. Several outfitter owned yurts in both valleys allow groups to stay deeper in the backcountry to access terrain day trippers are unable to reach and are so popular that most weekends are reserved a year in advance. Of this 750,000 acre area the only active avalanche control are the highway corridors over Banner Summit (outside the project area) and Galena Pass. The only professionals working in the winter backcountry are a dozen or so guides, three USFS avalanche forecasters and a USFS winter ranger. Active avalanche control in such a large area would be prohibitively expensive and would lessen the backcountry experience as the whole point of backcountry skiing is to ski untracked snow. And in the congressionally designated Wilderness part of the SNRA (about 240,000 acres), comprehensive avalanche control would violate the 1964 Wilderness Act (88th Congress, 1964). Therefore it is up to the individual or group to make go/no-go decisions, and for that, information is essential. A map highlighting dangerous terrain features would be a valuable tool when used in conjunction with current avalanche advisories, avalanche education and experience.

Besides its attraction to winter recreationists, the area was chosen for this study because it has a wide variety of terrain types. While the Sawtooth and Smoky Mountains are mostly granite, the Smoky Mountains are a bit lower with smaller drainages with tight topography and the Sawtooth Mountains are taller with big drainages and large areas of exposed rock and sculpted arêtes. The Boulder and White Cloud Mountains are mostly limestone with big open faces and long ridges. As Sitole and Vossleman (2004) suggest, this variety in mountain ranges will be useful in determining if a terrain feature analysis is applicable across multiple alpine terrain types.

CHAPTER FOUR: DATA

One goal of this study was to use data that is readily available to the general public at little or no cost. The terrain feature geoprocessing developed for this study relied primarily on raster Digital Elevation Models (DEM) at various resolutions. Forest cover analysis used a mid-resolution vegetation layer developed by the Sawtooth National Forest, high resolution Digital Orthophoto Quadrangles (DOQ) and high resolution Digital Raster Graphics (DRG). Several vector datasets were used to add image content (i.e. streams and roads) to the hard copy maps produced for the field trials. All of the data used in both the terrain feature analysis and forest density analysis are from the server based U.S. Department of Agriculture Sawtooth National Forest Spatial Database. This chapter provides details and sources for the different datasets used.

4.1 DEM

Several DEM datasets from the SNF Spatial Database were used in this study (Table 1). The Snowyside and Mount Cramer Quadrangles are from the U.S. Geological Surveys (USGS) DEM datasets. These 10 m datasets spatially correspond to the ubiquitous USGS 1:24000 topographic quadrangles and are organized by each datasets southeast coordinate, hence Snowyside Quadrangle's southeast coordinate is 43° 52' north, 114° 52' west. The Sawtooth National Forest also has 10 meter and 30 meter DEMs clipped from the seamless National Elevation Dataset (NED) and divided into two datasets each (north zone and south zone) for the extent of the Forest. The project area is entirely within the north half of the SNF and clips of both the 10 meter and 30 meter DEM datasets for the project area extent (see Data subsection 5.4) were created for the analysis. The DEM datasets used in this study as well as the DOQ and DRG datasets described below are available to the public from the Geocommunity website (http://data.geocomm.com/) for a modest fee.

Table 1: Summary of DEM datasets and source location.

DEM	Description	Resolution	Original Source
d435211452lat	Snowyside Quadrangle	10m	U.S. Geological Survey
d440011452lat	Mount Cramer Quadrangle	10m	U.S. Geological Survey
NorthZone10mDEM	North end of Sawtooth National Forest	10m	National Elevation Dataset
NorthZone30mDEM	North end of Sawtooth National Forest	30m	National Elevation Dataset

4.2 SNF Land Cover

The Sawtooth National Forest created a land cover dataset for its own forest management purposes. The dataset is a vector feature class that classifies all lands (public and private) within the Forest extent by an area's primary canopy cover. Although a polygon feature class the layer has the geometry of a 30 meter raster. Canopy cover is determined by a combination of techniques. Some areas were classified using aerial imagery evaluation in conjunction with field surveys. Other areas were classified with a process developed by the University of Montana using Landsat Thematic Mapper imagery taken by Landsat 5 satellite in 1995 (Sawtooth National Forest 2012). Disturbance events such as tornados, wildland fires and insect infestations were compiled by various USFS programs (i.e. fire or silviculture) and periodically added to the dataset. The dataset was last updated in 2008 although updates did not include using Enhanced Thematic Mapper imagery from Landsat 7. Attribute information for each polygon includes canopy cover descriptions for forested areas along with a numerical canopy cover code as well as other attributes such as desired canopy cover types. This dataset or other land cover datasets as well as the vector datasets (described in section 4.5) for other public lands can be obtained by the public through contacting an area's National Forest, National Park Service or Bureau of Land Management headquarters. The datasets are called "Existing Vegetation Layers" although the one used in this study is referred to as the "SNF Land Cover" dataset throughout this paper.

4.3 DOQ

Digital Orthophoto Quadrangles (DOQ) are high resolution (1m pixels) multiband, mosaic aerial imagery that is processed to reduce position displacements from terrain variation and camera distortion. These mosaics in which features are shown in their true ground position are then georeferenced, giving the datasets the quantitative and geometric qualities of a map (Bolstad, 2008, p. 234).

The DOQs used in this study (Table 2) were created by the U.S. Department of Agriculture National Agriculture Imagery Program and are natural color datasets comprised of three color bands: red, green and blue (NAIP 2013). Datasets in Idaho are available in either units that correspond to USGS quarter quadrangles or in county wide datasets. The county datasets are created by compressing quarter quadrangle DOQs into a single mosaic but are packaged in two parts (i.e. east and west) because of the large file sizes. Since the project area spans Custer and Blaine County, both county wide DOQs were clipped to the project area extent.

Table 2: Details about the two Digital Orthophoto Quadrangles mosaics used in the study.

DOQ	Description	Bands	Original Source
naip_2011_blaine_w	western half of Blaine County, Idaho	Red, Green, Blue	USDA NAIP
naip_2011_custer_w	western half of Custer County, Idaho	Red, Green, Blue	USDA NAIP

4.4 DRG

Digital Raster Graphics (DRG) are datasets created from scanned USGS topographic maps and georeferenced to provide a high resolution raster layer. Although 1:100,000 and 1:250,000 scale DRGs are available this study used a 1:24000 DRG of the Snowyside Quadrangle with a pixel size of approximately 1 meter. DRG datasets are stored as a GeoTIFF file and structured to allow 256 colors although only 16 colors were used in the Snowyside Quadrangle used for analysis.

4.5 Other Data

Several datasets were used to add visual content to the hard copy field trial maps and to provide visual reference during the validation process (Table 3). These vector datasets were not used analytically except for the Extent_24K feature class in which a selection of quadrangles was used to define the project area extent and clip all of the datasets used in the study that extended beyond the project area.

Table 3: Feature classes from the Sawtooth National Forest Spatial Database.

Feature Class	Description	Geometry	Original Source
Extent_24K	outlines of USGS quadrangles	polygon	USGS
lakes_polygon	water features with surface area	polygon	USGS
200ftContoursN	200 foot contours for north half of SNF	line	SNF Spatial Database
40ftContoursN	40 foot countours for north half of SNF	line	SNF Spatial Database
roads_arc	closed and open roads on SNF	line	SNF Spatial Database
trails_arc	official trails on SNF	line	SNF Spatial Database
streams_route_streams	streams, creek, river boundaries	line	USGS

CHAPTER FIVE: METHODOLOGY

In order to identify areas where avalanche trigger points or depositional terrain traps were more prevalent, a multipart process of several geoprocessing sequences was created to isolate and classify these features. Two raster layers representing potential avalanche trigger points and depositional terrain traps were created for both the 10 meter and 30 meter DEM datasets by incorporating bare-earth terrain extraction algorithms with forest density data as described in Figure 6. The resulting raster datasets with different terrain feature and attributes were evaluated quantitatively and qualitatively and the best approach then used to produce several maps used in field trials where the data was evaluated and compared to actual, on-the-ground hazards.

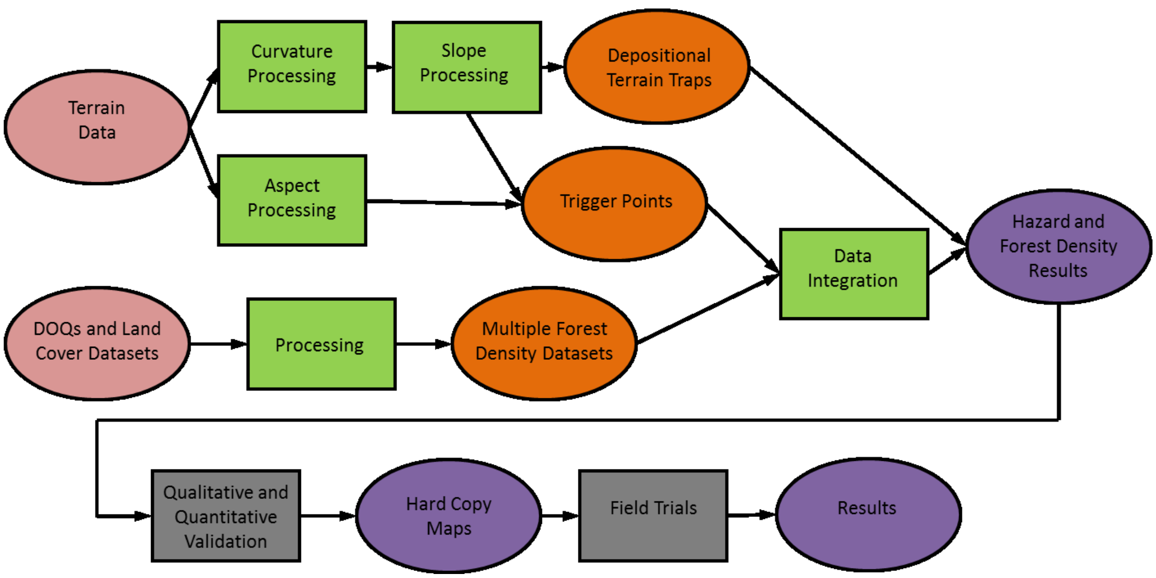


Figure 6: High level flowchart of methodology. Note that discarded intermediate data has been omitted to simplify flowchart.

Most of the geoprocessing was done in single steps using individual processing tools in ArcGIS 10.2 desktop suite while multi-step models were built for several components of the analysis using ArcGIS Modelbuider (Modelbuider, Esri 2013, http://resources.arcgis.com/en/help/main/10.2/index.html#//002w00000001000000).

ModelBuilder is a work flow tool that enables the creation and execution of consistent, repeatable models and was used to ensure the integrity of a particular model or set of analytical processes.

5.1 Terrain Feature Extraction

The terrain features this project sought to identify are all defined by dramatic changes in slope. To isolate these areas, a basic curvature analysis was run on both the 10 meter and 30 meter DEM datasets that combined planar and profile curvatures (Figure 7), then run through a low pass filter to clean out anomalies as described by Fan, Yang and Hu (2007). From this analysis ridges and trigger points register as convexities with positive valued curvatures while gullies (i.e. depositional terrain traps) register as concavities with negatively valued curvatures.

