# SNOW AVALANCHE RESEARCH AND FORECASTING WITH GIS AND GEOSPATIAL SCIENCES

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ABSTRACT: Geographic information systems (GIS) and geospatial sciences have been used effectively in data collection and snow avalanche related research for over 50 years. Improved processors and programs have provided more user-friendly data collection and management applications, and the modern digitization of avalanche atlases allows for consistent recording and easy identification of avalanche events and their locations. Historic weather records and observations of snow pack properties (depth, SWE, stratigraphy) can be efficiently correlated with observations of avalanche activity when records of both weather and avalanche activity are managed digitally. Weather data is stored with a spatial attribute to help account for spatial variability, and allow for correlation with topography derived from a digital elevation model (DEM). A majority of avalanche and weather data is collected in areas of high use, such as highways, towns, or ski areas. Therefore, there are few complete and thorough temporal records of avalanche activity and weather data, and spatially complete records are non-existent as remote locations between areas of concentrated use are rarely observed. Remote sensing instruments have been used to record avalanche activity data in backcountry areas, and satellites are used to collect a variety of snowpack properties. Avalanche forecasting applications using statistical correlation of avalanche activity and weather data have been explored in many regions, but these analyses are only exploratory and used as an expert aid in forecasting. Further exploration of creating more temporally and spatially complete datasets may lead to more thorough and meaningful analyses in snow-avalanche research.

## 1. INTRODUCTION

Geographic information systems (GIS) and geospatial sciences have become increasingly useful in snow and avalanche research. Increased availability of geospatial data coupled with decreasing costs of computing software and more efficient computing capabilities has enabled more snow scientists to use geospatial sciences in their research. In the fall of 2009 five students at Montana State University compiled a research paper to review studies that have incorporated GIS and geospatial sciences in snow avalanche studies, and to discuss the influence of GIS to suggest directions for the use of geospatial sciences in future snow avalanche research.

We explored the topics of avalanche mapping, avalanche forecasting, spatial variability, snow distribution, and water in the snowpack. We searched for articles relating to these topics in a number of popular scientific journals from the last twenty years, as they are all of fundamental importance to understanding, forecasting, and modeling avalanches. A “web of science” approach was used by checking the references of all reviewed articles for other articles that potentially used geospatial sciences for snow avalanche research. The literature review did not encompass every study that has linked snow science and GIS. However, an attempt was made to include all research related to significant topics in snow avalanche science over the last two decades.

Snow avalanche research incorporates a broad range of geospatial properties, so it is appropriate to narrow the definition of GIS and geospatial sciences as it is used in this review. This study focuses on research that uses GIS and computer software to collect, manage, analyze, or display geospatial data that has a traditional or potential component related to snow avalanche research. Specifically, this article will focus on the evolution of geospatial data management capabilities, and how geospatial sciences are essential to past and future research in forecasting, modeling, and mapping snow avalanches and related phenomena.

## 2. AVALANCHE MAPPING AND FORESCASTING

### 2.1 Hazard maps and avalanche atlases

Some of the earliest geospatial sciences used for snow avalanche research include the creation of avalanche hazard maps and avalanche atlases

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for towns and transportation corridors in Norway, Switzerland, and Colorado (Armstrong, 1976; Borrel, 1992; Frutiger, 1980; Hestnes and Lied, 1980; Ives and Plam, 1980; Miller et al., 1976). At the same time hazard maps and atlases were created, topographic maps at scales typically between 1:24,000 and 1:100,000 were used to define terrain parameters, such as slope, aspect, elevation, alpha angles, and curvature of avalanche paths, for modeling runout distance and risk to people and structures (Bakkehoi et al., 1983; Bovis and Mears, 1976; Frutiger, 1990; Hestnes and Lied, 1980; Lied and Bakkehoi, 1980; McClung and Lied, 1987). Terrain parameters for similar studies are modernly defined using a GIS and a digital elevation model (DEM) with a typical grid resolution between 5m and 100m (Gruber and Bartelt, 2007; Delparte et al., 2008; Forsythe and Wheate, 2003; Maggioni and Gruber, 2003). DEMs are essentially map layers of grid cells with an attached value for the elevation at the center of each cell. Various studies map risk and potential hazard in settlements using DEMs and GIS software to model runout distance for known, or potential, locations of avalanche paths (Cappabianca et al., 2008; Gruber, 2001; Gruber and Bartelt, 2007; Keylock et al., 1999; Maggioni and Gruber, 2003).

