Avalanche Hazard Mapping in the Cardiff Peak Area of Little Cottonwood Canyon (Utah, USA) using Geographic Information Systems (GIS)

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"Uncertainty is inherent in all avalanche hazard and risk assessments; it can be reduced, but never eliminated." - (Statham et al., 2017).

Introduction:

Mountain snowpacks provide essential water to about one sixth of the world's population that depend on spring melt for drinking and agriculture, among other uses (Stevens, 2020).These same snowpacks, however, also pose avalanche risks to these mountain communities as well as backcountry recreationalists.

Backcountry skiing, also known as alpine touring, involves skiing outside of resort boundaries in unpatrolled backcountry areas where avalanches are possible. Deciding where to safely travel and ski in avalanche terrain is a complex process. Decision making can be difficult and prone to human heuristics. Over the last ten winters, on average 27 people have died from avalanches each winter in the US (CAIC, 2023). There are countless more non-fatal avalanches and "near misses" that go unreported.

One tool used by skiers in terrain-based decision making is avalanche forecasts. These forecasts relay information about which slopes (across a region with varying aspects and elevations) are more prone to avalanche on a given day. Elements such as field observations, snow profiles dug, and knowledge of historic avalanche paths are all considered in composing an avalanche forecast. Physical terrain characteristics such as slope angle, aspect of a slope, and vegetation beneath the snowpack are also considered.

Experienced backcountry travelers will take these forecasts and further interpret them for a given area. Topographic maps, online mapping tools, and photos may be used to familiarize the skier with the terrain and identify hazards before ever stepping foot in the field. These physical terrain characteristics are largely unchanging and can be readily modeled in Geographic Information Systems (GIS). Numerous published studies have begun investing how GIS can be used as a tool in avalanche hazard identification. (See Appendix C for a non-exhaustive list of these studies, as referenced for this project).

This project seeks to establish a model in GIS for mapping avalanche-prone slopes in the Cardiff Peak area in Little Cottonwood Canyon (Utah). This area was selected for the study due to the author's familiarity with the terrain, extensive records kept of avalanche activity, and for the complexity of the terrain. This tool could be generalized to other areas and used to guide efficient terrain decisions by recreational users and professionals alike.

Site Description:

This project was conducted in the Cardiff Peak area in Little Cottonwood Canyon, Utah. Little Cottonwood canyon is located to the SE of Salt Lake City (see Figure 1 below).

Case Study Location within Greater Salt Lake City Area

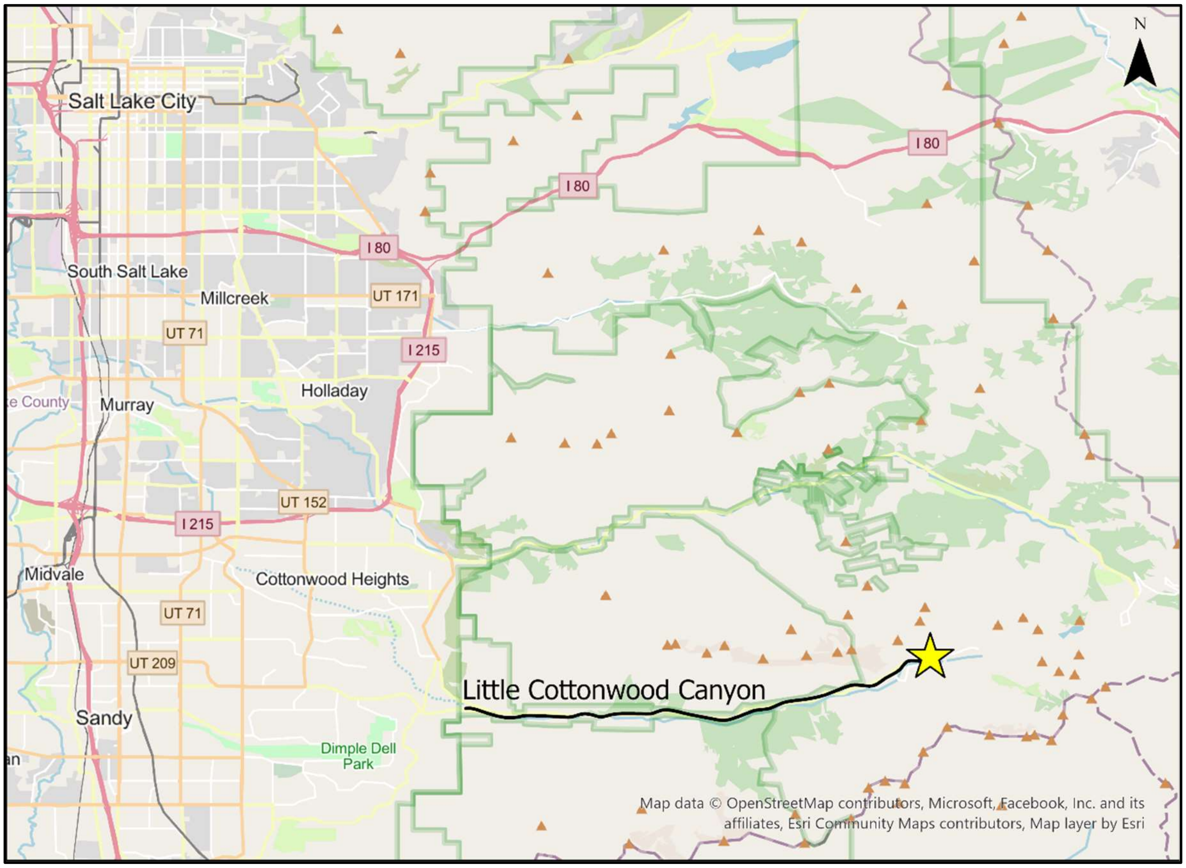

Figure 1. Case study location

This area is located on the slopes of Flagstaff Mountain and Cardiff Peak, which are a part of the larger Wasatch Range. The study area is bordered by two popular backcountry-access points: Superior Trailhead to the west and Grizzle Gulch Trailhead to the east (see Figure 2). The area extends up from the parking lot to the summit of Flagstaff Mountain/along its ridgeline. The total study area is 2.76km^2, or just over one square mile.