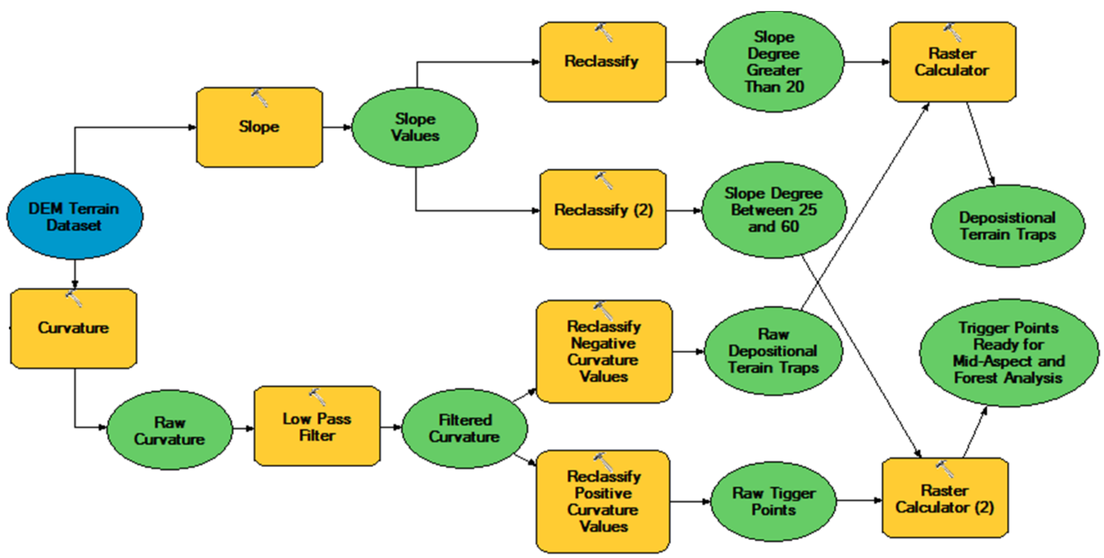


Figure 7: ArcMap 10.2 ModelBuilder geoprocessing workflow for curvature processing resulting in a five class raster layer of potential avalanche trigger points, and a four class raster layer of potential depositional terrain traps.

The gullies of interest were those that have a high degree of curvature and occur in areas where avalanches or avalanche run outs are possible. Generally slab avalanches do not initiate on slopes less than 25° (Schaerer & McClung, 2006, p. 101). To isolate the gullies of concern the filtered curvature analysis was reclassified into four classes (Table 4); three severity classes of concavities and one class of negligible concavity and all convexities. The range of the curvature classification values spans the range of curvature values from the 10 meter DEM dataset. Establishing the number of hazard classes and curvature value ranges for each class was a trial and error process based on the author's professional winter experience and familiarity with the project area. The North American Avalanche Danger Scale levels described in Figure 2 were not used because those classes depict overall avalanche risk based mostly on weather and snowpack and did not serve the purpose of the study.

Table 4: Curvature values for depositional terrain trap hazard classes.

Depositional Terrain Traps		
Class	Description	Curvature Value
0	Not Terrain Trap Hazard	37.00 - -0.75
1	Low Hazard	-0.76 - -1.50
2	Medium Hazard	-1.51 - -2.50
3	High Hazard	-2.51 - -30.00

A slope analysis was then run on the 10 meter DEM and the results reclassified into two classes; one class of slopes greater than 20° (value 1) and one class of slopes less than 20° (value 0). The two reclassified layers were multiplied in a raster calculator resulting in four raster classes depicting gullies where avalanche debris was possible and risk of being injured in an entrapment was heightened from the debris concentrating effect of the tight terrain. To be fair the 20° value is somewhat arbitrary and there are instances of "long runout" avalanche events in which the debris field of an avalanche extends into very low slope angles, but these are rare events and thus excluded from consideration.

The next step was to separate ridges from trigger points as both terrain features register as convexities. Ridges are always associated with changes in aspect. As an example if one walked east along an east-west trending ridge one would have a north-facing slope to their left and a south facing slope to their right. By contrast trigger points mostly occur on upper and mid slopes with a consistent or gradually changing aspect. Therefore isolating areas of aspect change is a way to identify ridges. A high pass filter amplifies boundary areas highlighting ridges and drainages but when run with the 10 meter DEM dataset the ridge top areas registered were incomplete and many ridges did not register at all.

A different way to isolate ridges involves binning a DEM into the eight cardinal and sub-cardinal directions (i.e. north, southeast) resulting in a raster layer with zones of each binned aspect. This can be converted into a polygon feature class in which each feature is a grouping of contiguous raster cells that have aspects within an aspect bin. These polygons can be converted again to a line feature class where the lines signify an aspect change in a process explained below and illustrated in Figure 8. Areas away from lines would then be slopes of consistent aspect or at least within 45°. However some slopes that occur near the breaking point of two aspects will show multiple aspect changes in close proximity even though the slope's aspect is fairly consistent. For instance a slope with an aspect of north-northeast falls just at the eastern limit of a north facing aspect (337.5°-22.5°) and the northern limit of a northeast aspect (22.5°-67.5°). Some areas of the slope are more east than the 22.5° limit and some areas are more north of the limit. While the slope in reality is fairly consistent, binning the aspect into cardinal and sub-cardinal aspects depicts the slope as an area of intense aspect change. A similar example of this can be seen in Figure 8.

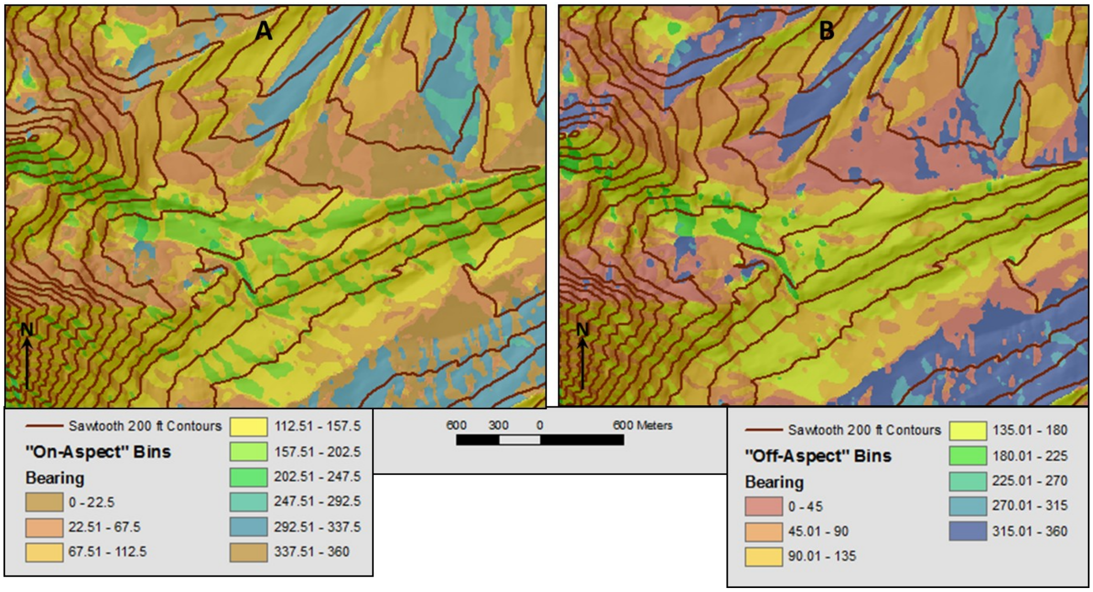


Figure 8: A hillside near Mt. Heyburn is divided into the eight cardinal and sub-cardinal aspect bins in Panel A and eight aspect bins skewed 22.5 in Panel B. Note that the south/southeast facing slope in the lower right of both panels registers as an area of intense aspect change in Panel A but is fairly consistent in Panel B. Also note that there are nine aspect bins in Panel A and the north aspect in Panel A is actually two bins (0-22.5 and 337.51-360) symbolized with the same color.

While identifying consistent slopes is one goal, so is identifying slopes with a gradually changing aspect such as a cirque or bowl. To correct for slopes occurring at the break point and to find gradually changing slopes, a double aspect analysis was developed described in Figure 9 and Figure 10. First a DEM derived aspect raster was binned into the nine aspects (north is binned into two aspects 337.5°-0° and 0°-22.5° but can be reclassed together) and reclassified into the eight cardinal and sub-cardinal directions which the study called the "On-Aspect" aspects.

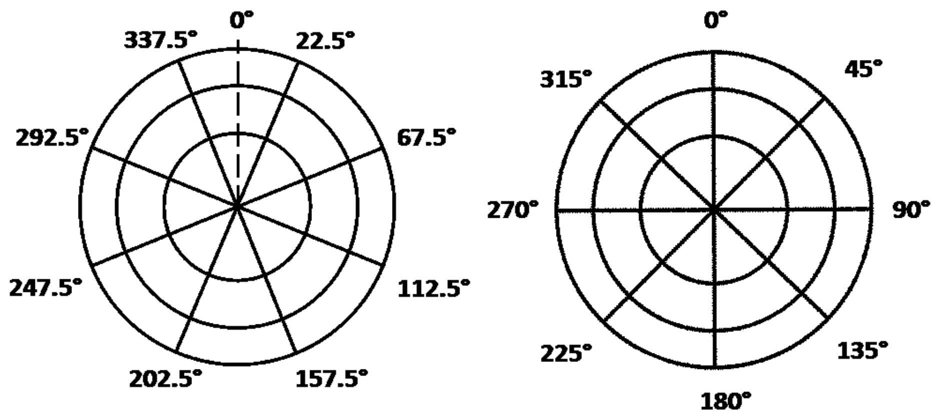


Figure 9: Bearing values for "On-Aspect" binning (left image) and "Off-Aspect" binning (right image).

The reclassified raster was then converted to polygons and the polygons to lines. For the ten meter DEM A 20 meter buffer was then created around each line (30 meter buffer for 30 meter DEM) resulting in a feature class depicting "On-Aspect" areas of change.

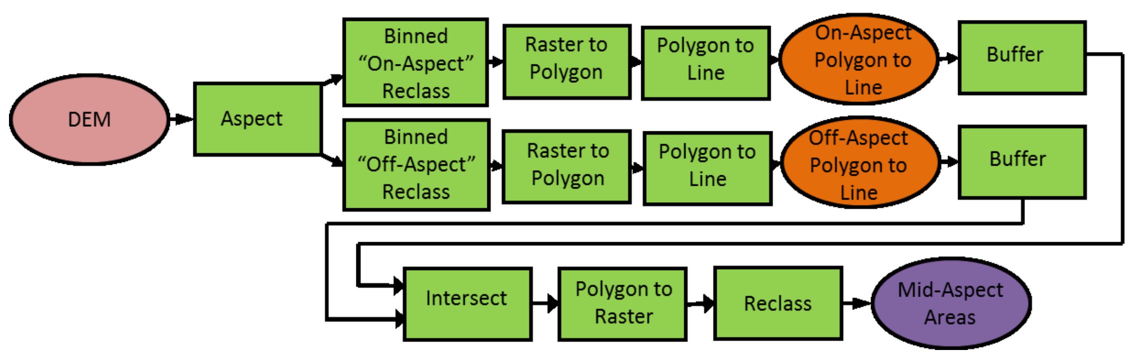


Figure 10: Mid-Aspect analysis flowchart.

The same DEM derived aspect raster was then re-binned into eight aspects skewed 22.5° called the "Off-Aspect" aspects. The previously mentioned north-northeast aspect would now register as a slope with a consistent aspect. This "Off-Aspect" raster was then reclassified and went through the same polygon, line, buffer process as the "On-Aspect" analysis. The intersection of the on-aspect and off-aspect buffers was then found and converted back into a raster layer with a cell size of the input DEM. The intersection of both buffers are areas where two or more aspect changes occur within 20 meters of each other (ridges and drainages) and the areas outside of the buffer intersection are slopes of consistent or gradually changing aspect as seen in Figure 11.

