Avalanche Risk

Terrain Susceptibility

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Statement of objective

The purpose of this project is to develop a model that can be used as a basis and/or a tool for the further research and development of avalanche risk assessment tools. Modeling terrain factors that contribute to the overall risk of an avalanche can identify areas that could be more likely or less likely to have a snow slide occur within them given appropriate circumstances based on snow and weather conditions.

Several terrain factors have been identified that contribute to an area's likelihood of producing a snow slide. Although avalanches can happen anywhere, and are endemic to mountain ranges worldwide, certain geographic areas may have a higher occurrence rate. This will be due primarily to snow conditions, however, certain areas of terrain are more susceptible.

Factors such as slope, aspect, curvature, and land cover can have data readily available or with the appropriate expertise and equipment, obtained. However, this is a time consuming and data intensive process. This project seeks to create a model that can be used within ArcMap 10.3 that will produce an avalanche susceptibility map for a given area of interest, requiring minimal inputs.

This model is meant to serve as a basis for understanding and a template model at best. Experienced professionals with far more knowledge regarding avalanche characteristics and mathematics should be able to contribute to this model to create a more precise predictive model.

Introduction

Every year avalanches claim lives and cause destruction all over the world. In the United States, over the past 10 years, there has been an average of 27 fatalities in connection with slides (Colorado Avalanche Information Center, 2015). Many fatalities are often in slides that are triggered by people, however, occasionally a naturally triggered slide will cause destruction and possibly death. Avalanches are endemic to every mountain range in the
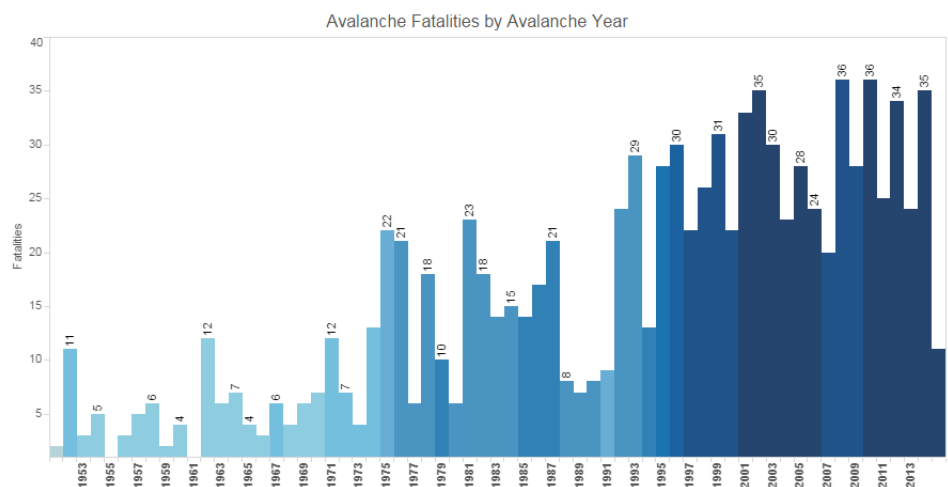
world. With the appropriate weather, snow, and terrain conditions, a slope will slide. A slide occurs when the snowpack on the surface cannot support the weight of the snow on top of it. Avalanches begin when weak layers of snow release the weight of the more stable snowpack above it, which then begins to travel downhill gathering speed and more snow. Avalanches causing fatalities are often triggered by human involvement such as a skier or snowmobiler.

An avalanche is influenced by weather, snow conditions, and terrain. Weather influences snowpack depth, temperature, and wind. Temperature can cause melting and freezing to occur at different rates within the snowpack which will stress the snowpack and weaken the ability of it to support its own weight. However, some melting and freezing, in the appropriate time, can actually help to improve the strength of the snowpack. The wind will cause build-ups of snow in certain areas, which leads to a higher weight which can overcome the strength of the snowpack. The snow conditions determine the strength and weight of the snowpack, which are the deciding factors in if a slide will actually occur. Terrain can influence areas to be more or less susceptible to avalanches. Things such as slope, surface cover, and slope (curvature) profile will affect the strength of a snowpack, while factors such as aspect will determine the amount of sunlight an area receives, influencing the temperature aspect.