Study Area Close-Up: Little Cottonwood Canyon (LCC)

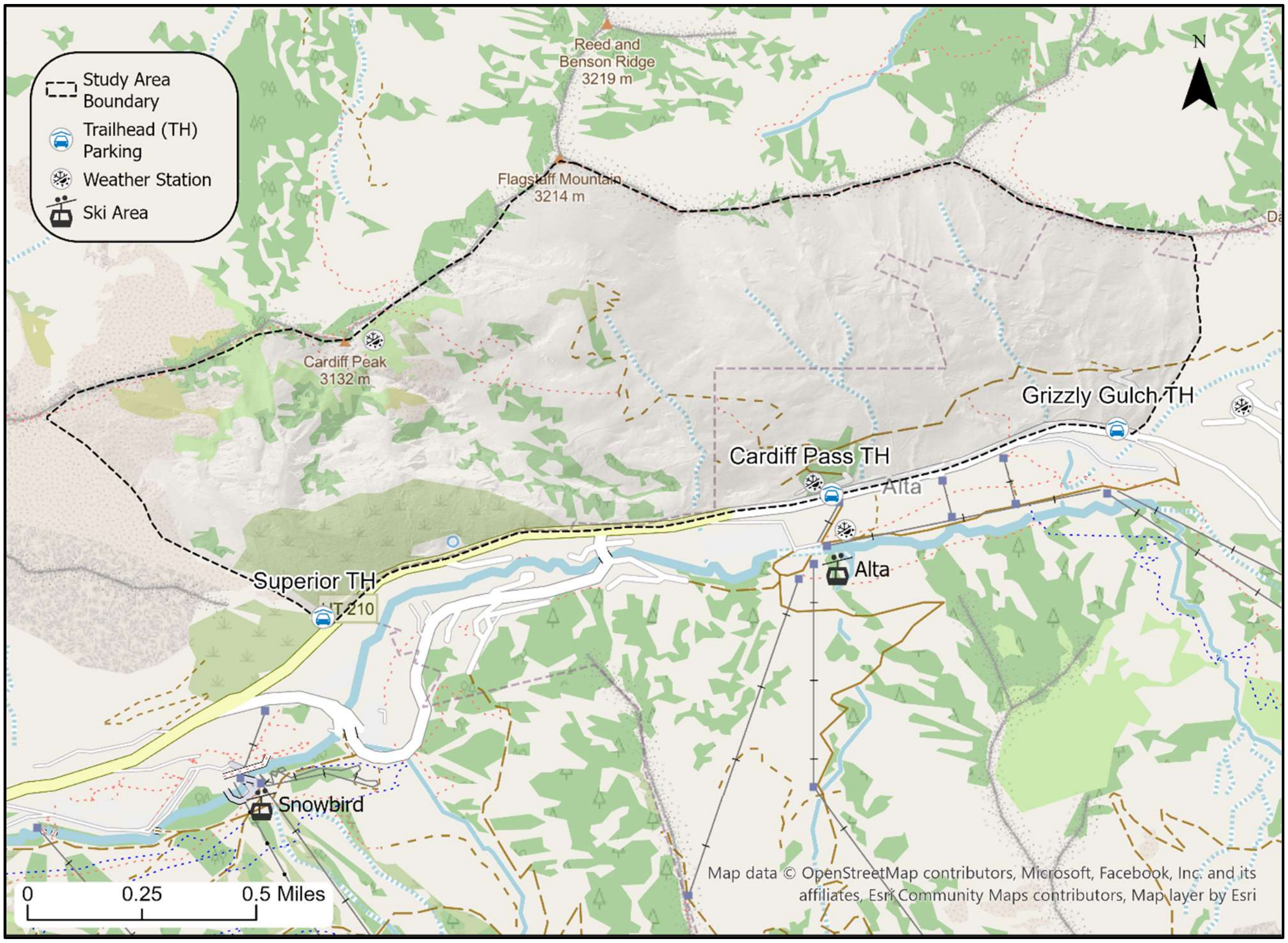

Figure 2. Study area close-up in LCC

This alpine terrain is rugged and rocky, with occasional vegetated areas containing shrubbery and trees (see Figure 3). Most of the vegetation's growth (especially trees) has likely been limited by continual avalanche activity/slide paths. This terrain is popular among local backcountry skiers and its access points are right across the highway from Alta and Snowbird ski resorts.

Study Area Terrain Overview

Figure 3. Study area terrain overview (Google Earth)

Data:

The following data sets shown in Table 1 were used to conduct this study.

Table 1. Data incorporated into this study

Dataset	Data Type	Source	Map Projection	Description
DEM	Raster (1m)	National Map Viewer (USGS)	WGS 1984 Web Mercator -> NAD 1983 UTM Zone 12N	High-resolution DEM raster datasets that, once combined, provide elevation data (in meters) for study area. This elevation data can then be processed into elevation contour lines, terrain slope, and aspect. Elevations range from 2551 – 3199m.
NAIP NDVI Imagery	Raster (1m)	ArcPro *Living Atlas* (USDA)	NAD 1983 UTM Zone 12N	High-resolution, four band aerial imagery pre-processed to calculate NDVI. NDVI values range from 0 – 209.
UAC Avalanche Records	Vector	Utah Avalanche Center (UAC) website	WGS 1984 Web Mercator -> NAD 1983 UTM Zone 12N	.csv spreadsheets of recorded avalanches throughout the State of Utah with slide characteristics and latitude/longitude. Earliest record from 1984 up to present.
Cardiff Peak Weather Station (IFF)	Vector	MesoWest (via UAC and UDOT)	N/A	Annual records of recorded telemetry data. Wind direction specifically was referenced from three years of wintertime records to determine prevailing wind direction. Average wind direction was 232°, 249°, and 231° for Winter '20/'21, '21/'22', and '22/23' (to date) respectively.

GIS Methodology:

Layer Creation Methodology

This analysis incorporated three major data layer inputs: (1) Slope, (2) Aspect, and (3) NVDI (Normalized Difference Vegetation Index) imagery. These data are typical for GIS analyses of avalanche hazard (Scott & Greene, 1970). Within these layers, data were assigned a weight depending on how much a given characteristic increased avalanche hazard at that location. These layers were then aggregated to create a map of avalanche hazard. Areas mapped with higher values are more likely to have avalanche occurrence than those with lower values.

All data were projected into the NAD 1983 UTM Zone 12N coordinate system as recommended by the Utah Geospatial Resource Center (UGRC) (JP, 2015).

Slope

An important terrain consideration for avalanche predictability is the slope of a given run (in particular, the slope at the “start zone” of the avalanche path). Avalanches tend to occur most frequently in terrain 30 to 45 degrees, and within that range, on slopes of 35 to 45 degrees (Tremper, 2018). Below 29 degrees, avalanches are seldom produced (only during periods of extreme instability) (Tremper, 2018). It is worth noting that an avalanche could start in steeper terrain (at the “start zone”) but then run onto flatter terrain well below 30 degrees (forming a “track” or “runout zone”).

Above 45 degrees, there is generally lower snow accumulation due to “sluffing” (snow shedding from steep surfaces). This, in general, inhibits buildup of the snow from a larger consolidated form (known as a “slab”). However, even in the lack of presence of large slabs, sluffing and smaller slabs can still be highly consequential to a skier.

