Using GIS data and mapping techniques to delineate areas most prone to hazardous rockfall in the state of Colorado

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Abstract

This paper presents the construction of a GIS geodatabase to effectively integrate, manage, and display rockfall hazard ratings for the Colorado Department of Transportation (CDOT). The intention of this project is to incorporate an existing database into GIS format for improved visualization and comparison of rockfall hazard with the factors suspected of causing rockfall. State highways are often constructed in geologic areas where rockfall is common. As a result, state Departments of Transportation (DOTs) are faced with the arduous task of maintenance and clean up of these highways. The development of a Rockfall Hazard Rating System (RHRS) has enabled many state DOTs to better assess the rockfall hazard in their state. The integration of the RHRS within a GIS will facilitate further preparedness by DOTs and their effective involvement with the travelers that frequent roadways attributed with rockfall hazard.

Introduction & Background

Certain areas of state highways are often constructed on steep terrain where rockfall is common. A variety of problems can be caused by rockfall, including traffic accidents, increased maintenance costs, blocked lanes and roads, as well as other hazards to the public (Bateman, 2003). In the past, state Departments of Transportation (DOTs) and their maintenance crews simply reacted to rockfall as they occurred by cleaning up the site and installing temporary mitigation structures (Russell, 2005). The continued occurrence of rockfall has prompted many states to establish a Rockfall Hazard Rating System (RHRS), enabling state DOTs to categorize the rock slopes according to the degree of hazard present. Colorado is one such state.

Numerous factors contribute to rockfall instability and incidents. These factors include climate, slope conditions, geological characteristics, and traffic conditions, and are further sub-categorized for additional rating features. Figure 1 shows the original RHRS developed by Pierson in 1994. The state of Colorado's current RHRS is a slight modification of the original RHRS. The original RHRS system used subjective terminology such as "Possible, Minor, Many; Low, Moderate, High; Few, Occasional, Many" etc. The state of Colorado has modified the original RHRS system to fit their needs by removing such terminology and replacing the scoring parameters with numerical values, 3, 9, 27, 81, ranging from low to high risk (Russell, 2005). In addition to the original RHRS parameters, the state of Colorado added five further parameters to their RHRS. These parameters include slope character, climatic conditions, geological conditions, discontinuity conditions, and traffic conditions. These characteristics will be discussed in further detail below.

Rockfall Hazard Rating System						
FACTOR			RANK			
			3 Points	9 Points	27 Points	81 Points
SLOPE PROFILE		Slope Height	25 to 50 ft	50 to 75 ft	75 to 100 ft	100 ft
SLOPE PROFILE		Segment Length	0 to 250 ft	250 to 500 ft	500 to 750 ft	750 ft
SLOPE PROFILE		Slope Inclination	15 to 25 degrees	25 to 35 degrees	35 to 50 degrees	50 degrees
SLOPE PROFILE		Slope Continuity	Possible launching features	Some minor launching features	Many launching features	Major rock launching features
GEOLOGIC CHARACTERISTICS		Average Block or Clast Size	6 to 12 in.	1 to 2 ft	2 to 5 ft	5 ft
GEOLOGIC CHARACTERISTICS		Quantity of Rockfall Event	1 cu ft to 1 cu yd	1 to 3 cu yds	3 to 10 cu yds	10 cu yds
GEOLOGIC CHARACTERISTICS	CASE 1	Structural Condition	Discontinuous fractures, favorable orientation	Discontinuous fractures, random orientation	Discontinuous fractures, adverse orientation	Continuous fractures, adverse orientation
GEOLOGIC CHARACTERISTICS	CASE 1	Rock Friction	Rough, irregular	Undulating smooth	Planar	Clay, gouge infilling, or slickensided
GEOLOGIC CHARACTERISTICS	CASE 2	Structural Condition	Few differen-tial erosion features	Occational erosion features	Many erosion features	Major erosion features
GEOLOGIC CHARACTERISTICS	CASE 2	Difference in Erosion	Small difference	Moderate difference	Large difference	Extreme difference
Climate and Presence of Water on Slope			Low to moderate precipitaion; no feezing periods; no water on slope	Moderate precipitation or short freezing periods, or intermittent water on slope	High precipi-tation or long freezing periods or continual water on slope	High Precipita-tion and long freezing periods,or continual water on slope and long freezing periods
Rockfall History (From Ride Through)			Few falls	Occasional falls	Many falls	Constant falls
Number of Accidents Reported in Mile			0 to 5	5 to 10	10 to 15	15 and over

Figure 1. CDOT's original RHRS, taken from Andrew, 1994.