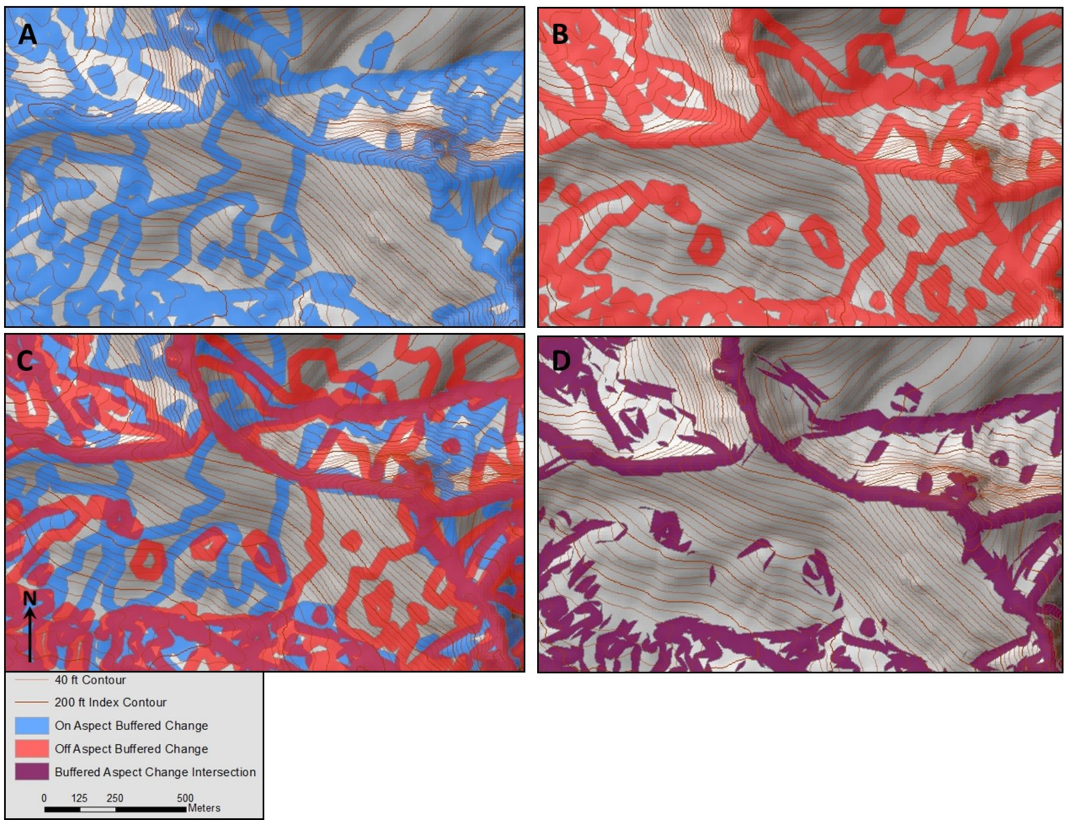


Figure 11: Example of 20 meter buffers around "On-Aspect" changes (Panel A), "Off-Aspect" changes (Panel B), the composite of "On-Aspect" and "Off-Aspect" changes (Panel C) and the intersection of "On-Aspect" and "Off-Aspect" changes (Panel D).

This analysis was developed on a single quadrangle sized DEM (~ 10 km by 14 km) with which the buffer operation included dissolving all interior partitions and the resulting intersection then converted to a raster layer. However, the entire project area encompasses over 2200 km^2 that required sixteen 10 meter DEM datasets. When the process was attempted on the complete 10 meter DEM mosaic, it failed repeatedly, likely due to the large file size. Thus an alternative method was developed for large datasets (Figure 13) in which the project area was split into three subareas (Figure 12).

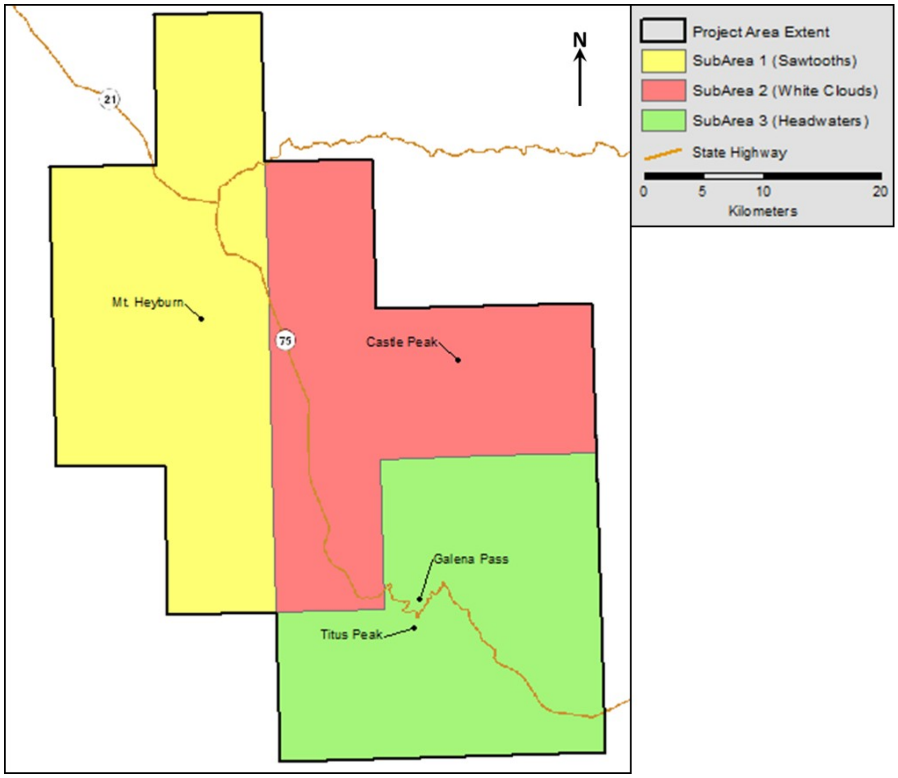


Figure 12: The three subareas of the project area used for large dataset processing.

Splitting the project area into three areas and processing the buffer operation with no dissolution of interior portioning worked but resulted in almost 200,000 polygons per project subarea. To simplify these polygons into a single, multipart polygon the three subareas were each erased from a single project area polygon and the erase operation results then erased from the project area polygon. The three subareas where then joined with a union resulting in a single multipart polygon of the desired buffer zone. These "On-Aspect" and "Off-Aspect" buffers were then converted into two-class raster layers (10 meter cell size) with areas of aspect change coded one and areas of no aspect change coded zero. Multiplying the two rater layers together with the map calculator tool resulted in the intersection of the "On-Aspect" and "Off-Aspect" areas of change.

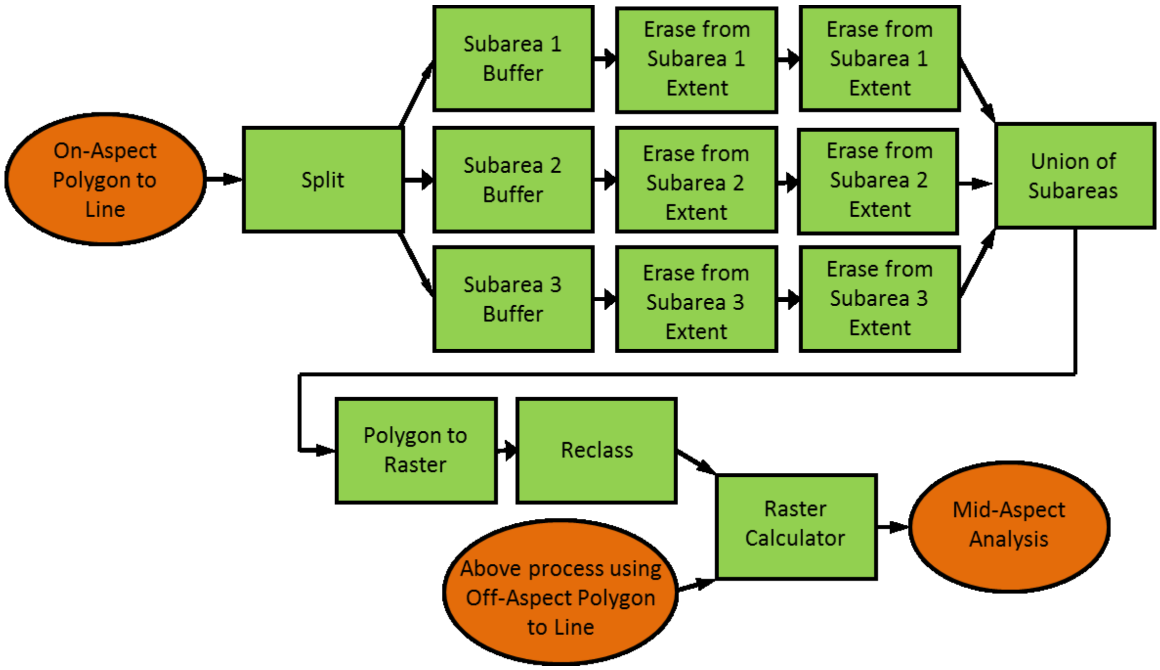


Figure 13: Alternative Mid-Aspect processing flowchart for large datasets. Note that the input data is the intermediate data noted in Figure 10.

As well as the 10 meter DEM dataset, a mid-aspect analysis was done with a 30 meter DEM dataset. The smaller file size of the 30 meter DEM dataset allowed the entire project area to be processed using the original process without problems.

To find trigger points, the convexities in the curvature analysis were reclassified into four classes of severity (see Table 5) and one class of negligible convexity and all concavities. This was then multiplied with the Mid-Aspect analysis using the map calculator.

Table 5: Curvature values for trigger point hazard classes.

Trigger Points		
Class	**Description**	**Curvature Value**
0	No Trigger Point Hazard	-30.00 - 0.75
1	Low Hazard	0.76 - 1.25
2	Low/Medium Hazard	1.26 – 2.00
3	Medium /High Hazard	2.01 – 3.00
4	High Hazard	3.01 – 37.00

In the Rock Mountains, avalanches rarely start in terrain less than 25° or greater than 60° (the terrain is so steep snow in unable to accumulate to a critical mass). Therefore the slope analysis was reclassified into two classes; one class for slopes between 25° and 60° (coded one), and one class for everything less than 25° or more than 60° (coded zero). This was then multiplied with the map calculator to the product of the mid-aspect analysis and convex curvatures resulting in potential bare-earth trigger points. To be fair there are plenty of hazards in 60° terrain, but for the very few skiers who venture in that terrain, avalanches are only one of several hazards (as a perspective most black diamond "expert" ski runs are between 33° and 38°). If one wanted to find ridges, the code values for the mid-aspect analysis would be reversed (buffer zones become one, consistent or gradual changing aspect becomes zero) and multiplied with the positive convexity curvature values. Since ridges are not necessarily steep, no filtering of low angle areas would be needed.

5.2 Forest Cover Extraction

The DEM derived terrain analyses all assumed a bare topography but avalanche activity is heavily influenced by forest cover. Heavy and moderate timber cover provides an anchor for snowpack that prohibits avalanche formation (Schaerer & McClung, 2006). Thin timber does not really inhibit avalanche formation and in some cases can actually promote avalanche activity by a fracture line connecting the small areas of weakness around the base of each tree (something like the perforations on a tear out piece of notebook paper). Bare ground is an obvious concern. Recall that the goal was to create a forest density layer using existing data sets available to the public that are not prohibitively expensive. Three approaches using different datasets were evaluated to develop a forest density layer that could filter out trigger points occurring in moderate and heavily timbered areas.

First approach

The first approach attempted to use the vegetation theme from a Digital Raster Graphic (DRG) of a quadrangle map (~ 10 km by 14 km). Component themes from USGS maps (i.e. contours, roads or vegetation) were once available and reasonably inexpensive but as of 2003 these themes, called map seperates, were discontinued as standard products (Gourda, 2003). Therefore the DRG was separated into its component color bands and the green color (vegetation) isolated. Unfortunately map features like contours and labels that overlay areas of forest cannot be removed, resulting in forests comprised of the forest bands with negative space for contours, labels or any other map feature. Other green features like marshes or orchards were also still present. Finally the USGS quadrangle maps only delineate one class of forest (those areas of forest thick enough to hide 30 men their horses and their captain of men from aerial observation (Alt, 2001)). These weaknesses in the DRG analysis made the results unusable and the approach was abandoned.

Second approach

The second approach (Figure 14) used 1-meter DOQ (three band) images covering the project area.

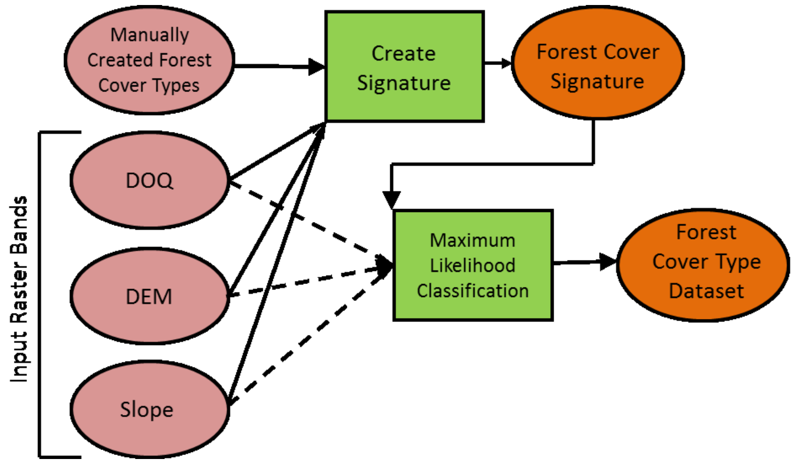


Figure 14: Flowchart for DOQ based forest cover processing.