Based off slope categorization described in (Kriz, n.d.), (Scott & Greene, 2010) and (Tremper, 2018), slopes were categorized as follows:

Table 2. Slope Weighting Criteria Used

Slope Angle (degrees)	Weight Assigned	Description
0 – 29	**1**	Seldom avalanches
30 – 34	**2**	Moderate hazard
35 - 45	**3**	Majority of avalanches occur
> 45	**2**	Low snow accumulation but sluffing/small slabs consequential

Aspect

The aspect of a given slope contains multiple facets of information. This study will focus on slope aspect relative to the prevailing wind direction. Snow blown onto a slope (known as "wind loading") during periods of new snow and/or high wind increases avalanche hazard. Snow on these "wind-loaded" slopes can deposit three times faster than falling snow (Cookler & Orton, 2004). Wind-transported snow also more readily forms cohesive slabs.

Wind-loaded slopes exist on aspects opposite to the direction of the wind. As shown in Figure 4 below, a west wind for example moves snow onto an east aspect.

Diagram of Wind Loaded vs. Prevailing Wind Direction

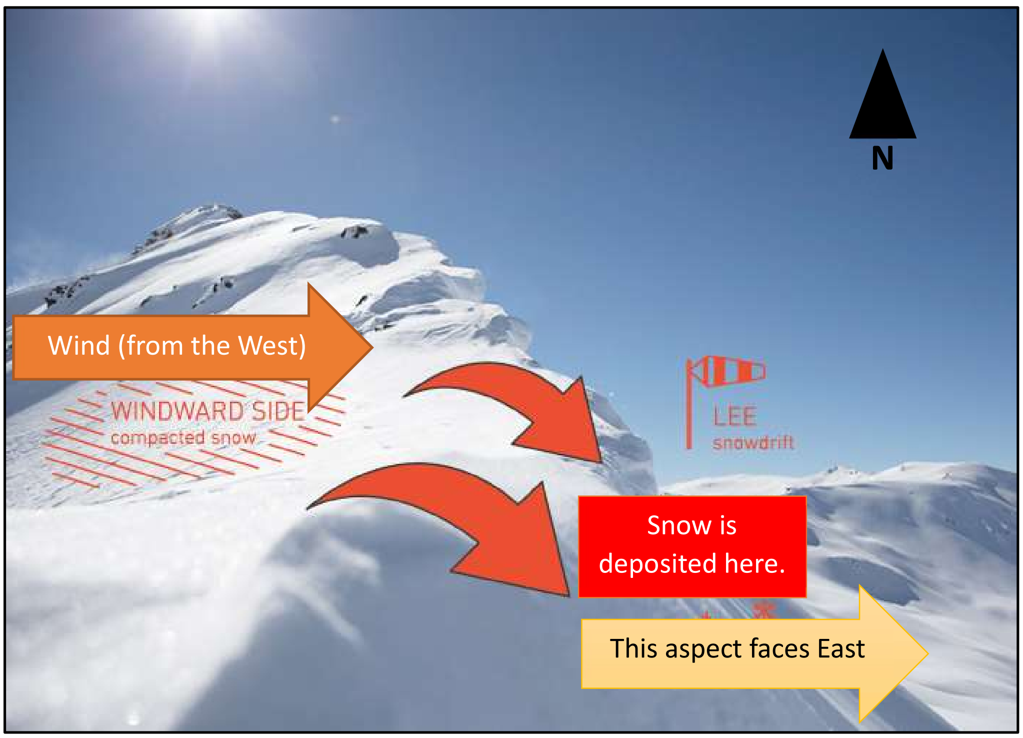

Figure 4. Wind loading of slopes vs. prevailing wind direction (Ortovox, 2023)

To determine the direction of the prevailing wind during wintertime (November through March), weather telemetry was obtained from the Cardiff Peak (IFF) weather station. This station is provided/processed by the Utah Avalanche Center (UAC) and Utah Department of Transportation (UDOT). This data was obtained through MesoWest on 3/10/2023. This weather station was chosen to best capture ridgeline wind direction (vs. other weather stations closer to the canyon floor where topography might affect wind patterns more). See Figure 5 for Cardiff Peak weather station location.

Location of Cardiff Peak Weather Station within Study Area

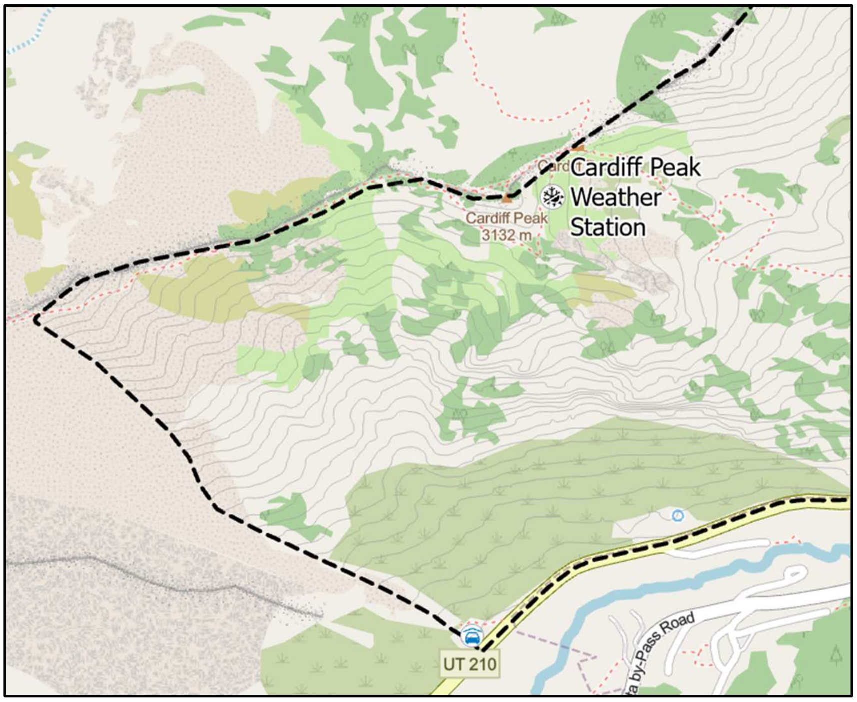

Figure 5. Cardiff Peak weather station location

Data was processed to determine average wind direction for Winter 2020/'21, Winter 2021/'22, and Winter 2022/'23 (thus far). The average wind direction over these last three seasons was calculated to be approximately 238°. This translated to a prevailing wind direction of SW. Thus, NE aspects are the most susceptible to wind loading in this area.