Slope

Four different parameters establish the slope profile. These four variables include slope height, segment length, slop inclination, and slope continuity (launching features). The total slope height was not changed from the original RHRS. Total slope height is measured from the road to the highest point of potential rockfall source (Russell, 1005), and was not changed from the original RHRS. The previous slope inclination was based on the slope angle score. However, research using the Colorado Rockfall Simulation Program (CRSP) has led to the adaptation of the slope angel score from degree values to a numerical system based on the consequence of whether a rock is more likely to bounce onto the roadway, fall directly into a ditch, or roll down hill with enough energy to reach the road (Russell, 2005).

The original criteria for delineating launching features were very subjective. Terms such as “often, many, few” were used to describe launching features and did not provide a clear description of the features. Since the features themselves are heavily related to geology, they will be discussed in further detail in the geology characteristics of this paper.

Climate Conditions

It has been argued that precipitation and frost wedging are the most important factors that contribute to rockfall. Annual precipitation in Colorado combined with freezing temperatures provides for a vast amount of freezing water. The temperature range for the eastern plains region of the state is in its extreme at 115ºF to 10-15º F below zero. It is difficult to generalize temperatures in the western mountainous area of the state due to its vast elevation differences. At the summits, there is an average of about 32ºF.

Elevation is also a contributing factor when discussing precipitation in this area. The state of Colorado has regions that consist of vast plains and others that are highly mountainous with extreme peak heights. These elevation differences greatly affect how the climate influences the area. The interplay between prevailing air currents from the Pacific and the mountains is very important in determining precipitation on either side of the Rocky Mountain range that crosses the state. These factors cause wide temperature differences to occur within short distances. The “mountain effect” is seen here as storms from the Pacific hit the Rocky Mountains, rise, cool and dump their precipitation on the mountaintops (Western Regional Climate Center website, 2007). This map of the annual precipitation shows the highest precipitation (indicated by dark blue color) precisely where the Rockies transect the state.