Representative areas were selected (~ 3 km by 2 km) and polygons manually created for six types of ground cover from a visual inspection of the DOQ and a slope angle layer. A signature profile was created using the DOQ, a 10 meter DEM derived aspect raster and a 10 meter DEM derived slope raster (in order of importance) as the input raster bands and the six class ground cover polygons as the input feature class (Figure 15).

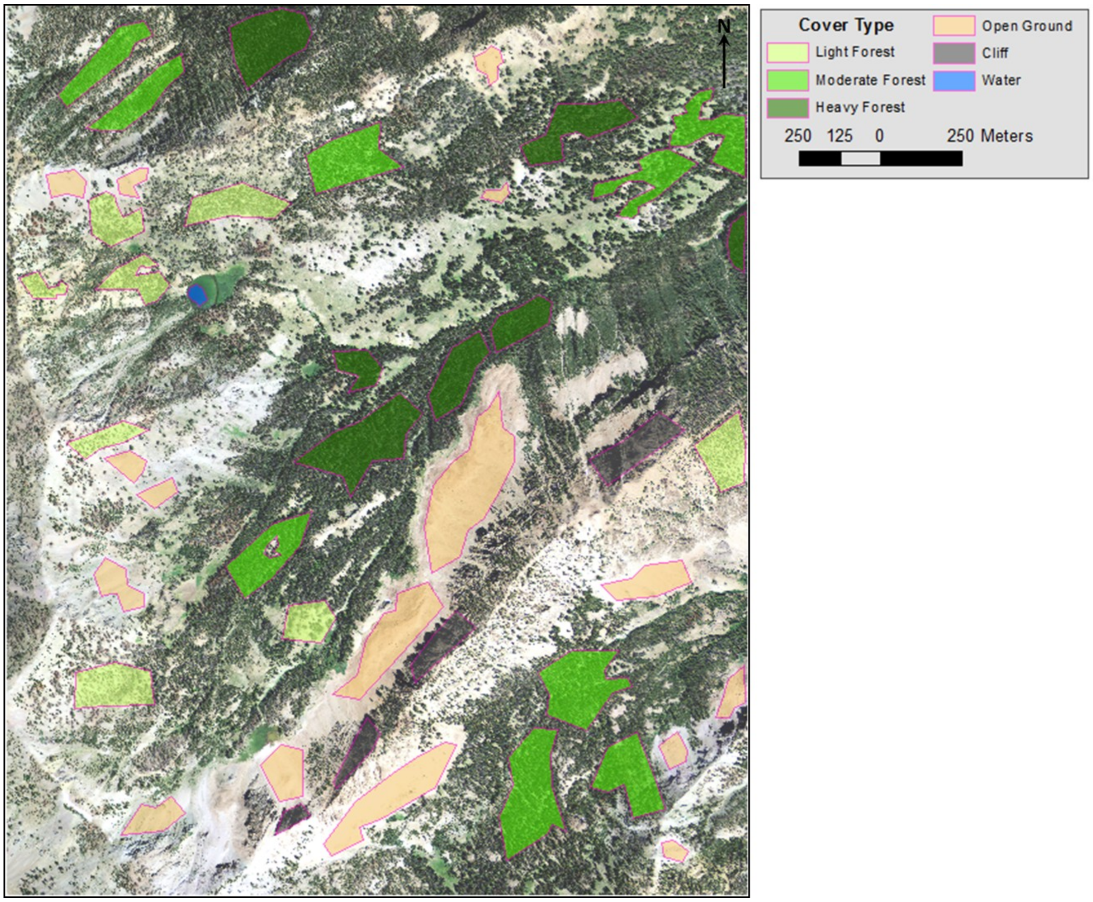


Figure 15: Example of manually created and classified polygons of cover types used in signature profile creation for DOQ based forest density cover near Titus Peak.

A maximum likelihood classification of the entire 6 km^2 area was then processed using the signature profile along with the DOQ, aspect and slope layers. The results of this were processed with the boundary clean tool to reduce anomalies. To filter out areas where trigger points were not a concern the six class raster layer was reclassified with thin forests, open ground and cliffs valued at one and moderate timber, heavy timber and water coded as zero. This two class raster layer was then multiplied with the bare-earth trigger points layer (from the terrain features extraction) with the map calculator.

Third approach

The third approach used a geoprocessing model with the land cover dataset produced for the Sawtooth National Forest (Figure 16).

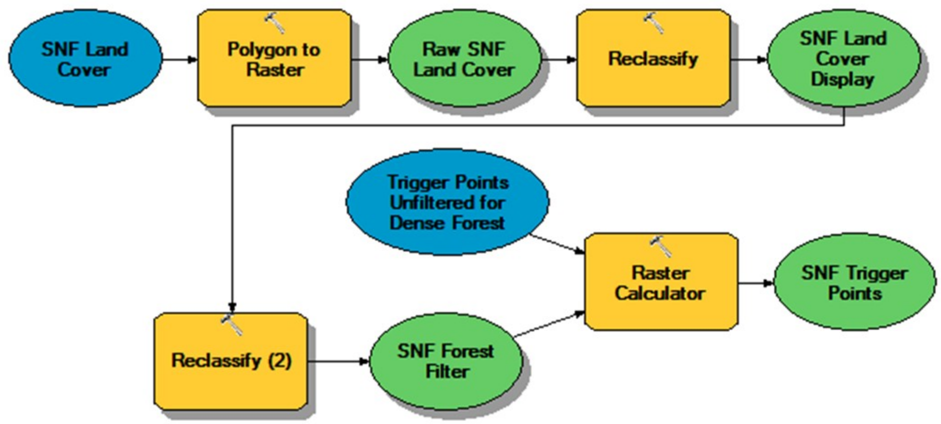


Figure 16: ModelBuilder geoprocessing for Sawtooth National Forest Land Cover dataset resulting in a raster display layer and a raster forest density layer to filter out trigger points occurring in moderate and heavy forest.

In this dataset ground cover is divided into 15 classes with four classes of forest density and 11 classes defining non forested ground cover. It is a raster geometry based layer (30 meter cell size) in a polygon feature class format so the first step was to convert it to a 10 meter raster layer in which each 30 meter cell consists of nine 10 meter "child" cells with the same value as the single 30 meter "parent" cell. This was done because the components of a raster calculator operation will be resampled such that each component's cell size matches the cell size of the largest celled component. For the 30 meter DEM analysis this was not an issue but was for the 10 meter DEM analysis because the results were coarsened and filtered 30 meter cells instead of filtered 10 meter cells. After the polygon to raster conversion the layer was reclassified into four classes (light, moderate and heavy forest and open ground) and symbolized in shades of green for display purposes (Figure 17). The display layer was then reclassified into two classes; moderately and heavily forested areas to zero and lightly forested and everything else to one.

This layer was then multiplied to the trigger points layer with the map calculator to filter out areas where trigger points were not a concern.

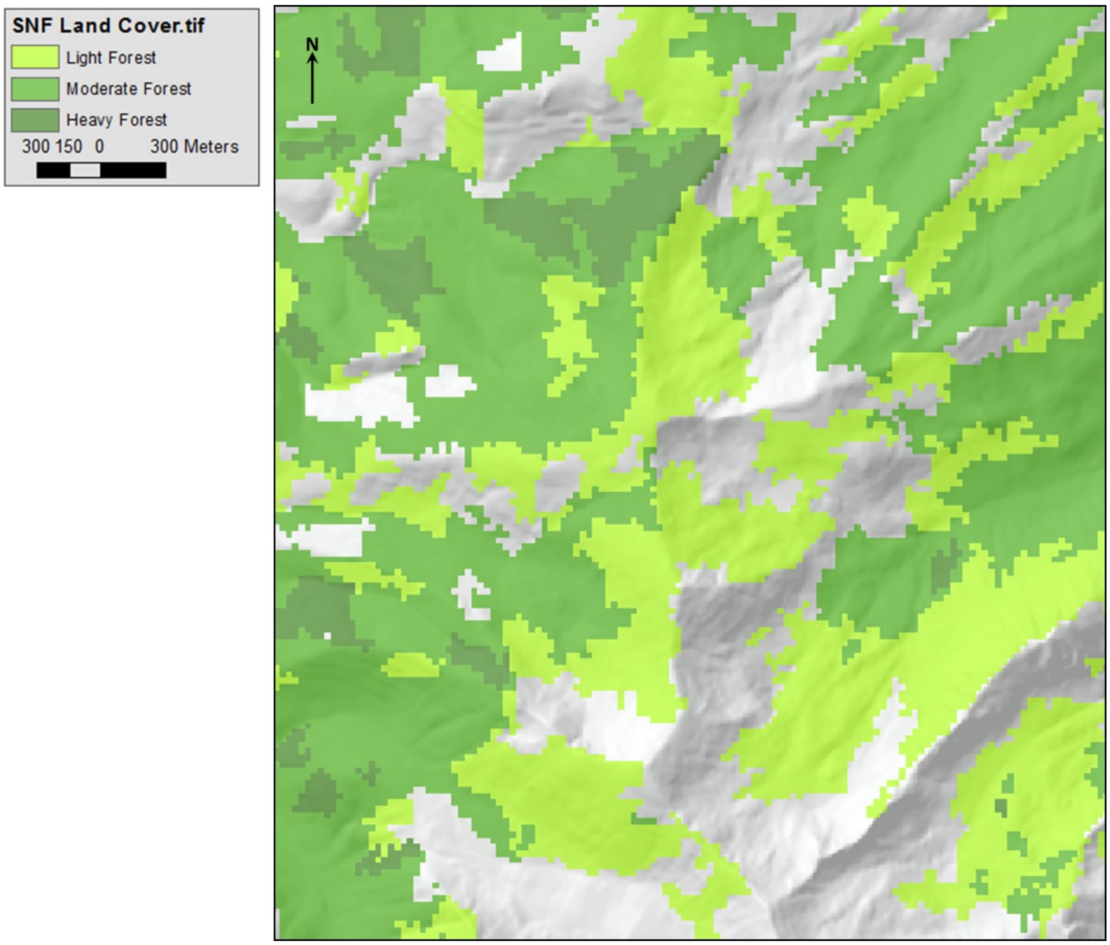


Figure 17: SNF Land Cover with display symbology overlaying a hillshade.

5.3 Validation

To assess the validity of the DOQ based forest dataset a visual comparison of the six class raster layer to the original DOQ was done. At small scales, in the 3 km by 2 km representative areas, the process worked well and the classes were coded reasonably well (Figure 18).