A slope is necessary for an avalanche to occur, however, various slopes will either increase or decrease the risk of a slide occurring. A slope of thirty to forty-five degrees are the most likely to slide, as they are shallow enough to allow an accumulation of snow, but provide a steep descent, upon which gravity will work to weaken the strength of the snowpack. Any slope between twenty-five and sixty can and do slide (United States Forest Service, 1968). A slope of less than twenty-five degrees is less likely to slide as the force of gravity from the slope will have less of a weakening effect on the strength of the snowpack. Slope in excess of sixty degrees are also less likely to slide because the force of gravity pulling down the slope is so severe that the snow does not hold enough strength to allow a significant amount of accumulation to occur. A serious of small, harmless amounts of snow will slide off these slopes.

Aspect is essentially the direction of the slope. Aspect can be described by using the cardinal directions, North, East, South, and West, as well as intermediate directions – Northeast, Southeast, Southwest, and Northwest – and anything in between. Aspect, with respect to the sun, is most important at mid latitudes, ranging from thirty to fifty-five degrees (United States Forest Service, 2015). In the Northern Hemisphere, the northern slopes receive less sun than the southern slopes, thus producing a cold snowpack. A cold snowpack tends to develop more persistent weak-layers than a warm snowpack, and thus more avalanches (United States Forest Service, 2015). Therefore the northern slopes will have a more likely chance to slide than southern slopes. Eastern slopes will develop a colder snowpack than western slopes due to the difference in morning sunlight versus afternoon sunlight. In the

Southern Hemisphere, the southern facing slope will receive less sunlight than the northern facing slopes, thus being the opposite of the Northern Hemisphere.

Slope Profile, or curvature, is the shape or curvature of the slope. The slope can be concave, meaning curving in or hollowed inward, or convex, meaning curving out or extending outward. A slope can have two curvatures, profile and planform curvature. Profile curvature is parallel to the slope, downward, and affects acceleration and deceleration of a flow down a slope (ESRI, 2015). Convex slopes are often referred to as having a 'tension zone'. A fracture line will occur within this tension zone because the weight of the snow will often exceed the strength of a convex slope (National Park Service, 2011).
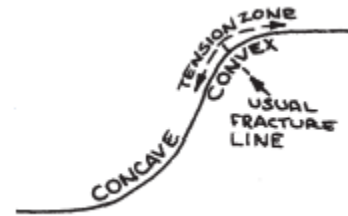
The type of terrain and the surface coverage will also influence the strength of a snowpack. Areas that are covered in trees, large bushes, and rocks will provide anchor points on to which snow can attach itself to. This will increase the strength of the snowpack, hence requiring more weight and a larger trigger to initiate a failure. Areas that are barren, or perennial ice and snow, or grassland will not provide anchor points and offer less friction to stop an avalanche, hence making them more likely to occur.

Methodology

Using GIS, a model requiring minimal inputs, resulting in an output that can show a likelihood of avalanche danger can be created using python scripting for a model within an ArcGIS Toolbox. Within the tool will be contained multiple geoprocessing steps that will alter, create, reclassify, and produce the final output raster.

Inputs required for this model consists of two data source files and one area of interest file. The area of interest file is to be a shapefile containing within it an area which will be used to clip the data source files down to a manageable size. Examples of such files could be a shapefile containing a polygon of a county boundary, state boundary, or polygon surrounding the area within a new development.

The two data source files are used to provide elevational data and land cover data. Elevational data can be obtained from many sources. Data for America can be reliably obtained from the United States Geological Survey and the National Map. Previously elevation data was represented using contour lines and bare earth digital elevation models (DEMs). For the past fifteen years the National Elevation Dataset (NED) was the primary elevation layer. A 30 meter NED could be used for this analysis and is historically available for much of the United States. However, with the new 3D Elevation Program (3DEP) now operational, not only are bare earth surface features identifiable, but above ground features can be distinguished as well. The 3DEP

uses light detection and ranging (LIDAR) data throughout the United States, and interferometric synthetic aperture radar (IFSAR) data in Alaska (USGS, 2015). Products available from the 3DEP included seamless bare earth DEM layers at 1/3, 1, and 2 arc-second resolutions. 1/9 and 1 meter resolutions are available in some areas and will continue to increase coverage as the project continues. For this analysis, a 1/3 arc-second (the highest resolution available with continuous coverage) bare earth DEM will be used. This can be obtained, free of charge, using the National Map data viewer which allows one to specify a location by geographic coordinates or location names. Depending on the size and location of the area of interest, more than one DEM raster may need to be downloaded and merged together.