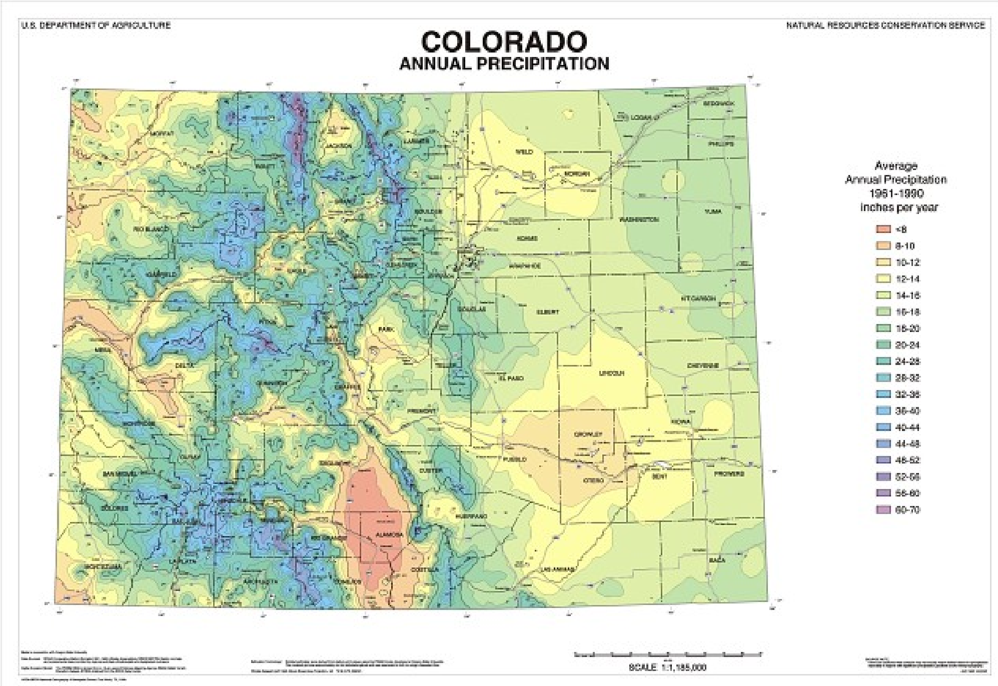


Figure 2. Annual Precipitation, Colorado

At this point, it is necessary to define a freeze/thaw cycle. One cycle is a 24-hour period, which has demonstrated temperature fluctuations above and below freezing conditions and had moisture on the surface that was enough to create freeze/thaw conditions (Arnold, 1996). The map below shows the annual freeze/thaw cycle distribution for the state of Colorado. This map is helpful because it delineates areas by how many freeze/thaw cycles they have experienced in that area in that particular year. Using this information in conjunction with other factors, we may be better equipped to understand why rockfall incidents occur where they do. A dynamic freeze/thaw cycle may be more conducive to allowing ice to melt deeper into the rock, which in turn causes and increased degree of instability. This contributes to rockfall incidents. (One must also consider the geological type of the surface material. This topic will be expounded upon in the following section.)

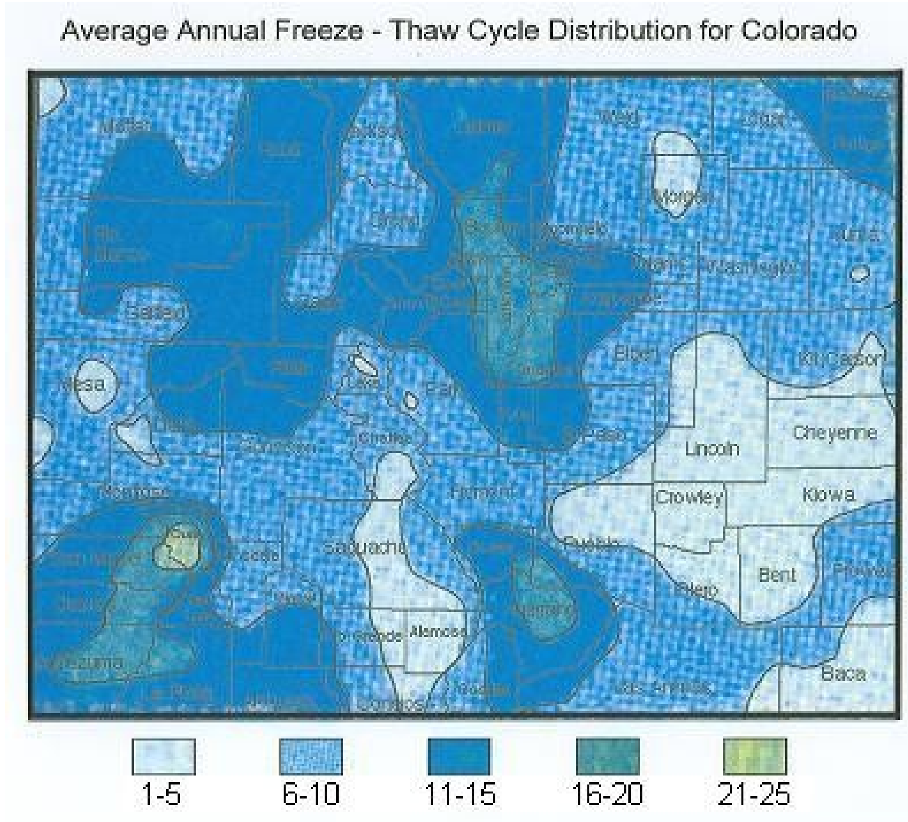


Figure 3. Annual average freeze/thaw cycle distribution for Colorado. Arnold et al. 1996

It is important to consider that slope aspect and direction of the incline determine how the surface of the incline is impacted by climate, to a certain degree. Slope measures the rate of change of elevation at a surface location and aspect is the directional measure of slope (Chang, 2006). For example, the slope facing in a certain direction may experience a more dynamic freeze/thaw cycle annually than slopes facing another direction. To have a better understanding of which areas are prone to rockfall, climate must be considered from all angles.