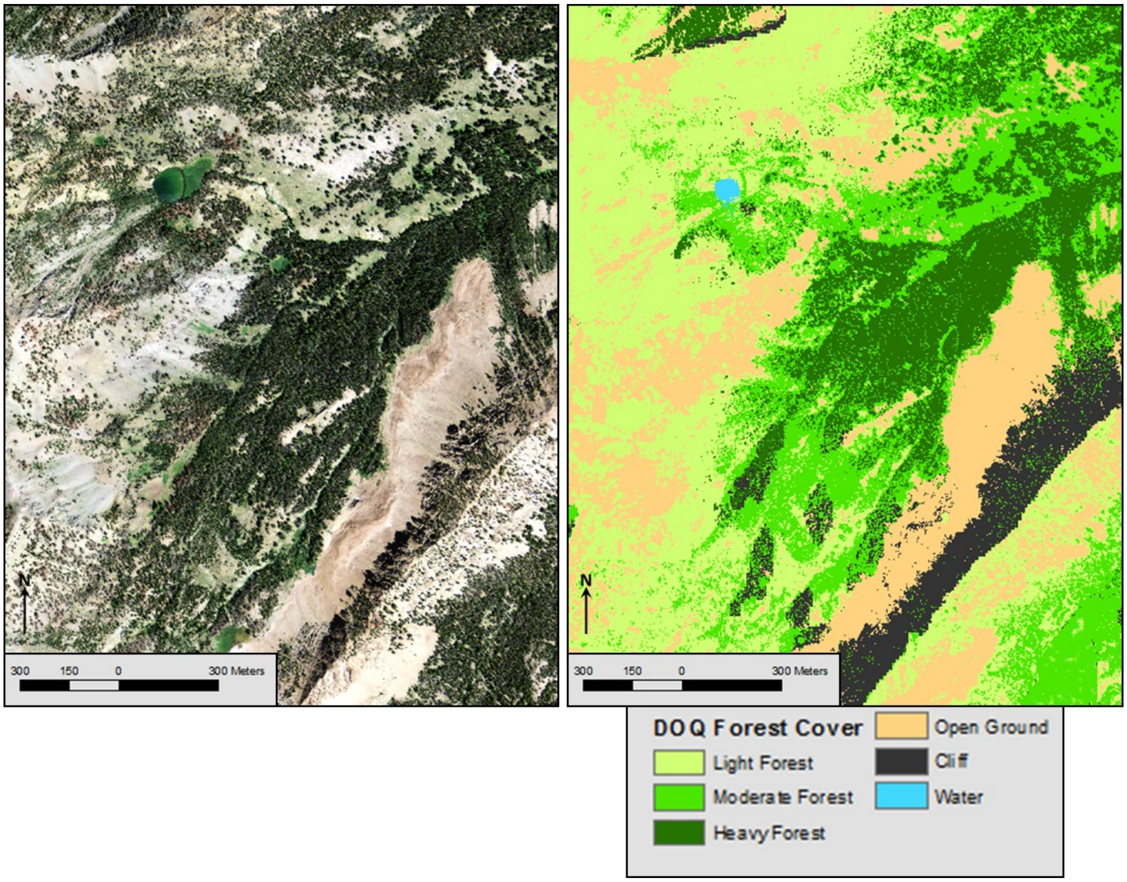


Figure 18: Example of well classified DOQ based land cover near Titus Peak (right image) compared to the original three band (red, green and blue) DOQ. In both images the right hand side is mostly forest fading into alpine open ground, talus slopes. Note the band of cliffs in the lower right and the small water body in the upper left.

At larger scales (~ 10 km by 14 km) areas outside of the sample area had large misclassified areas and become unusably inaccurate. There were two primary areas of misclassification. The first being low elevation areas of open ground with primarily grass or shrub ground cover being coded as forested (Figure 19). This was likely due to the green color of the grass versus the light tan/white color of open ground in the high country where the signature profile was created. A larger sample area with more elevation dependent classifications like low elevation open ground could be created but the added complexity and time was deemed less than worth the effort.

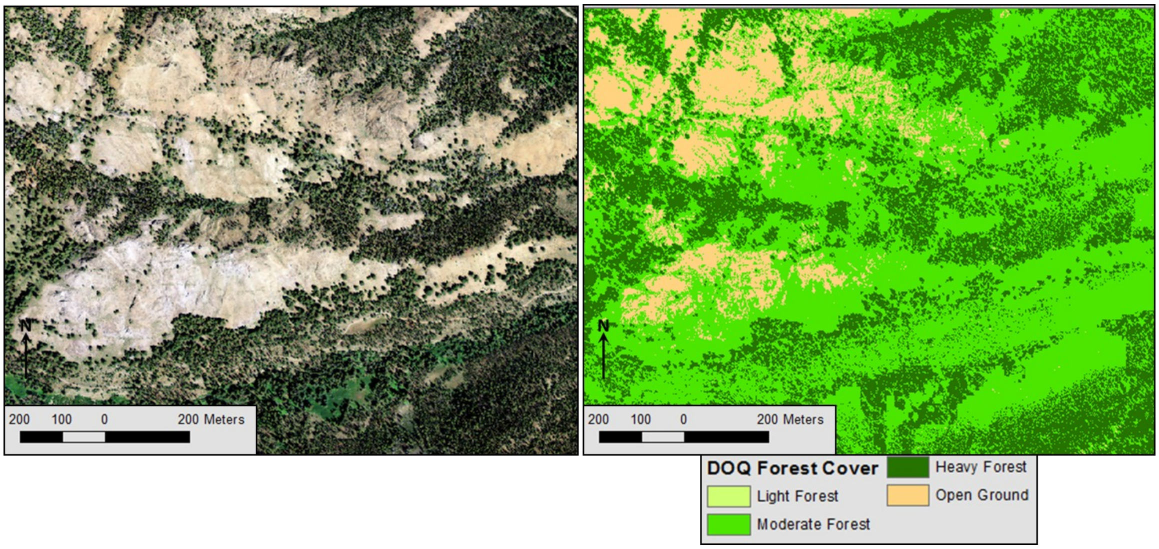


Figure 19: Example of forest cover misclassification in an area 10 km east of Titus Peak and outside of the sampling area. Much of the light colored open ground in the red, green and blue band DOQ (left image) has been misclassified as light and moderate forest in the right image.

The second type of misclassifications were shadowed areas in the high country. Generally aerial photos are taken in the summer, ideally around noon so shadows are minimized but in highly mountainous areas there are almost always shadows somewhere. The Custer County DOQ over-flights done in the Sawtooth Mountains was probably done in late morning as any steep mountain generally had a large shadowed area on northwest aspect. As such, most of the shadowed areas either classified as heavy forest or cliff when they clearly were neither. Although Yuan and Bauer (2006) evaluated a process through which shadows caused by forests could be classified as forests the approach did not work for terrain based shadows. Areas of terrain based shadows could be identified but there was no way to correlate those areas to forest density. Based on the inconsistency of the DOQ based forest density layer and the poor results from the DRG based forest layer only the SNF vegetation dataset provided consistent enough results to filter out nonhazardous trigger points across the entire project area.

Results from the 10 meter and 30 meter terrain analysis were compared to each other on their slope classifications and terrain feature analysis. Both terrain feature analyses filtered potential hazards by slope classification. The 10 meter DEM had a greater range of slopes and a greater area at higher slope angles especially at the slope angle extremes (Table 6). The upper limit of 60° for trigger points had an almost negligible filtering effect on the 30 meter DEM since so little of the datasets registered above 60°. Comparatively, the 0.2% of the 10 meter DEM that registered above 60° filtered out a noticeable number of trigger points. For those areas the extreme closeness of contour lines is warning enough the terrain's hazards.

Table 6: Comparison of 10 meter and 30 meter DEM datasets based on slope classification statistics.

	10 meter DEM		30 meter DEM	
Slope Characteristic	**Count**	**Project Area %**	**Count**	**Project area %**
Greater Than 20°	11,575,026	52.6%	1,185,219	47.9%
Greater Than 25°	8,215,348	37.3%	819,828	33.1%
Between 25° and 60°	8,169,410	37.1%	818,474	33.1%
Greater Than 60°	45,706	0.2%	1354	0.0005%
Total	22,004,851		2,474,633	

In the terrain feature analysis, the 10 meter DEM based analysis outperformed the 30 meter DEM based analysis in both range and extent. In areas with low curvature (curvature value near zero) both datasets had similar results although small features present in the 10 meter analysis did not register on the 30 meter analysis. At the curvature extremes, the 10 meter DEM based analysis had an overall range five times that of the 30 meter DEM based analysis. This discrepancy further manifested itself in the area of curvature classes. In the trigger point analysis, five times more area registered as class 1 in the 10 meter analysis compared to the 30 meter analysis (Table 7). The effect becomes more pronounced at higher curvature values for both trigger points and depositional terrain traps. From a visual standpoint, at a 1:24000 scale the coarseness of the 30 meter analysis was readily apparent (Figure 21). For features that registered in both the 10 meter and 30 meter datasets the 30 meter derived feature might just note a hazard where as the same feature in the 10 meter dataset would register as a multi-pixel feature with some indication of the feature's shape and orientation. From these results only the 10 meter dataset results were subjected to field testing.

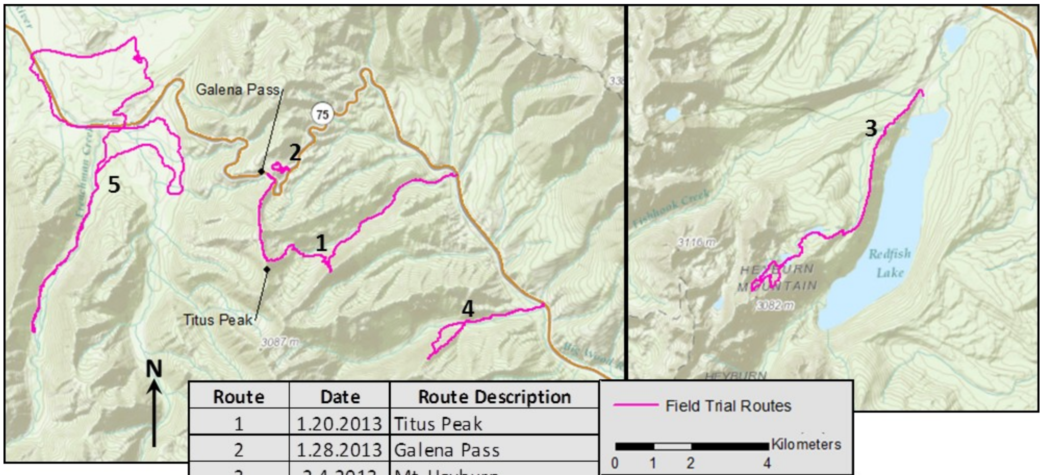
Table 7: Results from terrain hazard analysis showing curvature values, pixel counts and percentage of the project area for each class.

Avalanche Trigger Point Analysis (slopes between 25° and 60°)						
	10 meter DEM			30 meter DEM		
Class	Curvature	Count	Percentage	Curvature	Count	Percentage
0	-30.00 - 0.75	7,180,911	87.9%	-5.00 - 0.74	844,900	98.1%
1	0.76 - 1.25	623,598	7.6%	0.75 1.24	12,919	1.5%
2	1.26 – 2.00	279,356	3.4%	1.25 – 1.99	3,445	0.4%
3	2.01 – 3.00	69,601	0.9%	2 – 2.99	431	0.05%
4	3.01 – 37.00	19,344	0.2%	3 – 8.00	34	0.004%
Total		8,172,810			861,264	

Depositional Terrain Traps Analysis (slopes greater than 20°)						
	10 meter DEM			30 meter DEM		
Class	Curvature	Count	Percentage	Curvature	Count	Percentage
0	37.00 - -0.75	9,178,996	79.3%	-8.00 - -0.74	1,131,587	93.8%
1	-0.76 - -1.50	1,401,952	12.1%	-0.75 - -1.49	69,970	5.8%
2	-1.51 - -2.50	660,424	5.7%	-1.5 - -2.49	4,826	0.4%
3	-2.51 - -30.00	336,005	2.9%	-2.5 - -5.00	362	0.03%
Total		11,586,384			1,206,383	

5.4 Field Testing

Field testing was done on five single day backcountry surveys. Three of the field tests were done in the Wood River Basin on skis and two were done in the Sawtooth Mountains on skis and snowmobile (Figure 20).



Route	Date	Route Description
1	1.20.2013	Titus Peak
2	1.28.2013	Galena Pass
3	2.4.2013	Mt. Heyburn
4	2.28.2013	Owl Creek
5	3.8.2013	Frenchman Creek

Figure 20: Overview of field trail locations and routes. The Galena Pass/Titus Peak area (left image) is in the southeast part of the project area and the Mt. Heyburn route (right image) is in the west/central portion of the project area.

To prepare for the field tests 8.5"x11" layouts were made for each area at a scale of 1:24,000. The layouts consisted of a hillshade (derived from a 10 meter DEM) underneath the SNF Land Cover based forest density display layer. On top of these layers were trigger points (in shades of red) and depositional terrain traps (shades of purple). The top most display layers were streams, trails and topography (40 foot contours with 200 foot index contours) as seen in Figure 21.