Modern digitization of avalanche atlases and hazard maps combined with computer literate practitioners has enabled the establishment of easily manageable and updateable databases that hold records of avalanche events, spatial representations of avalanche paths, and are critical for the creation and validation of models, which may aid in future understanding and forecasting of snow avalanches (Borrel, 1992; Jaedicke et al., 2008; Jaedicke et al., 2009; Schmidt and Hartmann, 1988). Models and databases can be used in combination with meteorological data to correlate temporal patterns between avalanche activity and weather or snowpack properties at daily to seasonal scales (Jaedicke et al., 2008; Schmidt and Hartman, 1988).

### *2.2 Avalanche forecasting models*

Early programs, such as SnowBase software used at Alta Ski Resort, Utah, were used for management of meteorological data, snow stratigraphy data, and avalanche occurrence. The database was used to model conditions with an output of snow cones, which show a variety of parameters stratified by aspect and elevation in polar graphs, and snow roses, which show wind patterns and snow loading considerations on different aspects and elevations (Atkins, 1992; Tremper, 1992). Snow cones and snow roses are still used by avalanche forecast centers, and also show danger ratings for given mountain ranges.

GIS has been a valuable interface for managing historic records along with spatial data to create models. Historic data of meteorological conditions collected at remote weather stations, and snowpack properties collected by researchers and ski patrol, have been useful in linking weather patterns and snowpack properties with past records of individual avalanche events or cycles (Brabec, 2001; Brabec and Meister, 2001; Bovis, 1977; Gassner et al., 2000; Giraud, 1992; Hendrikx, 2004; Hendrikx et al., 2005; McCollister et al., 2002; McCollister et al., 2003, Purves et al., 2003; Rashpal, 2002). Regions that have long historic records, such as the mountainous regions of Europe, have found this approach to be helpful in identifying weather patterns leading to avalanche events and cycles. Forecasts in France began daily recordings of snowpack and meteorological data in 1971, and in 1986 initiated a computerized forecasting model, which now covers over 5000 km$^2$ (Garreaud, 1990). Weather data (i.e. snowfall, wind direction, wind speed), weekly snowpack profiles, and all avalanche activity were recorded three times daily. The GIS assisted in statistical calculations using a nearest neighbor approach in which present meteorological conditions were compared to days in the past with similar conditions to determine avalanche probabilities. A daily historical record of ~4000 meteorological days and 400 snow pack profiles from past winters was used for this analysis. Hazard estimations derived from historical patterns can be incorporated in a graphical snow cone format where risk and natural avalanche type are displayed for different aspects and elevations. Forecasts derived using these types of data with a probabilistic approach are only useful in conjunction with local expert knowledge of snow climate and terrain characteristics, and are not solely used to create forecasts. However, they are an aid in forecasting and identification of weather and snow property patterns that lead to avalanche events and cycles.

## 3. REMOTE SENSING AND SNOW DISTRIBUTION

Historical records are unfortunately limited to areas of settlement and activity, and therefore do not provide a continuous spatial or temporal record of activity. In remote regions where the availability of historical data is limited, remote sensing applications and digital terrain analyses using GIS have been tested to develop databases of avalanche events, and collect weather and snow distribution data (Bitner et al., 2002; Bühler et al., 2009; Cartwright, et al., 1990; Forsythe and Wheate, 2003; Gruber and Haefner, 1995; Hall et al., 2002; Hendrikx et al., 2005; Klein et al., 1998; Maggioni and Gruber, 2003). The purpose of these remote applications is to obtain data about locations that have limited observations of weather, snowpack properties, and avalanche events due to remoteness, limited accessibility, and/or hazardous conditions.