The land classification data is available from National Land Cover Database from 2011 (NLCD, 2011). The NLCD 2011 is the most recent national land cover product available from the Multi-Resolution Land Characteristics (MRLC) Consortium (Homer, 2011). A user with access to ArcGIS online can connect to an ArcGIS Server. The NLCD 2011 data is contained within the ArcGIS server 'Landscape 5', which can be clipped to an appropriate area within ArcMap and used in lieu of downloading the entire NLCD 2011 dataset which is data-intensive. Data is available across the United States at a resolution of 30 meters. A decision-tree classification based on 2011 Landsat satellite data is used to identify land cover. A 16-class land cover classification scheme that is adapted from Anderson Land Cover Classification System of 1976.

Class\ Value		Classification Description
Water		
	11	Open Water - areas of open water, generally with less than 25% cover of vegetation or soil.
	12	Perennial Ice/Snow - areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover.
Developed		
	21	Developed, Open Space - areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
	22	Developed, Low Intensity - areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units.
	23	Developed, Medium Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.
	24	Developed High Intensity -highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.
Barren		
	31	Barren Land (Rock/Sand/Clay) - areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.
Forest		
	41	Deciduous Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
	42	Evergreen Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
	43	Mixed Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.
Shrubland		
	51	Dwarf Scrub - Alaska only areas dominated by shrubs less than 20 centimeters tall with shrub canopy typically greater than 20% of total vegetation. This type is often co-associated with grasses, sedges, herbs, and non-vascular vegetation.
	52	Shrub/Scrub - areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.
Herbaceous		
	71	Grassland/Herbaceous - areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.
	72	Sedge/Herbaceous - Alaska only areas dominated by sedges and forbs, generally greater than 80% of total vegetation. This type can occur with significant other grasses or other grass like plants, and includes sedge tundra, and sedge tussock tundra.
	73	Lichens - Alaska only areas dominated by fruticose or foliose lichens generally greater than 80% of total vegetation.
	74	Moss - Alaska only areas dominated by mosses, generally greater than 80% of total vegetation.
Planted/Cultivated		
	81	Pasture/Hay – areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.
	82	Cultivated Crops – areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.
Wetlands		
	90	Woody Wetlands - areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
	95	Emergent Herbaceous Wetlands - Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

The first stage of the model utilizes the geoprocessing tool 'Extract by Mask' within the extraction toolset in the Spatial Analyst toolbox twice, once for the elevation data and once for the land classification data. The Spatial Analyst extension must be checked out. The extract by mask tool is used to clip the elevation data raster and land classification raster to the area of interest. The tool requires an input of a raster layer to be clipped or extracted and an area defining the extraction area. The raster layer is to be the elevation data raster and then again as the land classification raster. The area of interest polygon will be the area defining the extraction area for both times the tool is utilized. The outputs will be passed on through the rest of the model as the clipped elevation data and the clipped land classification data.

The next stage of the model utilizes the clipped elevation data to create slope, aspect, and curvature data. The slope tool is the first geoprocessing tool utilized. Slope is defined as the maximum change in z-value for each cell (ESRI, 2015). The inputs required for the tool are an elevation data raster and optional inputs of output measurement or z-factor. The output measurement can either be degrees or percent rise. Degrees will cause the measurement of the inclination to be between 0 and 90 degrees. If percent rise were to be selected, the range is zero to essentially infinity. A 45 degree surface will have a 100 percent rise. As that surface becomes more vertical, the percent rise will increase. An output is created with a value between zero and ninety for every cell.

The next tool used is the aspect tool. Aspect is derived from a raster surface and identifies the downslope direction of the maximum rate of change for elevation. It can also be thought of as the direction of the steepest slope, or slope direction. The output for aspect ranges from 0 to 360 degrees and is corresponding with the compass direction that the steepest slope faces.