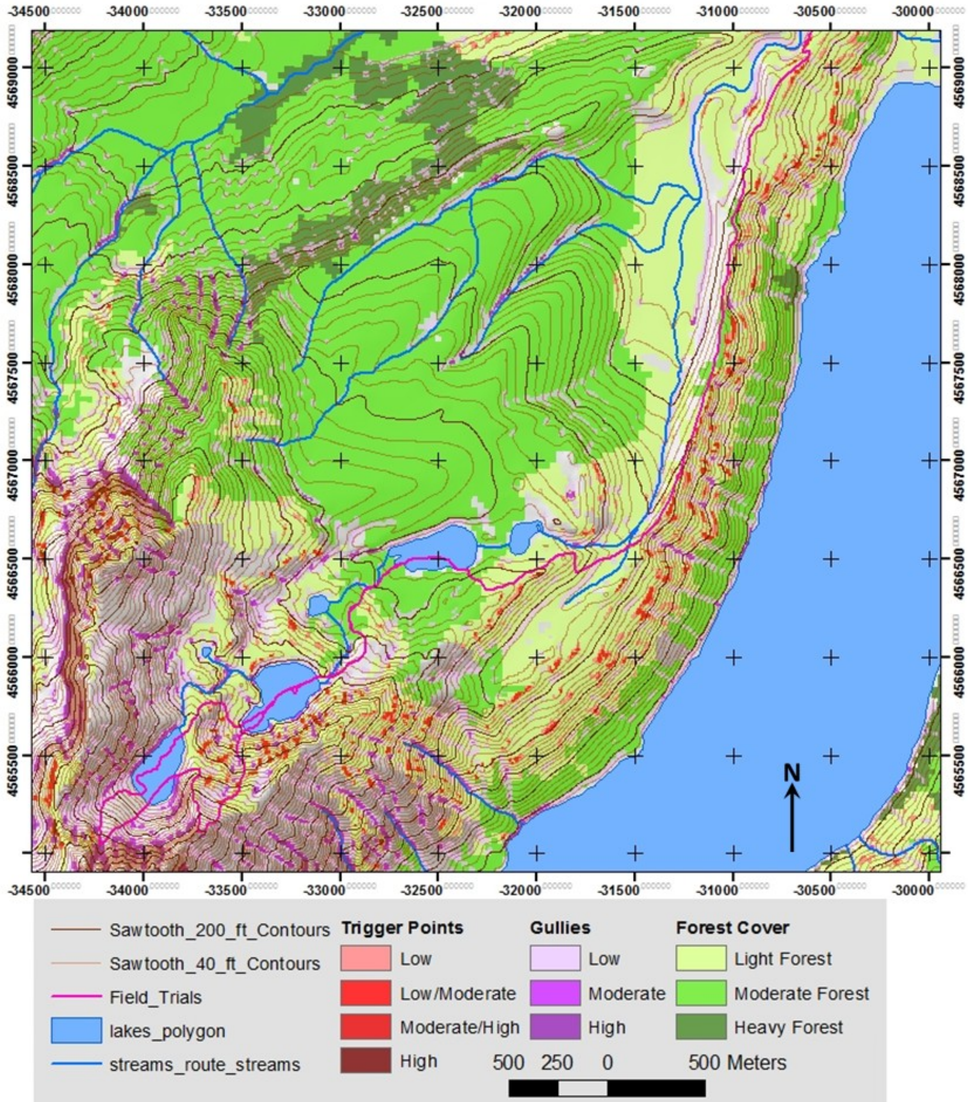


Figure 21: Excerpt from layout of hard copy field trial map near Mt. Heyburn. GPS Route of field trial added post-trial (Field_Trials). The SNF Land Cover based forest display is used for vegetation, water bodies are lakes_polygons and water features like streams are in the streams_route_streams layer.

The Titus Peak area was one area in which the DOQ based forest density layer produced good results and a second map was made in which this forest cover was displayed with correlating trigger points (Figure 22). Navigation in the field was done with a recreational class GPS unit (Garmin Legend) and to aid this, 500 meter UTM tick marks were added to the map.

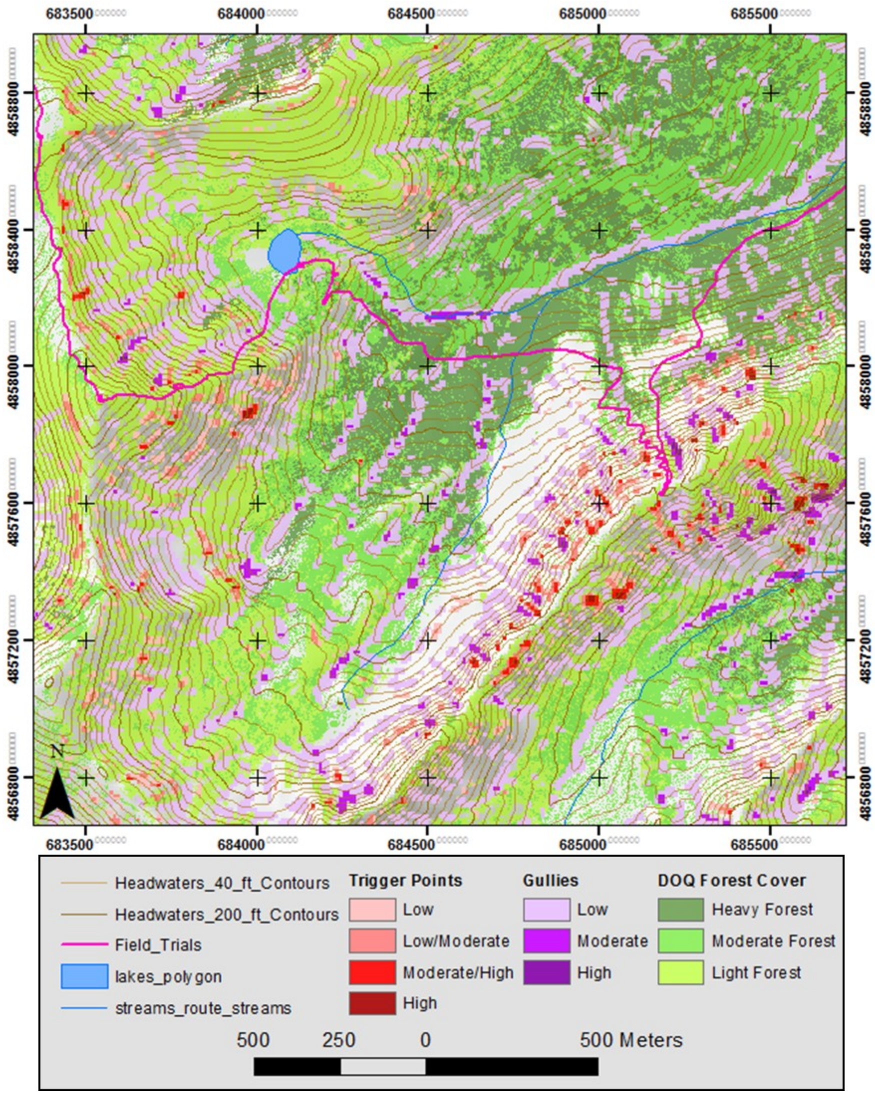


Figure 22: Excerpt from layout of hard copy field trial map near Titus Peak. GPS Route of field trial added post-trial (Field_Trials). The DOQ based forest density layer is used for vegetation, water bodies are lakes_polygons and water features like streams are in the streams_route_streams layer.

In the field, as the route came close to trigger points or terrain traps noted on the map, the spot was marked in pencil (a poked hole with notes on the backside of the map) and the route was penciled in to that point. A survey of the area was taken to ascertain if a hazard was present or not. Field evaluation of hazards was done from some distance (generally 20 to 50 meters) as closer proximity to said hazards could have exposed the researcher to undue risk. Correlating hazards on the map to on-the-ground hazards can be difficult as navigation with a recreational

GPS with only 5-15 meter accuracy does have some inevitable error. This error can be compounded by the known error of DEM datasets and derivative datasets as noted by McCollister and Birkeland (2006). Hazards that were identified on the map and present in the field were deemed true positives. Hazards that were noted on the map and not found in the field were deemed false positives. Some hazards found in the field were not noted on the map and deemed false negatives. In the terrain analysis convexities were divided into four classes and concavities into three classes. Hazardous features noted on the map were generally multiple contiguous cells composed of different combinations of the classes. In the field, this resulted in any particular hazard being recorded (somewhat arbitrarily) on a five class scale (Table 8) based on the overall size and severity of a particular. The field trial, trigger point hazards noted had a high degree of accuracy with high severity hazards and most hazards noted being in the low/medium to medium severity. Accuracy at low end of the scale probably had more to do with the severity class breaks than with accuracy as many of the low severity features did correlate to a noticeable change in slope but the features noted did not seem hazardous, hence the low accuracy rate. Medium to high severity depositional terrain trap hazards also had a high degree of accuracy although low severity hazards were not very accurate. For the smaller, low severity gullies much of the inaccuracy was that many features simply filled in with snow.

Table 8: A tally of field trial observation results. Potential trigger points and gullies were evaluated on whether the map correctly identified an actual hazard (true positive) miscoded the hazard (false positive) or failed to identify the hazard (false negative).

Avalanche Trigger Points					
Severity	**Survey Sites**	**True Positive**	**False Positve**	**False Negative**	**Accuracy**
Low	1	0	1	0	0%
Low/Medium	13	10	3	0	76%
Medium	9	9	0	0	100%
Medium/High	4	4	0	0	100%
High	2	2	0	0	100%
Total	29	25	4	0	N/A
Depositional Terrain Traps					
Severity	**Survey Sites**	**True Positive**	**False Positve**	**False Negative**	**Accuracy**
Low	5	2	3	0	40%
Low/Medium	1	0	0	1	0%
Medium	8	6	1	1	75%
Medium/High	0	0	0	0	N/A
High	3	3	0	0	100%
Total	17	11	4	2	N/A

CHAPTER SIX: RESULTS

From the validation process and field trials, strengths and weaknesses of both the forest density analysis and terrain feature analysis were apparent. Following are qualitative and quantitative results from the SNF land cover and DOQ based forest density analyses in the area near Titus Peak, while results from the 10 meter and 30 meter DEM based terrain analysis are compared in an area near Mt. Heyburn. The maps in this chapter use a 10 meter DEM derived hillshade and imperial topographic contours to provide a visual sense of the terrain and do not reflect on the analysis process.

6.1 Forest Cover

For display purposes the DOQ based forest layer looked better than the SNF Land Cover based forest layer. At scales greater than 1:24000 the SNF based forest layer (Figure 23, Panel B) appears chunky and imprecise compared to the DOQ based forest layer (Figure 23, Panel A). An added advantage to creating a forest type density layer from a DOQ was that other land cover types like water and cliffs had to be accounted for in the signature creation process therefore adding useful classes to the layer (Figure 23, Panel A).

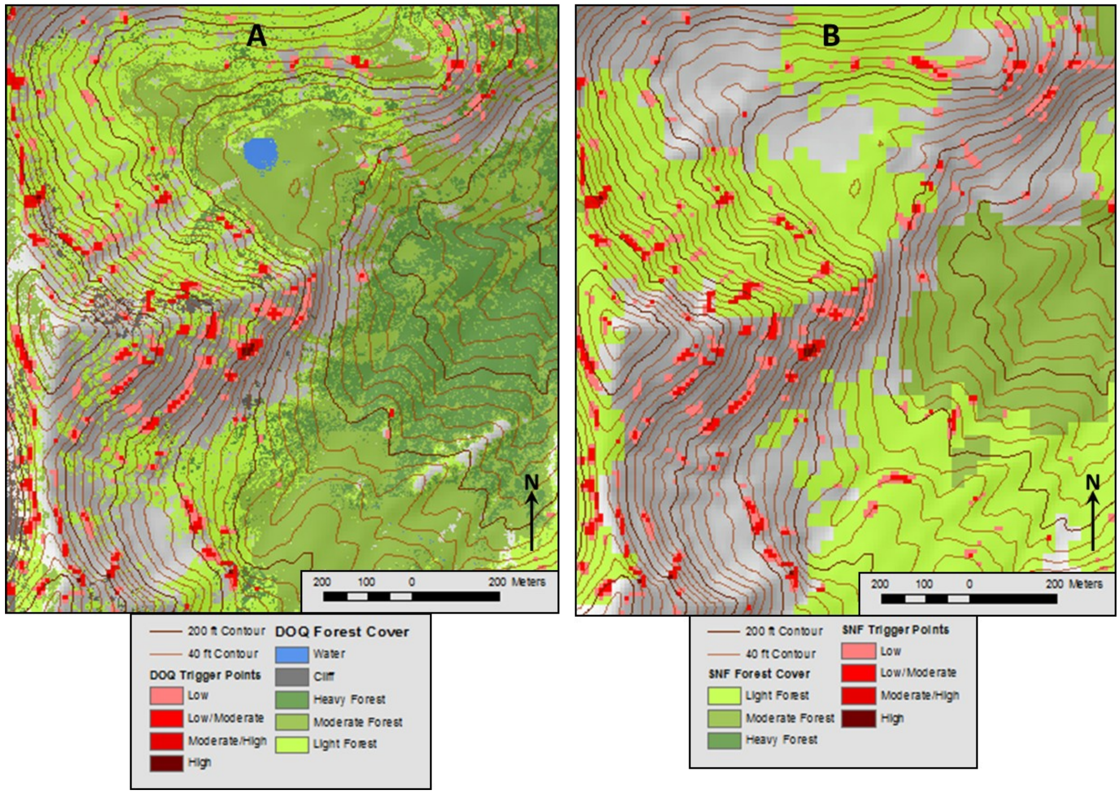


Figure 23: Side by side comparison of 10 meter DEM dataset trigger point results near Titus Peak with DOQ based forest cover and terrain features (Panel A) versus Sawtooth National Forest Land Cover Dataset based forest cover and terrain features (Panel B).