### *3.1 Snow property distribution models*

Studies focusing on distribution of snow properties (i.e. snow depth, SWE) and spatial variability have recently benefited from technological advancements in remote sensing and GIS capabilities. Improved modeling and data collection capabilities of snow property distribution and spatial variability may aid in improved forecasting models. Prior to the mid 1980s interpolating values between remote weather stations or test sites was the norm for providing relatively accurate values for snow depth, or snow water equivalent (SWE) across a region and remains a primary tool in many regions across the world today. Over the course of the last fifty years the availability of land-based remote sensing equipment and aerial/satellite imagery has increased dramatically along with computer processing capabilities and software. Snow cover maps have been produced using data collected from remote sensing equipment by the National Oceanic and Atmospheric Association (NOAA) (Hall et al., 2002), the National Operational Hydrologic Remote Sensing Center (NOHRSC), the National Environmental Satellite, Data, and Information Service (NESDIS), and the National Aeronautical and Space Administration (NASA).

Remote sensing technology has also assisted in creating snow transport models, quantifying radiation input and output over a surface, interpolating SWE, and exploring terrain properties associated with surface hoar formation (Corripio et al., 2004; DeBeer and Pomeroy, 2009; Deems et al., 2002; Liston et al., 2007; Molotch, 2009; Schaper et al., 1999; Schauffhaser et al., 2008; Schweizer and Kronholm, 2007; Tesche and McNally, 1988). Also, snow cover area, grain size, albedo, and surface water content were all calculated from remotely sensed data over an area covering nearly all of the Sierra Nevada (Dozier et al., 2009). The ability to model and remotely collect data for the distribution of snow properties may aid in more robust correlations between snow properties and avalanche events in the future.

### *3.2 Limitations and uncertainties associated with remotely sensed data and snow models*

DEMs derived from remotely sensed data are made available by the United States Geologic Survey (USGS) in varying resolutions and have been a significant tool in mapping and modeling of snow properties. Many snow distribution models use terrain parameters, derived from DEMs, as inputs to predict a value (i.e. snow depth, SWE, albedo) at an unobserved location. The accuracy of DEMs is a major limitation in models. Studies have found decreased modeling accuracy with lower resolution DEMs (Wu et al., 2008) as analysis is limited by the lowest resolution data. For example, Prokop (2008) acquired terrestrial laser scanner data with 9cm resolution, but the correlation analysis was limited by the 5m resolution of modeled airflow data. Measurement errors associated with data collection equipment can also create uncertainties. These uncertainties can often be accounted for if the measurement error can be defined. Furthermore, incomplete records of historical avalanche events can create problems when correlating weather events with avalanche events. In efforts to obtain more complete avalanche observations some areas such as Little Cottonwood Canyon, Utah and Teton Pass, Wyoming use infrasonic avalanche monitoring systems. These represent an electronic “trip wire” to remotely locate avalanche occurrence, which are then automatically input to a GIS and displayed on a time graph and hillshade view to locate the temporal and spatial occurrence (Yount et al., 2008).

Although accuracy of data may limit the accuracy of results, data quality and completeness has improved and will likely continue to improve with easier data management and collection capabilities. DEMs have improved from 30m to sub-meter accuracy with Light Detection and Ranging (LiDAR) data. GPS units are now capable of delivering locations with 1cm accuracy. Terrestrial scanning lasers can measure snow depths with accuracy below 10cm (Prokop, 2008). Improvements in accuracy, completeness, and resolution of data will both promote more studies using GIS and increase the significance of these studies.

## 4. CONCLUSION

The combination of snow and geospatial science was once limited simply to maps of known avalanche areas before technological advancements allowed for user-friendly data management and easily updateable documents on a computer interface. Advancements in GIS technology, improved data resolution, establishment of avalanche atlases and databases, and sophisticated remote sensing and satellite technology combined with an increase in computer literate researchers and practitioners supports a promising future of robust and efficient research in the field of snow avalanche science.

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