Following methodology outlined in (Durlević, 2022), aspects were assigned the following weights. It is worth noting that NE aspects are not the only aspect that may receive wind-transported snow. Any aspect is susceptible, but aspects equal to and around NE aspects have a higher likelihood. This approximation was confirmed by reviewing avalanche forecasts published in the last three seasons by the UAC that mentioned wind-caused avalanche problems ("wind slabs").

The following weights were assigned to the aspect layer:

Table 3. Weighting Scheme for Aspect Layer

Cardinal Direction	Aspect Start (°)	Aspect End (°)	Weight
N	0	22.5	2
NE	22.5	67.5	3
E	67.5	112.5	2
SE	112.5	157.5	1
S	157.5	202.5	0
SW – *prevailing wind*	202.5	247.5	0
W	247.5	292.5	0
NW	292.5	337.5	1
N	337.5	360	2

NDVI / Vegetation Imagery

The final layer analyzed was NVDI (Normalized Difference Vegetation Index) imagery. This imagery is provided as part of the USDA's *National Agriculture Imagery Program (NAIP).* This data layer, "USA NAIP Imagery: NDVI" was obtained through ArcPro's *Live Atlas.* Other landcover/satellite imagery sources were investigated during this project. However, the NAIP data was deemed the most appropriate in representing vegetation coverage for this alpine area. NAIP data is already used recreationally by experienced backcountry skiers in visualizing treed terrain and forest thickness.

NDVI serves as one metric to assess vegetation presence/density. Bare vegetation slopes increase the likelihood of an avalanche compared to heavily vegetated areas (e.g., forested sections) that may hinder avalanche formation. It is worth noting that, in some cases, forested areas must be very dense to help "anchor" a snowpack / "stabilize" the slope. Sparse trees alone may not prevent a slope from releasing.

NDVI is obtained through calculations with satellite-obtained light band spectrums. Typically, these calculations yield a value between 0 and 1. Values obtained from the NAIP NDVI however ranged from 0 to 209. Different NAIP values were assessed against satellite imagery for the area to determine what NDVI ranges best represented areas with high vegetation.

It was determined that NAIP NDVI values from 0 to 10 best represent areas with dense tree coverage. While ground truthing these values, some limited areas of trees did not "show up" within this value range. Values beyond 10, however, inaccurately portrayed bare slopes as having vegetation. Therefore, the number 10 was adhered to with the goal of conservatively underestimating vs. overestimating tree coverage.

NDVI data was therefore weighted as follows:

Table 4. NDVI Data Classification

NAIP NDVI Value	Land Cover Represented	Weight
0 – 10	Moderate to high density tree coverage	0
11 - 209	Low to no tree coverage	1

Such a simplistic range/weighting schema was used as there was little information found about detailed methodology to do avalanche-related NDVI analyses.

Utah Avalanche Center (UAC) Avalanche Records

To assess the accuracy of mapped hazard ratings, historical records of avalanches (dating back to 1984) in the Cardiff Peak area were downloaded and processed. Each avalanche event occurring within the study area boundary was mapped. These points were then overlaid onto the Hazard Value Index Map. The Hazard Value at each historic record location was extracted to determine how likely the model was to accurately estimate the likelihood that location would produce an avalanche.

A summary of the methodology used in this report is shown in Figure 6.

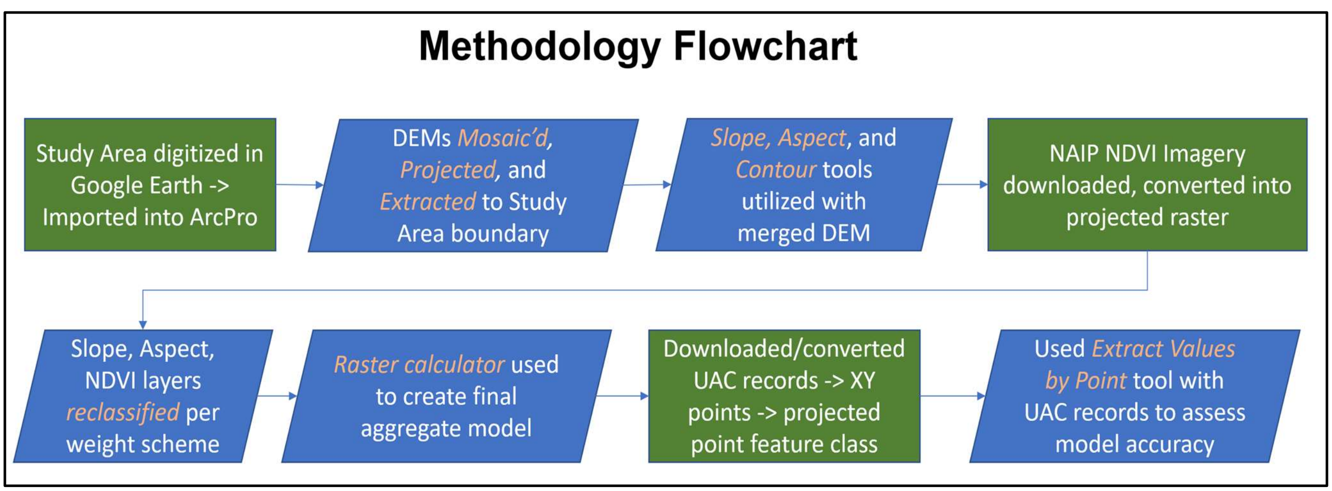

Figure 6. Abbreviated flowchart for methodology used in this study

Results

Using the methodology mentioned above, the following maps were produced:

Resulting Slope Map:

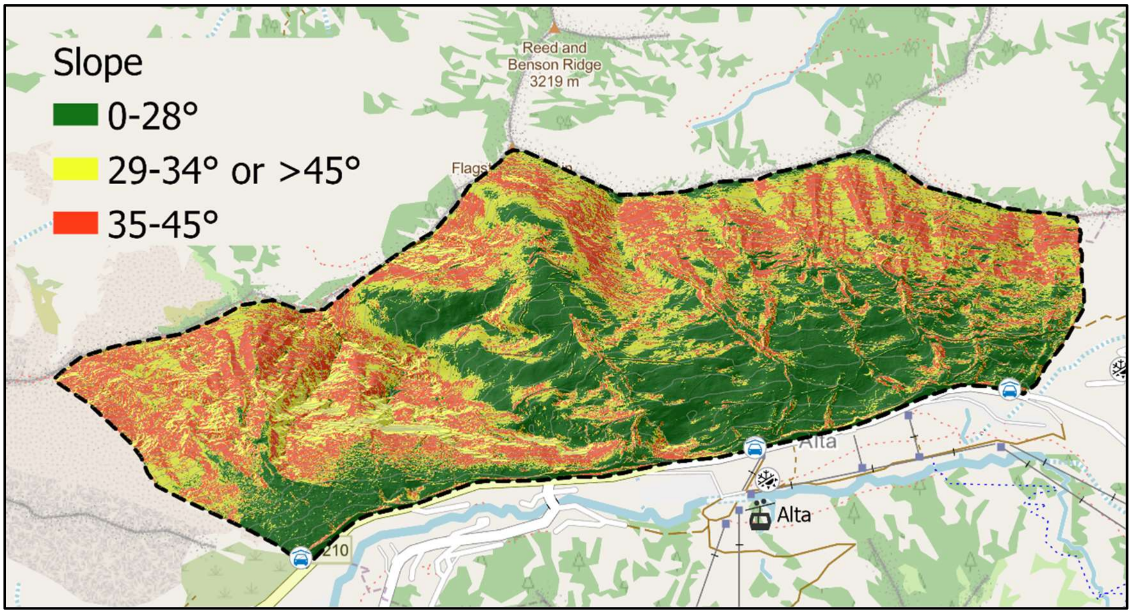

Figure 7. Resulting slope map

Resulting Aspect Map:

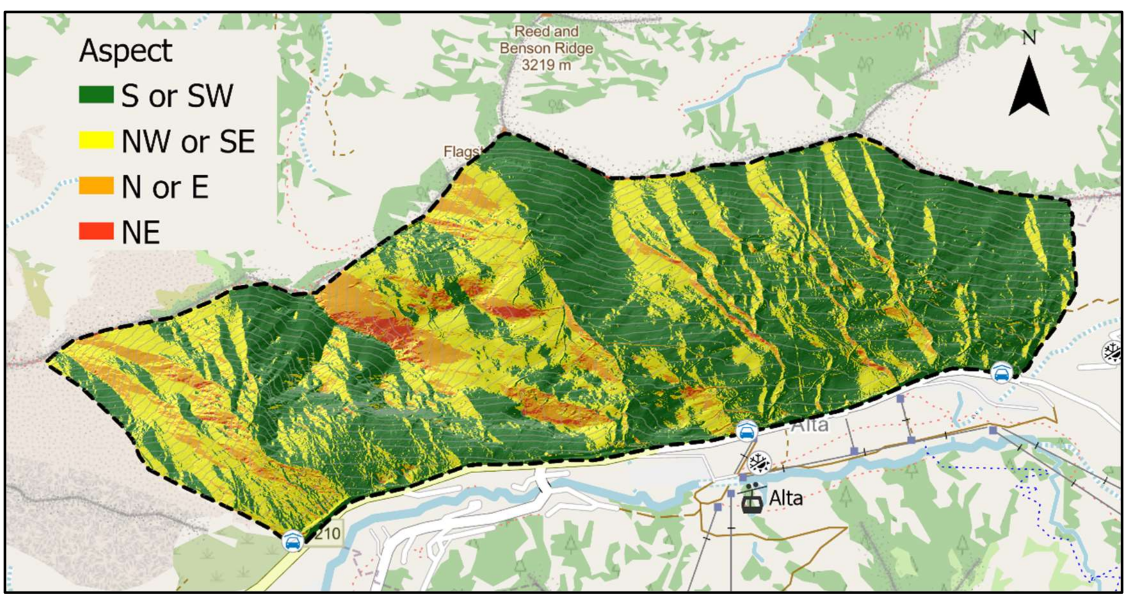

Figure 8. Resulting aspect map

Resulting Tree Coverage/NDVI Map:

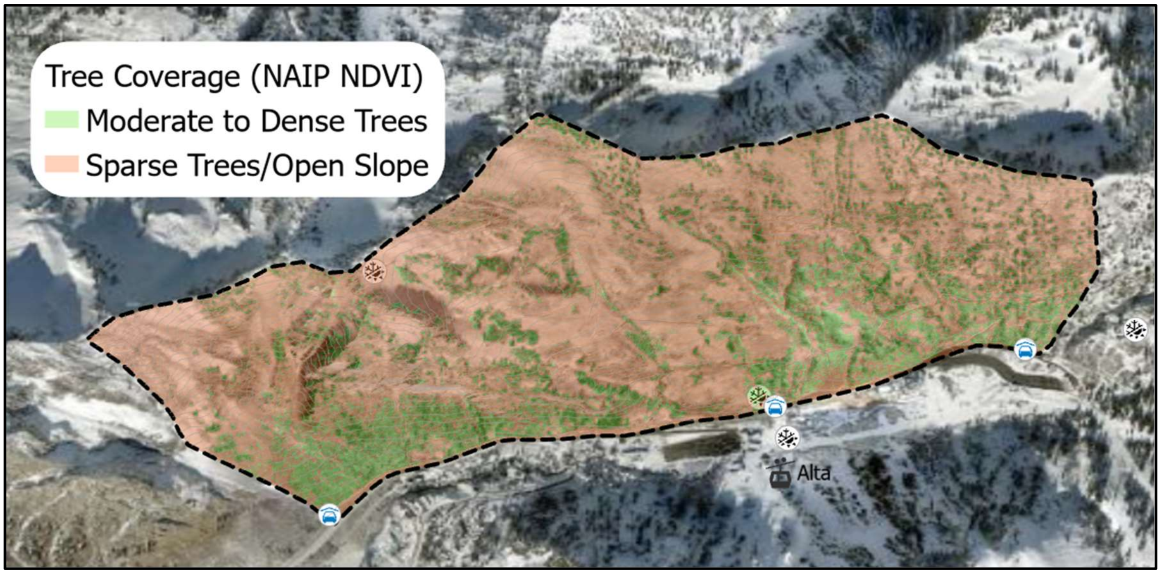

Figure 9. Resulting NDVI map

When combined into an aggregate map, the following map of Hazard Index values was produced (Figure 10). Reference Appendix 1 for a full-page version of this map.