In the 6 km^2 area near Titus Peak that produced good DOQ based forest density layer (shown in section 5.3, Figure 18), the analysis resulted in six classes of land cover for the DOQ based analysis and four classes of land cover for the SNF Land Cover based analysis (Table 9). In terms of area classified, the SNF Land Cover based layer was 1.3 times more likely to classify an area as open ground compared to the DOQ based layer. For lightly forested areas the SNF Land Cover was 1.7 times more likely to classify an area as lightly forested compared to the DOQ based layer. For moderately forested areas the DOQ based layer was 1.5 times more likely to classify an area as moderate forest as the SNF Land Cover based layer. The biggest discrepancy between the two layers was in heavily forested areas where the DOQ based layer classified 40 times more area than the SNF Land Cover based layer. In the terrain feature/forest cover integration process, potential trigger points were excluded if they were in an area of moderate or heavy forest. The DOQ based layer had twice as much area to exclude as potential trigger point in comparison to the SNF Land Cover based layer.

Table 9: Results from DOQ and SNF Land Cover based forest density analysis. Note that in the DOQ based results "Non Forest" is an aggregate of Open Ground, Cliff and Water although they are displayed as individual classes in Figure 20, Panel A.

DOQ Based Forest Coverage				SNF Land Cover Based Forest Coverage			
Cover Type	Class(es)	Pixel Count	Area (meter2)	Cover Type	Class	Pixel Count	Area (meter²)
Light Forest	1	1,462,365	1,462,365	Light Forest	1	25,770	2,577,000
Moderate Forest	2	1,906,064	1,906,064	Moderate Forest	2	13,545	1,354,500
Heavy Forest	3	1,076,212	1,076,212	Heavy Forest	3	252	25,200
Non Forest	4,5,6	1,821,187	1,821,187	Non Forest	0	23,637	2,363,700
Open Ground	4	1,434,921	1,434,921				
Cliff	5	380,920	380,920				
Water	6	5,346	5,346				

While the image quality of the two forest density displays is noticeably different, the terrain feature results are remarkably similar (Figure 23). Almost any particular feature noted in either panel is present in the other although the size and shape of a particular feature might vary from panel to panel. Both forest density layers result in feature number, areas and average area/feature within 10% of each other for Moderate/High and High severity trigger points (Table 10). The DOQ based layer resulted in more than twice as many Low/Moderate features but the total area is within 10% of the SNF Land Cover layer. This will benefit any future study as 30 meter land cover datasets are more common and the reduced processing due to coarser data will streamline any analysis.

Table 10: A comparison of the number, total area and average area of individual potential trigger points derived from both forest density extraction strategies.

SNF Land Cover Based Trigger Points				DOQ Based Trigger Points			
Class	Feature Count	Total Area (m²)	Average Area/ Feature (m²)	Class	Feature Count	Total Area (m²)	Average Area/ Feature (m²)
Low	1,027	188,104	183	Low	911	143,623	158
Low/Moderate	202	97,238	481	Low/Moderate	453	85,740	189
Moderate/High	151	26,003	172	Moderate/High	149	24,739	166
High	30	5,754	191	High	28	5,518	197

6.2 Terrain Feature

While the 30 meter DEM based results were not evaluated in the field they did produce results that are comparable to the 10 meter DEM based results (Figure 24). The coarseness of the 30 meter DEM resulted in steeper slopes being underreported (shown in section 5.3, Table 6). This effect carried through the curvature analysis causing smaller curvature values (shown in section 5.3, Table 7) and fewer terrain features. Compared to the 10 meter DEM derived data (Figure 24, Panel A) the 30 meter DEM derived data (Figure 24, Panel B) consistently downgraded areas of moderate/high and high risk and failed to register many areas of low and moderate risk.

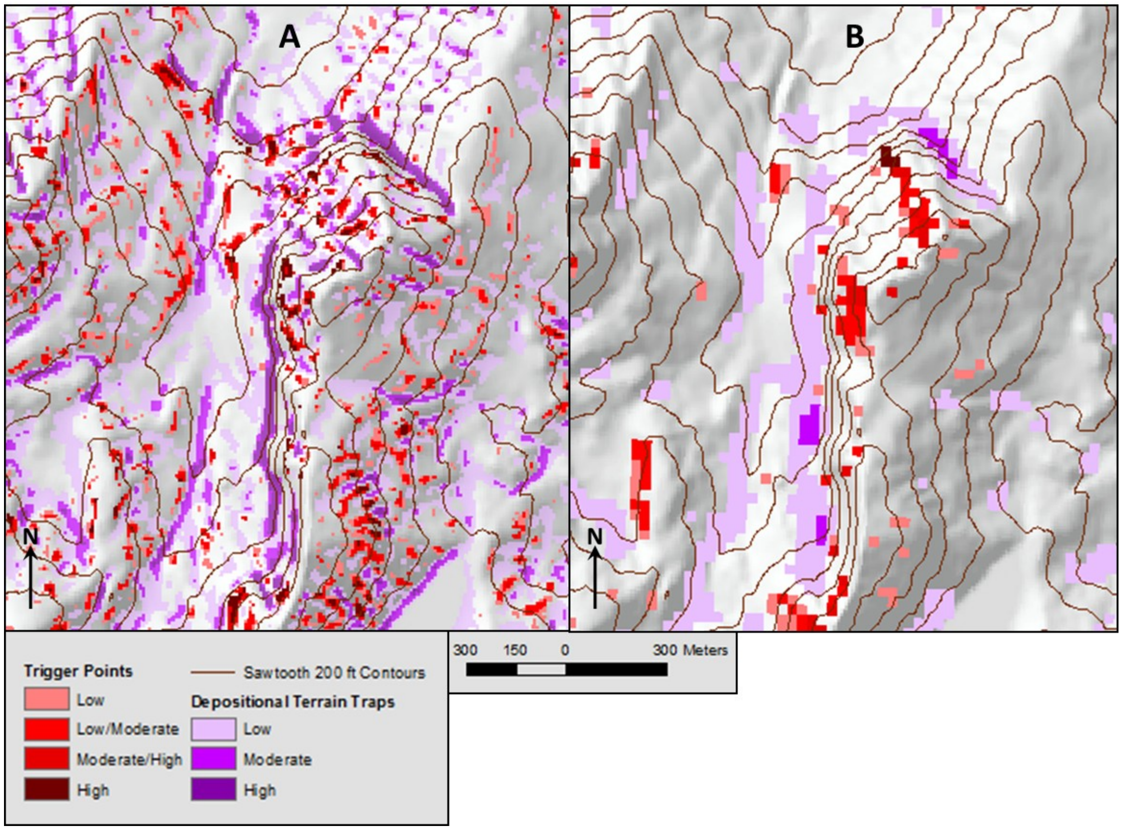


Figure 24: Side by side comparison near Mt Heyburn of the 10 meter DEM based results (Panel A) versus the 30 meter DEM based results (Panel B).

The discrepancy between the extent and detail of the 10 meter DEM derived data is apparent in Figure 25. In Panel B the 30 meter DEM derived terrain analysis resulted in three areas of potential low hazard for depositional terrain traps. In Panel A the 10 meter DEM derived data classifies the two westernmost terrain traps in Panel B as one continuous feature of low hazard nesting an area of moderate hazard with two pockets of high hazard. From Panel A one can see that the feature is an east facing gully that doglegs to the north before opening up to a flatter area. Besides the enhanced definition of that particular hazard several other moderate hazards are apparent from the 10 meter DEM derived data that do not appear in the 30 meter DEM derived results.

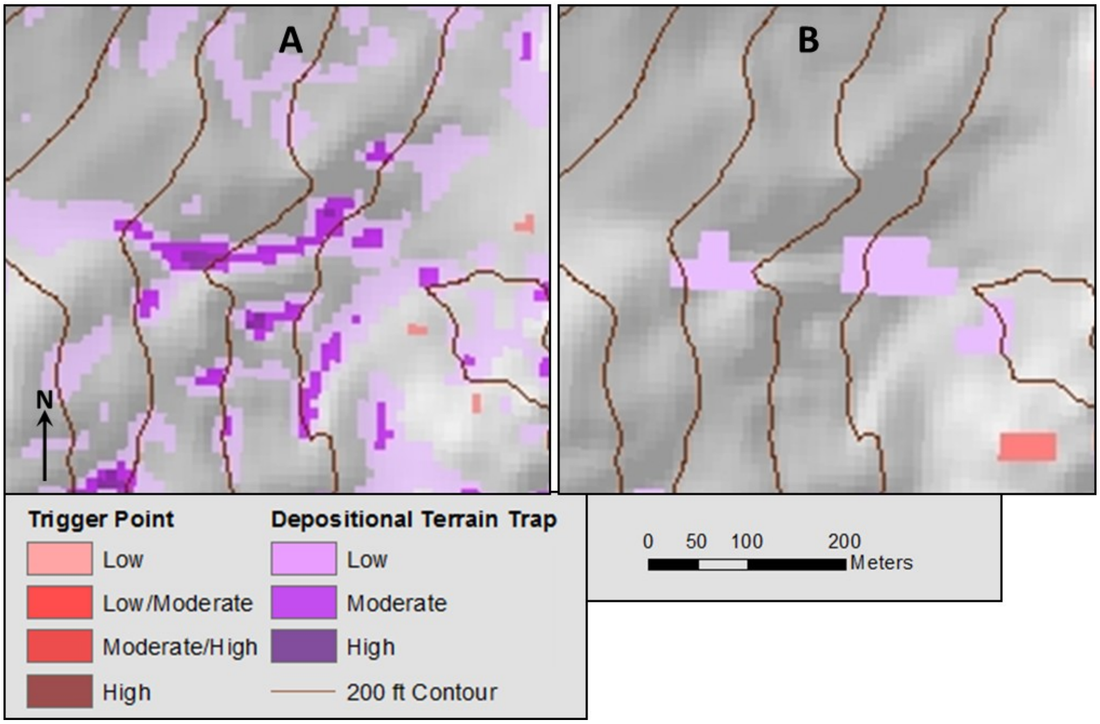


Figure 25: Close up comparison from Figure 21 of 10 meter DEM derived depositional terrain trap features (Panel A) versus 30 meter DEM derived data (Panel B) on an east facing slope.

As one would expect, the potential trigger points identified in the 10 meter DEM derived data were more detailed than the 30 meter derived data as well. One problem with the 30 meter derived data was that the mid-aspect processing used to filter out ridges was not as effective as the 10 meter derived mid-aspect processing. In Panel B of Figure 26 there are several low severity hazard trigger points along the north ridge of the small peak. That these features are not in the 10 meter DEM derived data and the north orientation of the features suggest that they are ridge curvature that did not get filtered out in the 30 meter mid-aspect processing. In the 10 meter DEM derived data trigger points are absent along ridges and most of the features (especially those near the center of Panel A) are oriented perpendicular to the slope, which would indicate a rollover or an area where the slope transitions from a relatively low to a steeper angle.