The last tool that produces data derived from the elevation dataset is curvature. Curvature is defined as the second derivative of the surface, or the slope of the slope (ESRI, 2015). Optional outputs that are included with the curvature tool are the profile curvature and the planform curvature. Profile curvature is the curvature in the direction of the maximum slope, or the aspect, and is in the vertical direction. Planform curvature is perpendicular to the profile curvature and is in the horizontal orientation. Curvature can either be classified as convex or concave, and if it is neither of those it is flat. Profile curvature is the variable that this model with be concerned with. A negative value indicates a convex slope while a positive value indicates a concave slope as shown below.
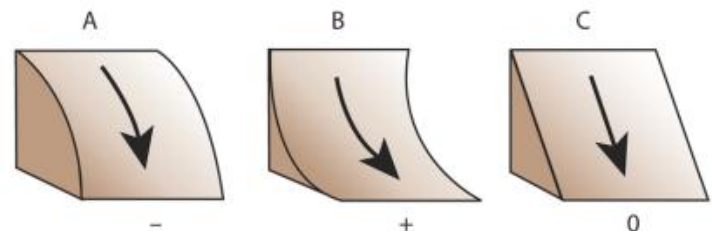
The three outputs produced with the slope, aspect, and curvature tools will be used in conjunction with the land classification layer in order to produce a final avalanche risk layer. But before the map algebra can be done on these layers they must be reclassified into values that will make sense to the map algebra equation. The final equation will produce values between zero and three. Each variable (slope, aspect, profile curvature, and land cover) will be assigned a coefficient indicating its proportional level of contribution to overall terrain risk.

In order to produce final values between zero and three, all layers must be reclassified in order to only contain values between zero and three. A classification scheme can be developed, and modified as needed, for the reclassification. A value of three will indicate an area that is more likely to slide, while a value of zero will indicate unlikeliness of a slide occurring. The reclassification of slope, for example, assigns a value of three to cells that contain slopes of between thirty and forty five degrees. The rest of the cells will be reclassified according to an arbitrary observation of the likeliness of avalanche occurrence while citing the following bell curve, which shows the percentage of avalanches that occur at each slope (Utah Avalanche Center, 2014). While this graph only provides insight to a sample of all avalanche data, it serves as a guide to be used with data from other sources in order to select reclassification values.
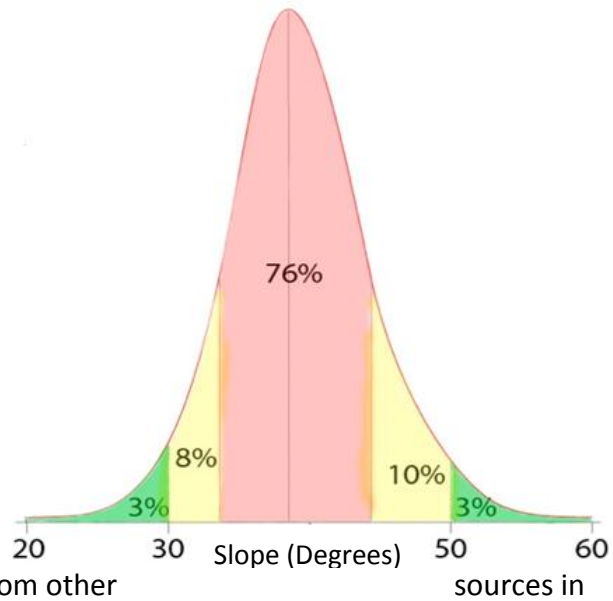
Similarly, aspect is reclassified giving northern facing slopes a higher classification value, while giving eastern or southern slopes lower values, and western values the lowest value. Curvature is reclassified to give convex (negative values) a value of three, while positive values are reclassified to a value of zero.

The land classification layer is reclassified giving to each of the sixteen classes a value between zero and three. Land classes such as 'developed' are given scores of zero or near zero while classes such as 'barren' or 'annual ice' are given values at or near three. All values are assigned based upon a estimate of the likelihood of a slide occurring.