Geological Characteristics

As all the parameters introduced thus far have varying levels of involvement with rockfall incidents, they must then, be weighted as such. With that being said, out of all the factors affecting rockfall, geological conditions contribute the most to rockfall potential by far. This is such an important parameter that even if all other factors involved point to a hazardous slope, the geological material type of the slope may sway the hazard rating in the other direction.

As most geological features are in fact a layering of different geologic material types, it is also very important to consider not only the outer, exposed surface material, but the underlying surface as well. One must consider the thickness of the layer, order of the layers and what type of material each layer is composed of to best understand the type of slope you are dealing with geologically speaking. Further considerations for material type are different weathering effects, durability levels and how it handles friction with other layers. While the below ground parameters are clearly important, it is also practical to consider the surface in terms of vegetation. Answers to questions about vegetation, such as, how much, what species, root system details will also play heavily into the complicated question of hazardous inclines. Vegetation has its pro's and con's. It is widely agreed that in general vegetation assists in stabilizing soil on slopes. However, root wedging and force of wind on vegetation my have negative effects on the slope by enhancing physical erosion (Russell, 2005).

Lastly, and perhaps most obviously, any large geological feature placed in precarious positions on an incline with a certain slope value is clearly a cause for concern. Kinetic energy for the feature must be calculated to ascertain the likely hood of the feature reaching the roadway. The size and shape of the feature will certainly weigh heavily in those calculations (Russell, 2005). (See figures 4-7 below for example of the range of launching features.)

Figure 4. This picture is showing a relatively smooth slope with low level launching features. This would have a RHRS rating of 3 points.

Figure 5. This picture demonstrates a slope profile that has minor launching features that could cause rockfall. This would have a RHRS rating of 9 points.

Figure 6. This picture is showing many launching features that could result in rockfall. This would have a RHRS rating of 27 points

Figure7. This picture is showing the highest level of danger of rockfall, with a highly irregular slope profile and large launching features. This situation would have a RHRS rating of 81 points.

GIS Data

A rockfall hazard rating database has been provided courtesy of the Colorado Department of Transportation (CDOT) and Colorado School of Mines. The database contains rockfall hazard information and parameters surrounding sites in Colorado in which data has been collected. This information will be imperative towards the creation of feature classes to accompany the geodatabase. In the methods section below, some of these feature classes and data are described in more detail. Additionally, elevation and geological data were acquired from the United States Geological Survey, and precipitation data from the Natural Resources Conservation Services website.

Methods

A geodatabase was developed using the rockfall hazard data provided from the Colorado Department of Transportation (CDOT). The CDOT data is in a database format, and was converted into GIS format as needed for various feature classes. The geodatabase has projected coordinate system of North America Albers Equal Area Conic with the geographic coordinate system being GCS North American 1983. The geodatabase contains the following feature classes:

1. Annual Precipitation feature class- Precipitation data was downloaded from the Natural Resources Conservation Services website as a shapefile.
2. DEMs were downloaded from the seamless.usgs.gov website and incorporated into the geodatabase. These files will be important for reference to certain areas of Colorado that exhibit high occurrences of rockfall.
3. Colorado county data was downloaded from the US Census Bureau website as a shapefile.

4. Geological data was downloaded from the USGS website.
5. Major routes data was provided by the CDOT as a shapefile.
6. Freeze/thaw data is given in jpeg map format. The map was digitized in ArcMap by creating a georeferenced feature class that was snapped to the counties feature class. Four control points were selected based on their 3-way intersection with the county boundaries. The completed feature class was then placed within the geodatabase.
7. Maintenance boundaries and accident data were received via email as a shapefile from the CDOT.
8. A point feature class was created containing the average point from the beginning and ending milepost markers from the database. A new feature class was created and the corresponding points were digitized and snapped to the highways feature class.