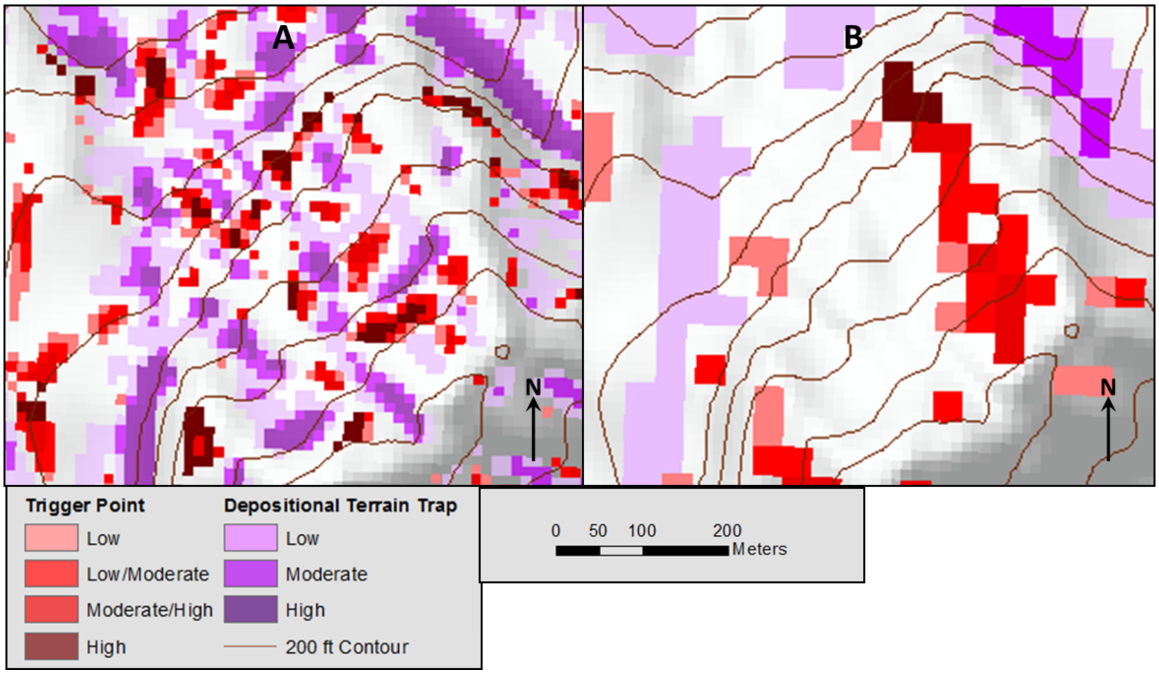


Figure 26: Close up comparison from Figure 21 of 10 meter DEM derived potential trigger point features (Panel A) versus 30 meter DEM derived data (Panel B) on a northwest facing slope.

The Mount Heyburn Field Trial provided an abundance and diversity of hazards to evaluate (and avoid). The features evaluated can be seen in Figure 27 and the corresponding evaluation results in Table 11. At site 1 a medium severity depositional terrain trap was noted in steep creek bottom. The map only suggested an area of low hazard and the feature was noted as a false negative. A low/medium severity trigger point was noted at site 2 corresponding to the feature directly south of the observation site. This particular feature was a rock outcrop in a short but fairly steep area and was a good idea to avoid. At site 3 the depositional terrain trap suggested turned out to be the transition between a frozen alpine lake and the hillside. Since this feature was perpendicular to the slope, debris would disperse instead of concentrating, thus the false positive result. A high severity depositional terrain trap was suggested above site 6, which was true. However, this particular feature is the Petzoldt Couloir which is a popular ski mountaineering route when the conditions are right (field trial conditions were not that great, hence the descent from site 6 and the alternate high point at site 9). That feature highlights the variable element of risk in the backcountry and the amount of risk one is willing to accept. Some features such as the high severity trigger point at site 8 (a rock outcrop that rolled into a large cliff) are so severe that they could be excluded from a severity map. The two medium severity trigger points at sites 10 and 11 were excellent examples of what this study sought. Both features were small rollovers on a relatively open slope. That particular slope is a great pitch for skiing and would be easy for a skier to carelessly ski over. The presence of those marked hazards plus the other hazards on the slope due west of the route helped the researchers thread a low risk route through the area.

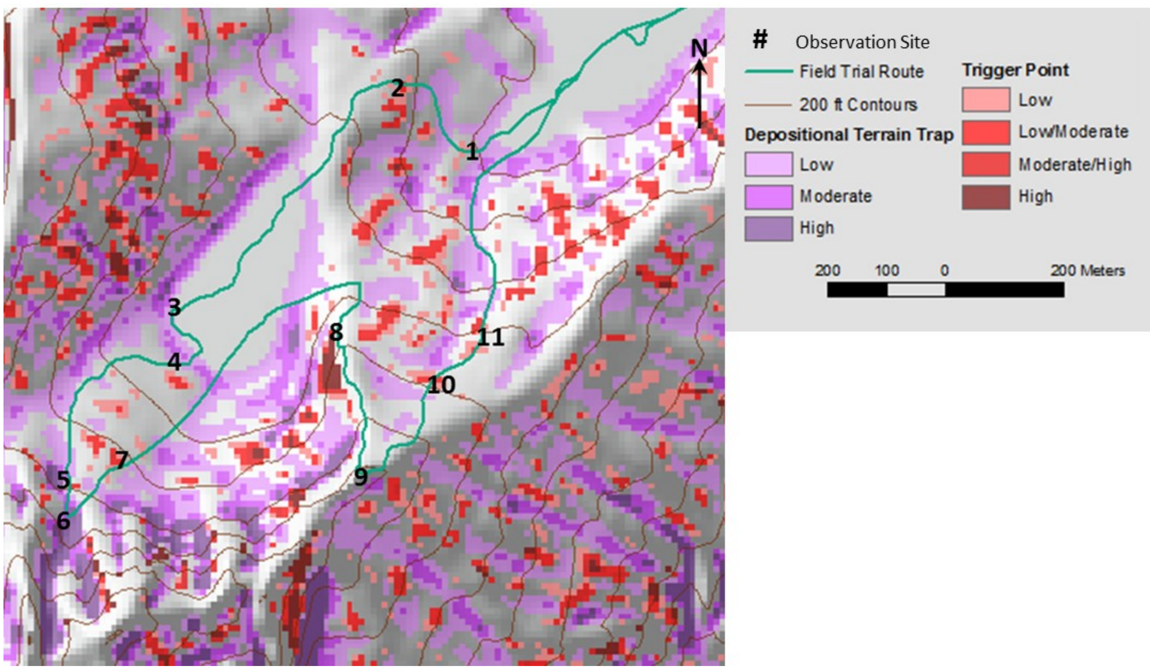


Figure 27: An example of observation sites along the Mount Heyburn Field Trial on 2.4.2013. Observation locations and results were recorded on the hard copy field trial map. The route was recorded with a Garmin GPS unit and observation site locations were added post field.

Table 11: An example of hazard observation results from the Mount Heyburn Field Trial.

Observation Site Number	Hazard Type	Severity	Result
1	Dep. Terrain Trap	Medium	False Negative
2	Trigger Point	Low/Medium	Positive
3	Dep. Terrain Trap	Low	False Positive
4	Trigger Point	Low/Medium	Positive
5	Dep. Terrain Trap	Medium	Positive
6	Dep. Terrain Trap	High	Positive
7	Trigger Point	Medium	Positive
8	Trigger Point	High	Positive
9	Dep. Terrain Trap	High	Positive
10	Dep. Terrain Trap	Medium	Positive
11	Dep. Terrain Trap	Medium	Positive

CHAPTER SEVEN: CONCLUSIONS AND FUTURE WORK

Since there is no crystal ball that can definitively say a particular slope will produce an avalanche on a given day, the next best strategy is one of cautious judgment, experience, attention to environmental variables and a good understanding of the immediate terrain. For backcountry skiers the ability to combine the terrain information from a conventional topographic map with highlights of areas with increased risk is a valuable tool. This study successfully showed that two types of terrain based hazards; slope rollovers that are more susceptible to triggering an avalanche, and steep sided gullies that concentrate avalanche debris, can both be identified for large areas from readily available data sources. The effect of forest density on these features was also accounted for and both hazard types and forest density could be displayed on a map to aid winter backcountry travel. It was also shown that this analysis could be done using data that is available to the public and is relatively inexpensive (a similar sized project could probably obtain all of the data for less than $300).

The hard copy maps used in the field trials were printed a 1:24000 scale. At this scale it was difficult (but not impossible) to correlate smaller features on the map to reality. For a winter backcountry user it is probably enough information to know an area or a particular slope contains hazards but more effort than it is worth to pinpoint specific features relative to one's position. In the future, recreational grade GPS units will probably have larger display areas plus the ability to easily add data and users will be able to view topographic data at scales greater than 1:24000. Until then the forest density layer created from the Sawtooth National Forest (SNF) Land Cover dataset or a similar dataset will probably suffice.

While the 10 meter DEM results are more precise and define areas of risk in more detail with more variation than the 30 meter DEM results, the 30 meter DEM results are not without value. For areas where 10 meter DEM data is not available (i.e. Alaska), 30 meter DEM data will provide some results with the caveat that some hazards may be under classed or not reported at all. For larger areas, 30 meter DEM data may be advantageous for the smaller file sizes and shorter processing time. For this study area's size (~ 2200 km^2) the 10 meter DEM dataset was 136 megabytes (MB) and the 30 meter DEM dataset was only 8 MB. The large difference in file sizes is partly due the nine fold increase in the number of pixels but also due to the pixel depth in the 10 meter dataset being 32 bits versus 16 bits in the 30 meter dataset. The initial processing sequences for this research were developed in ArcGIS 10.1 and then continued with ArcGIS 10.2, in which the Modelbuilder models (Figure 6 and 13) were developed although there is no substantial difference between the two versions. This study had access to a server based GIS platform which allows for larger temporary data files during geoprocessing operations than desktop versions. Someone without access to a server based GIS platform may need to divide a project area into smaller subunits (Figure 12) than this study did. A 30 meter DEM based analysis is fairly quick and could be used a starting point for a 10 meter DEM analysis. The 30 meter DEM results would be used to isolate areas of the 10 meter dataset which would be clipped and processed, reducing processing times and file sizes.

There are some areas in which the results from this study can be improved. Class breaks for this study were made somewhat arbitrarily as there was no data to base them on. A future study could select a small representative area and do more comprehensive field testing with a series of terrain analyses in which the range and interval of hazard classes is varied. Perhaps low severity hazards could be ignored unless they were contiguous or within a certain proximity to moderate or high severity hazards. This project was a terrain based analysis that took no account of snowpack. This was due to the extreme variability in snowpack depth and layering. In the future, better remote sensing or data collection of winter weather patterns could produce snowpack models for large areas that took into account wind loading and scouring, variable precipitation rates and local topographic effects. Such a model could be used to increase or decrease the hazard classification of some features. There is also a need to find the best way to display the information on a user map. Conventional topographic maps already contain an immense amount of information and the addition of new feature types may overwhelm other information (i.e. contours or canopy cover). For this study shades of red and purple were used to denote trigger points and gullies respectively but perhaps there is a more intuitive color scheme or one that is less obtrusive.

Lastly this study sought to find a process through which potential areas of risk could be identified. This was mostly done using single geoprocessing steps with a few processing sequences automated with ArcMap ModelBuilder. For this process to be readily usable for land managers or avalanche experts the component processes need be coalesced into a single automated package in which geoprocessing sequences are linked and ordered such that users only need to provide input data and specify variables.

In years to come, backcountry ski gear will get lighter and better, and people will venture deeper into the winter backcountry. There will never be enough money or people available to control all the avalanche hazards in all of our wild places. Even if there was, such an effort would detract from the untamed grandeur of the winter landscape and defeat the purpose of being there. The best we can do is improve the information available and foster a backcountry ski culture in which one's education, judgment and experience is held equal to their technical ski ability.

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