Avalanche Hazard Index Map (Final Result):

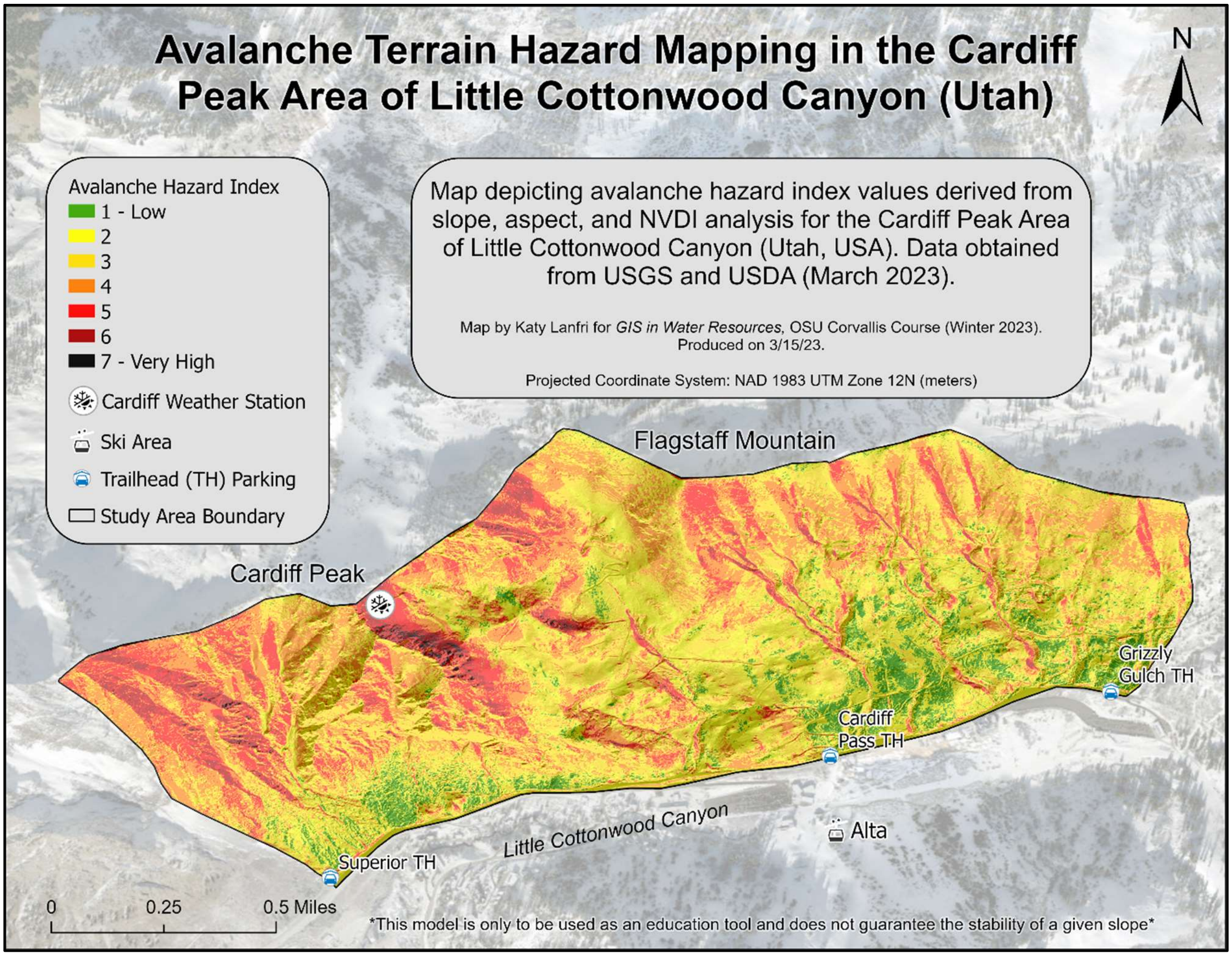

Figure 10. Avalanche Hazard Map

The hazard index map produced shows large areas of moderate to high danger terrain for the Cardiff Peak Area. Lower hazard areas appear toward the bottom of the slopes. These results align with personal experience recreating in the area. This terrain is complex to manage, with several start zones. Even with lower hazard areas toward the bottom, avalanches started up high could easily runout onto lower slopes.

This map helps paint a picture to users unfamiliar with the area/terrain of zones to be extra attentive to. This map can be used as one tool in the toolbox of decision making in avalanche terrain. It should not (and no produced hazard map should) be used alone to make travel decisions.

Combined with UAC historic avalanche records obtained per methodology described above, the following map was produced to assess the accuracy of the hazard map (Figure 11). See Appendix 2 for a full-page version of this map.

Hazard Map compared to UAC Records:

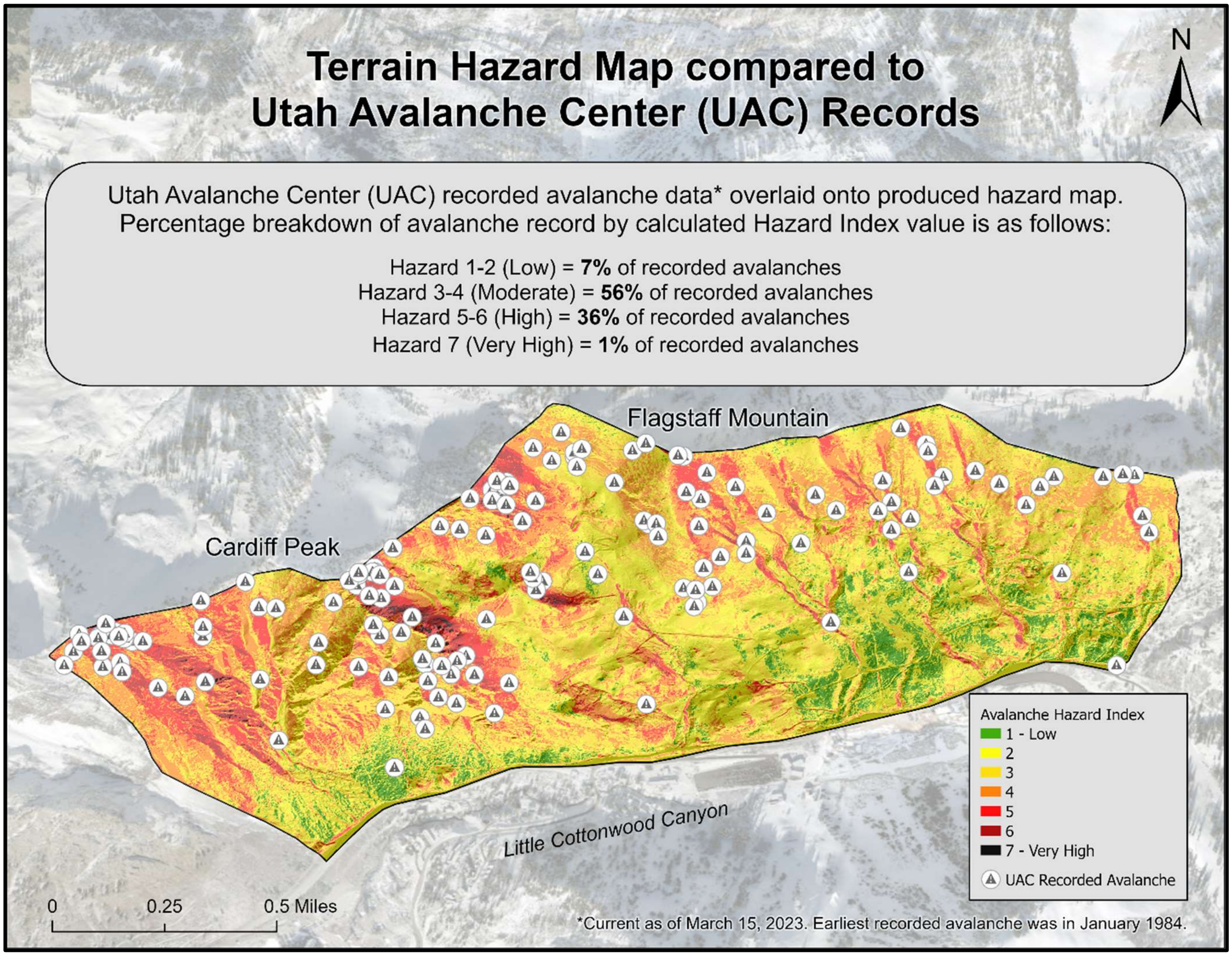

Figure 11. Hazard map with referenced UAC records

This information can also be displayed graphically as shown in Figure 12.

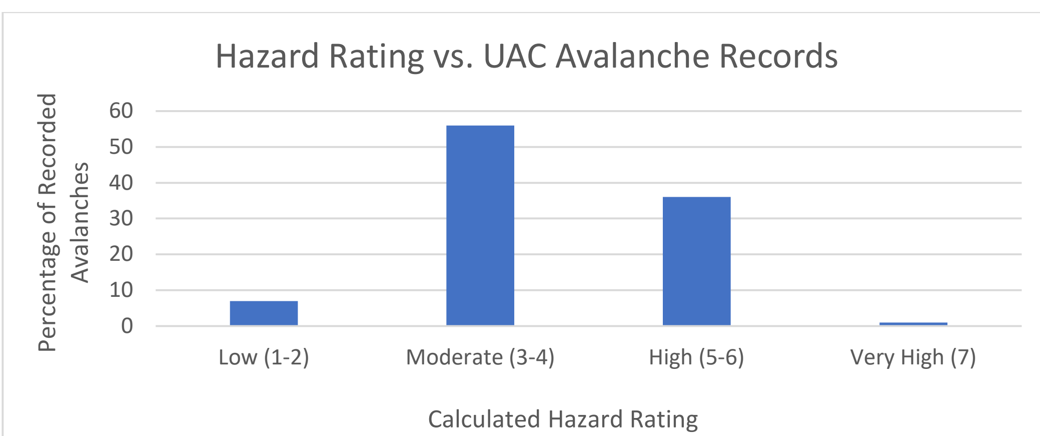

Figure 12. Graph of calculated hazard rating vs. UAC avalanche records

Conclusion

Overall, the hazard index model appeared to be fairly accurate compared with historical recorded avalanches. Under 10% of locations with historic avalanches were marked as a "low" hazard. (Though, even small percentages of unidentified potential avalanche start zones/paths can translate to big, real-life consequences).

The model performed adequately in identifying areas with moderate to high hazard. In the avalanche world, where nothing is definite nor written in stone, this result is therefore "good enough". Regardless of the distinction between moderate and high probability, an experienced user who chooses to travel in that terrain assumes the higher level of risk and should be prepared for the worse case scenario. No map or model can truly predict the uniqueness of avalanche conditions on a given day.

Model Limitations

It is worth pointing out several limitations to this model. The most prominent is that this model only accounts for terrain-influenced avalanche hazard factors. It does not incorporate any snowpack, weather, or "trigger" (what causes the avalanche) factors. A terrain-based hazard map only paints part of the picture.

Additionally, the DEM used as a base for this model, while of high resolution (1m), will inevitably miss micro features on a slope face (McCollister & Birkeland, 2006). Even small spots oversimplified by the model can still be start zones that propagate an avalanche outward. Angles may be underpredicted and terrain on the edge of being steep enough to avalanche may not be caught by the model if data is unintentionally over-smoothed during analysis.

As mentioned prior, this map demonstrates hazard areas where avalanches could start. However any terrain, no matter how flat the slope, is affected by the terrain above it. An area marked as "low hazard" on the map could be easily overrun by a destructive avalanche that was triggered in steeper terrain above.

Recommendations for Further Studies:

There are studies published (e.g., Cookler & Orton, 2004) that explore the use of weather station telemetry and interpolation to attempt to account for weather-based avalanche hazard factors. Given the number of local weather stations in Little Cottonwood Canyon with publicly accessible data, this avenue would be worth exploring.

There are also studies employing the use of machine learning to improve mapping results (McCollister & Birkeland, 2006). Given the availability of UAC avalanche record data state-wide, this could afford a valuable machine learning opportunity. With the amount of local knowledge and expertise within the local backcountry community, one could further validate produced models.

Programs have been developed to link historic weather and avalanche data with a given area's terrain map (Cookler & Orton, 2004). This allows users to quickly create hazard maps on days with conditions similar to past patterns. Incorporating this historic knowledge into a model would further increase its accuracy. While explored more extensively in Europe, these types of programs do not appear to have as much traction yet in the US.

Appendices:

Appendix A: *Figure 13 - Avalanche Hazard Index Map (Full Page)*

Appendix B: *Figure 14 - Hazard Map compared to UAC Records (Full Page)*

Appendix C: Bibliography

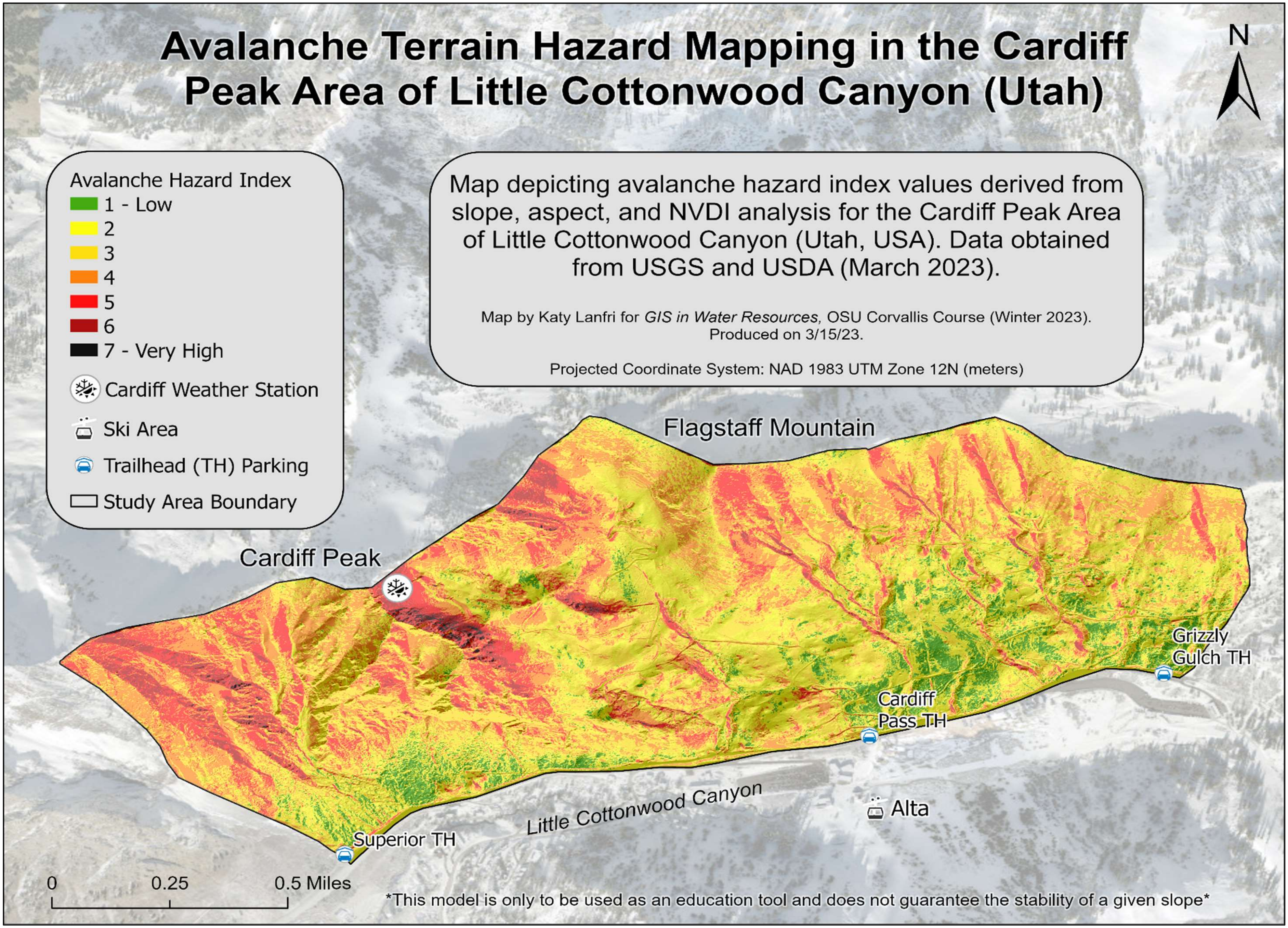

Figure 13. Appendix A - Avalanche Hazard Index Map (Full Page)

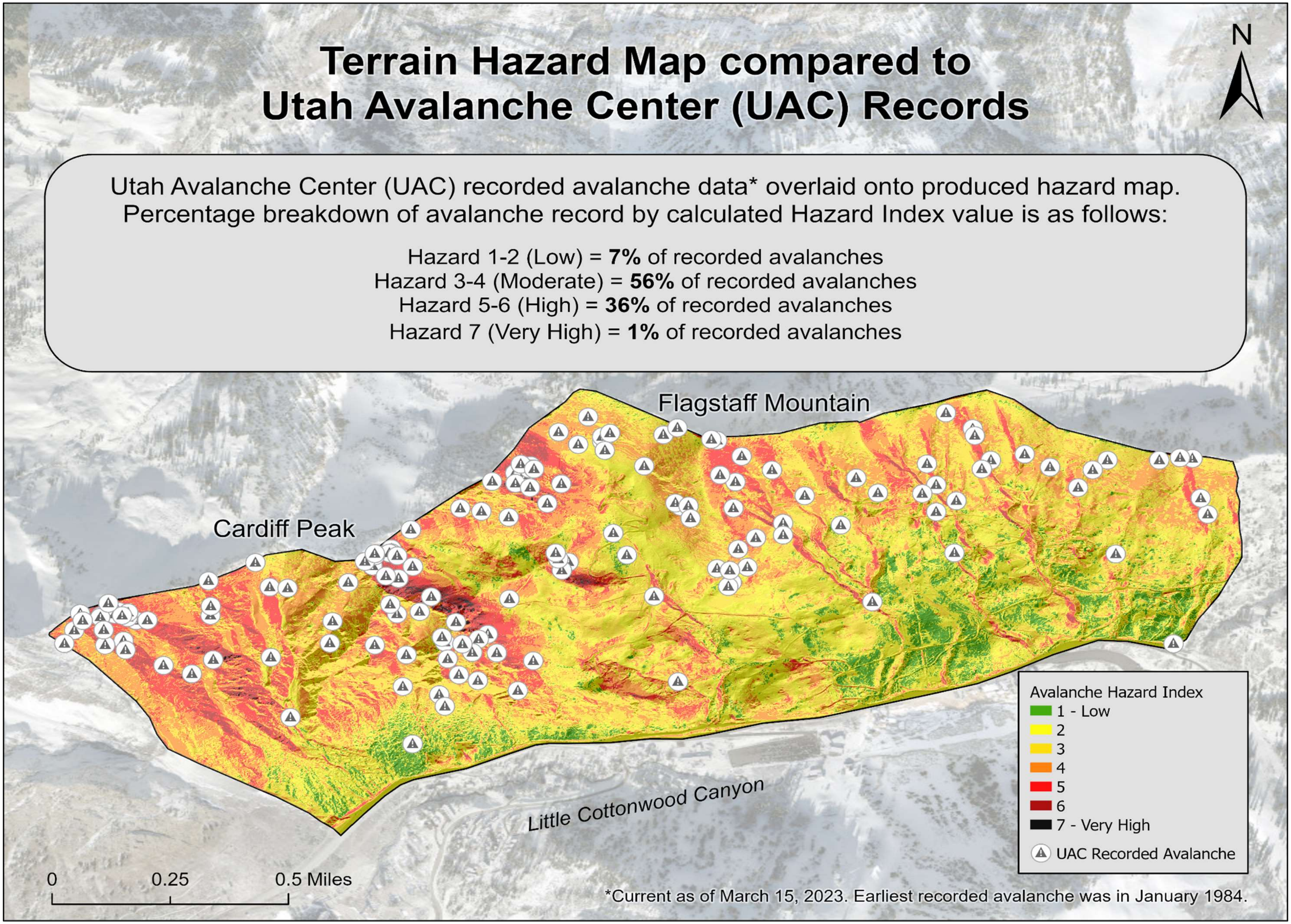

Figure 14. Appendix B - Hazard Map compared to UAC Records (Full Page)

Appendix C: Bibliography

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