Upon receiving the initial data set, all files were projected to the correct coordinate system as mentioned above. Those files that were not already in feature class format were converted to a feature class and exported to the geodatabase. The DEM was selected based on the points where the hazard ratings were scores. Three separate DEM's were downloaded to cover the study area. They were then incorporated into the geodatabase and the mosaic tool was used to merge them into one DEM image. All feature classes were then clipped to the DEM mosaic image size.

It was decided at this point to create an index model to effectively represent the correlation between the numerous variables that potentially affect rockfall, and ultimately observe any connection between these variables overall. Furthermore, the addition of traffic volume and accidents reported in the study area was also a relationship that we wanted to consider.

To accomplish this task, model builder was used to create an index model. Five layers were chosen as input layers for the index model. These layers included the annual precipitation, freeze/thaw, geology, and elevation layer, which was further processed to obtain the slope and aspect, which were the third and fourth input layers respectively. With the exception of the elevation layer, the remaining layers were converted to a raster image. Each layer required the addition of a field representing its rockfall hazard rating, as it related to the original database provided by the CDOT. Four different values were used, 3, 9, 27, and 81. When running the model, the calculations were based on this value in each layers attribute table.

Initial processing on the elevation layer required the resampling of the DEM to a more practical cell size for geoprocessing. It was decided that a cell size of 50 would maintain an accurate representation of the elevation while keeping the model process from slowing down or crashing the system. Upon resampling, the DEM was again geoprocessed with the use of two separate tools, slope and aspect, located in the spatial analyst-surface tools. The slope and aspect layers were then reclassified to the index values chosen above. Once the layers were pre-processed to get them in the appropriate format, the remaining task was the addition of all five rasters to obtain an overall index value representing the hazard rating for our study area. Below is a finished diagram of the model.

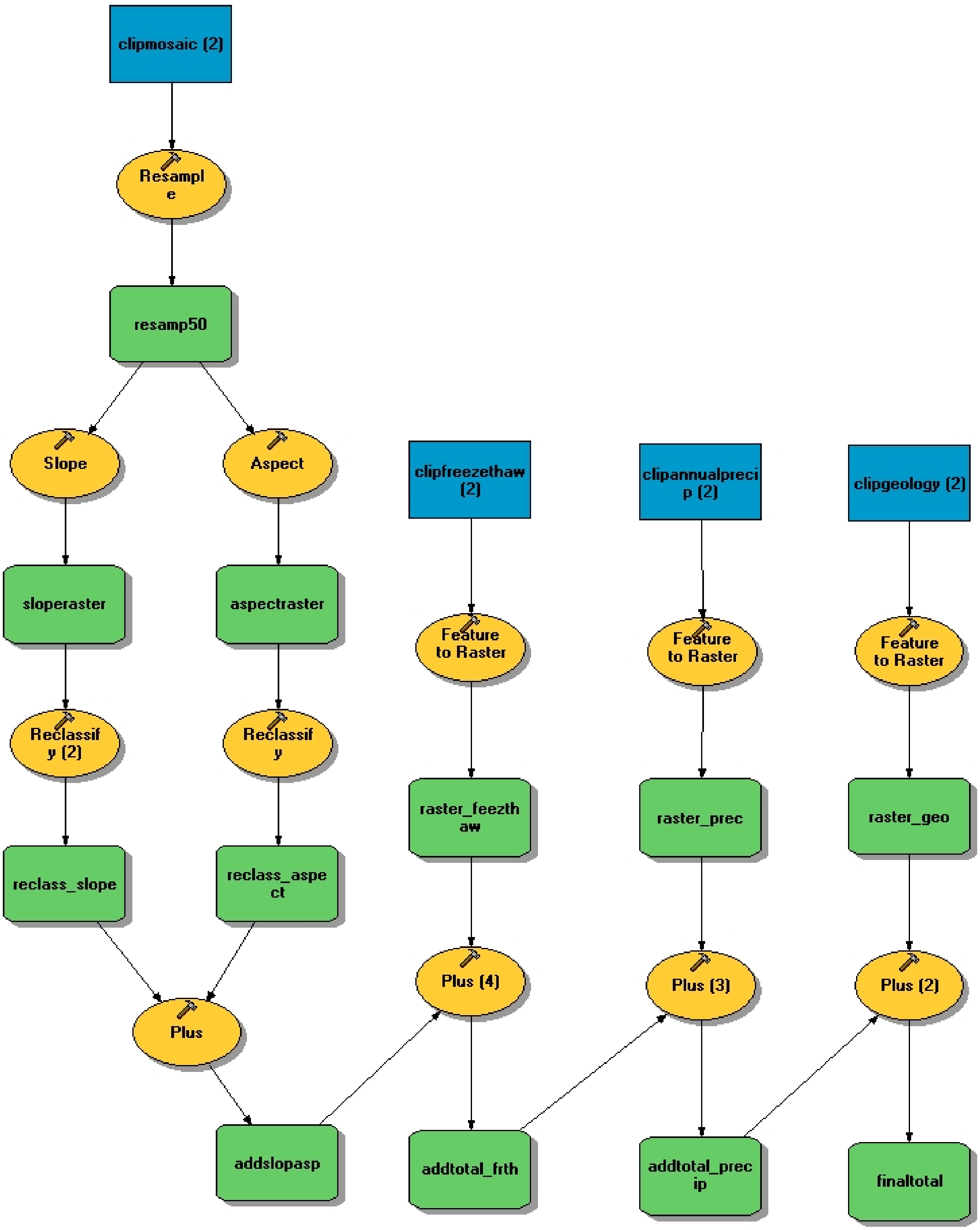


Figure 8. Index Model created for CDOT Rockfall Hazard Rating System

Results

As expected, we were to be able to utilize GIS to map out areas of rockfall hazard for our selected area in the state of Colorado, where rockfall hazards are a dangerous and costly problem. The created geodatabase aided in storage and organization of all the data that was incorporated into this map. Although there were many factors that contribute to rockfall hazard, based on data that was available at this time, we chose to base our final rockfall hazard score on the following five factors: precipitation, geology, freeze/thaw, slope and aspect. These layers were all a factor that were scored based on the same index values of 3, 9, 27, and 81 from the initial database that was received from CDOT. For example, certain types of surface geology were rated a "9", where as another type of surface geology was rated a "27". All of these layers were converted into raster format so that they could be easily added together. The results are shown below in figures 9-13. The slope and aspect layers were initially reclassified to obtain these results, while the remaining layers only needed an index value field added to their attribute tables prior to conversion from feature class to raster. After each layer was reclassified using RHRS, they were then added together to produce a "grand total" calculation map for our area (see Figure 14). This means to say that each pixel of our study area had a calculated score based on the five reclassified factors mentioned above.

Elevation of the study area

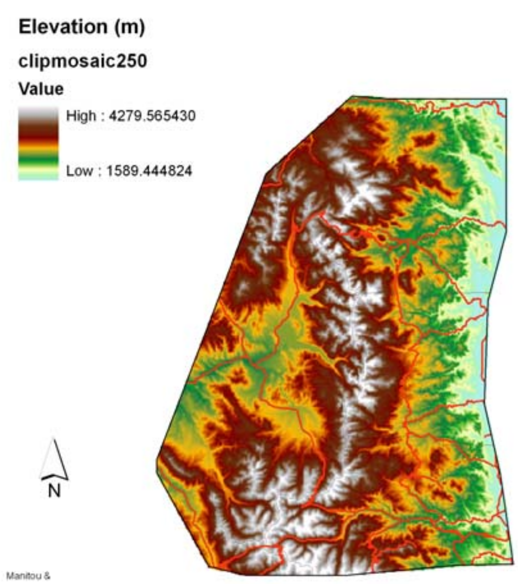


Figure 9 Elevation Raster

Annual Precipitation

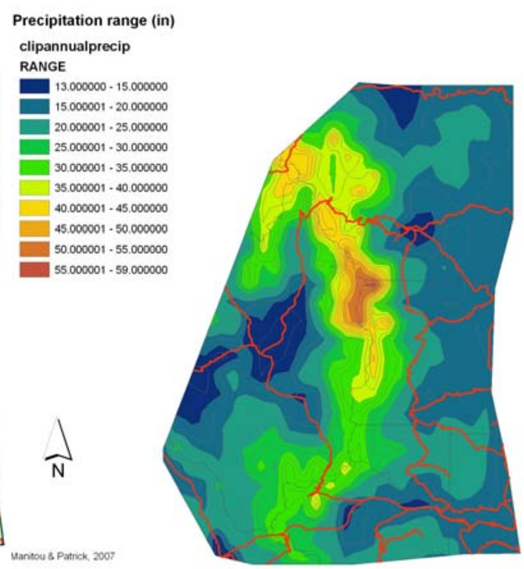
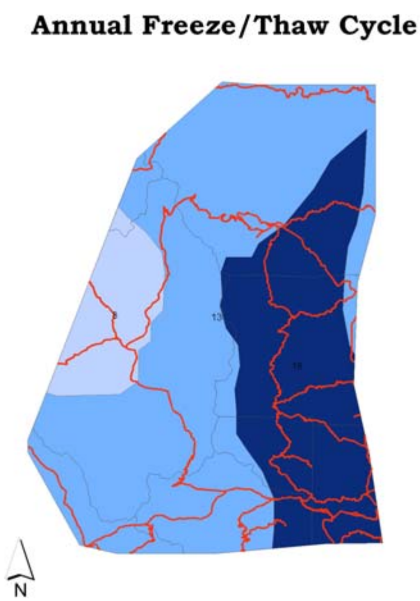


Figure 10 Precipitation Raster



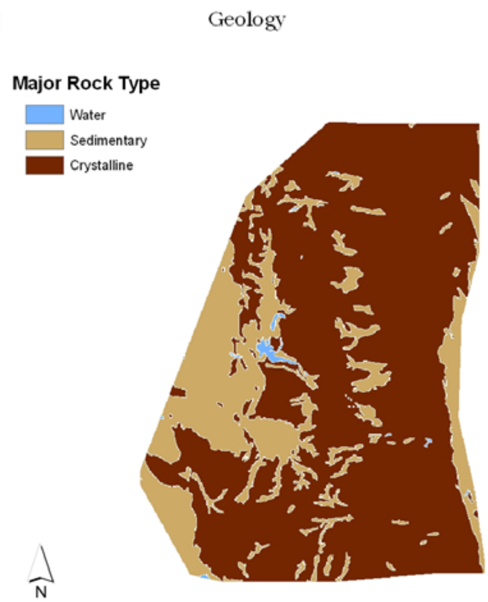


Figure 11. Freeze/Thaw Cycles Raster

Figure 12. Geology

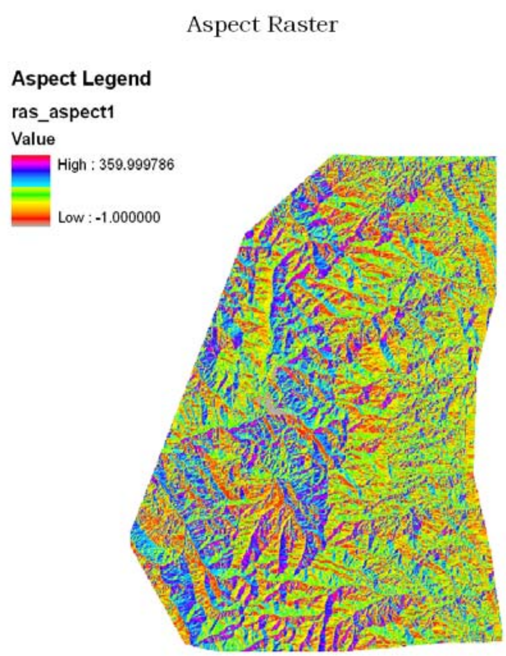


Figure 13. Aspect Raster

This total score calculation map is considered the final product of this project. From this final raster, one can easily see the area where there the highest risk is located. The picture becomes even clearer when the accident locations layer and highways layer are stacked on top of the final calculation raster. We have produced a useful map that even an untrained eye would be able to decipher. As the saying goes, a picture is worth a thousand words, and all these map layers combined are worth countless tables of data.

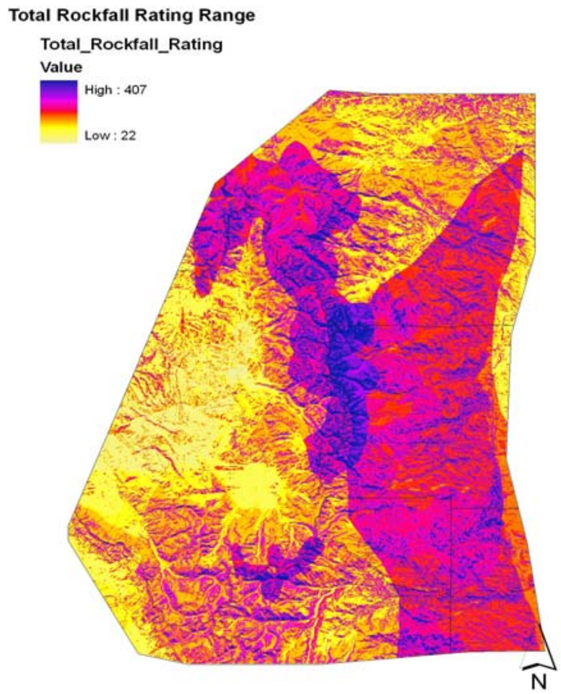


Figure 14

Conclusions and Discussion

From the final "grand total" raster, the area that is predicted to be the most dangerous in terms of rockfall hazard are shown in the center of our study area, indicated in the dark blue color. As can be seen from the elevation raster, this is also the area where a segment of the Rocky mountains intersect the state. An obvious conclusion can be drawn that the mountainous regions of Colorado have higher rockfall hazards associated with them.

Due to several factors, we chose to center our determination on five of the factors contributing to rockfall hazard in the state of Colorado. When the data from the area studied in this project is compared with that of CDOT, there is a clear correlation between the two (figure 16).

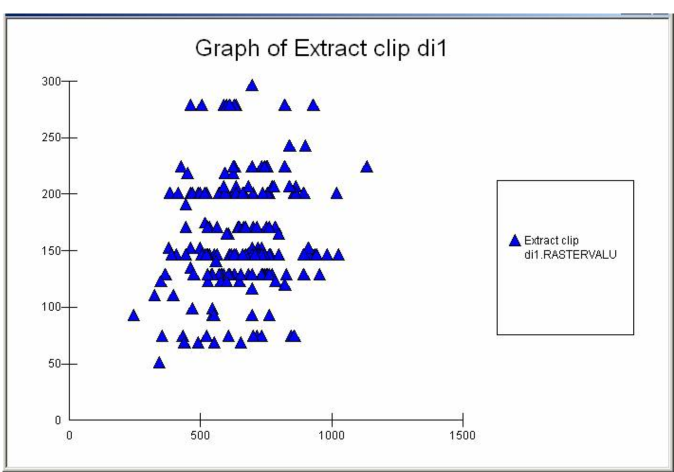


Figure 16.
The x-axis is representing the CDOT data and the y-axis the data used in this study.
The numbers are higher on the x-axis due to the fact that CDOT are incorporating all the parameters that contribute to rockfall whereas this study did not include all of the parameters.

This relationship between the two datasets shows that the factors, that were chosen to be used in this project have a strong influence on the total rating system.

The objective of the project is to be realized as an actual working component of the CDOT. Their idea is to have more ground-truth data points taken and measured in other areas in the state of Colorado, which can then be added to the existing geodatabase and model we have created. As more information may be made available to CDOT, in theory, the final calculation raster could be expanded to cover the entire state or more. As a result, all risk areas could be easily monitored and dealt with rapidly in situations of emergency. This would aid the state of Colorado in all areas of rockfall incidents from prediction to prevention to repair and beyond.

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