Map algebra is performed on the four reclassified layers and an output with values between zero and three is created and saved as the output. All of these tools and reclassifications are scripted and contained within a Python Script. The script is attached to a created toolbox with ArcMap that requires four parameter inputs: the file name and location of

the elevation data and the land classification data, the file name and location of the area of interest shapefile, and a specified location for the output file.

```
import arcpy
from arcpy.sa import *

arcpy.env.overwriteOutput = True

arcpy.CheckOutExtension('Spatial')

#inputs
in_dem = arcpy.GetParameterAsText(0)
in_landcover = arcpy.GetParameterAsText(1)

aoi = arcpy.GetParameterAsText(2)

output_filepath = arcpy.GetParameterAsText(3)

#Clip to area of interest
in_dem_clip = ExtractByMask(in_dem, aoi)
in_landcover_clip = ExtractByMask(in_landcover, aoi)

#Run Slope tool
outSlope = Slope(in_dem_clip, 'DEGREE')

#Run Aspect tool
outAspect = Aspect(in_dem_clip)

#Run Curvature tool
outCurvature = Curvature(in_dem_clip, out_profile_curve_raster = 'profile')

#Reclassifications
slp = Reclassify(outSlope, 'Value', RemapRange([[0,25,1],[25,30,2],[30,45,3],[45,55,2],[55,180,1]]), 'NODATA')

aspt = Reclassify(outAspect, 'Value', RemapRange([[0,45,3],[45,225,2],[225,315,1],[315,360,3]]))

curv = Reclassify('profile', 'Value', RemapRange([[-10000000000000000000000,0,3],[0,10000000000000000000000,0]]))

lc = Reclassify(in_landcover_clip, 'Value', RemapValue([[11,0],[12,3],[21,0],[22,0],[23,0],[24,0],[31,3],[41,1],[42,1],[43,1],[51,2],[52,2],[71,3],[72,3],[73,3],[74,3],[81,2],[82,2],[90,1],[95,1]]))

#Equation
risk = (0.4 * slp) + (0.15 * aspt) + (0.2 * curv) + (0.25 * lc)

#Output
risk.save(output_filepath)

arcpy.AddMessage('Complete!')
```

A portion of the code used for the model

Results

This model is built and meant to be used by any professional or academic-minded individual with access to ArcMap 10.3 and the appropriate data. A demostration using the Lake County, Colorado area was done to show how the model works and to demonstrate the ease of use. Lake County is located in Central Colorado. Lake County contains the highest natural point in Colorado as well as in all of the Rocky Mountain Range with Mount Elbert rising 14,440 feet above sea level. Avalanches are common in the mountains region that encompasses Lake County. Due to the limited amount of residents in the county, many avalanches are not destructive to property or dangerous. However, fataltities still occur as result of avalanches within Lake County with the most deadly avalanche occuring in 1962 and fatalties as recently as 2014. Displayed is the location of the Lake County Area within the state of Colorado.
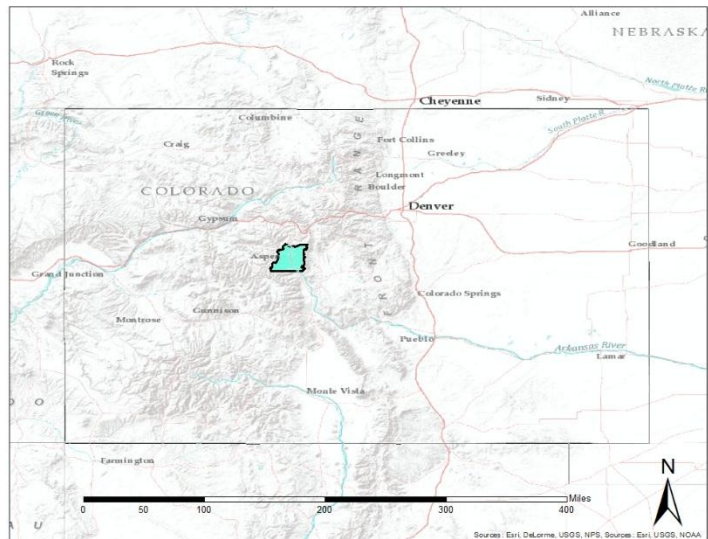
To obtain data used for the Lake County example, multiple sources were used. The county boundary was obtained by selecting and exporting the boundary of Lake County from the 2014 Census County Boundaries shapefile (US Census Bureau, 2015). The USGS National Map was used to locate a elevation dataset for an area encompassing all of Lake County. An image of the elevational data and subsection used is shown below. A subsection of the NLCD 2011 dataset was obtained using the ArcGIS Server.
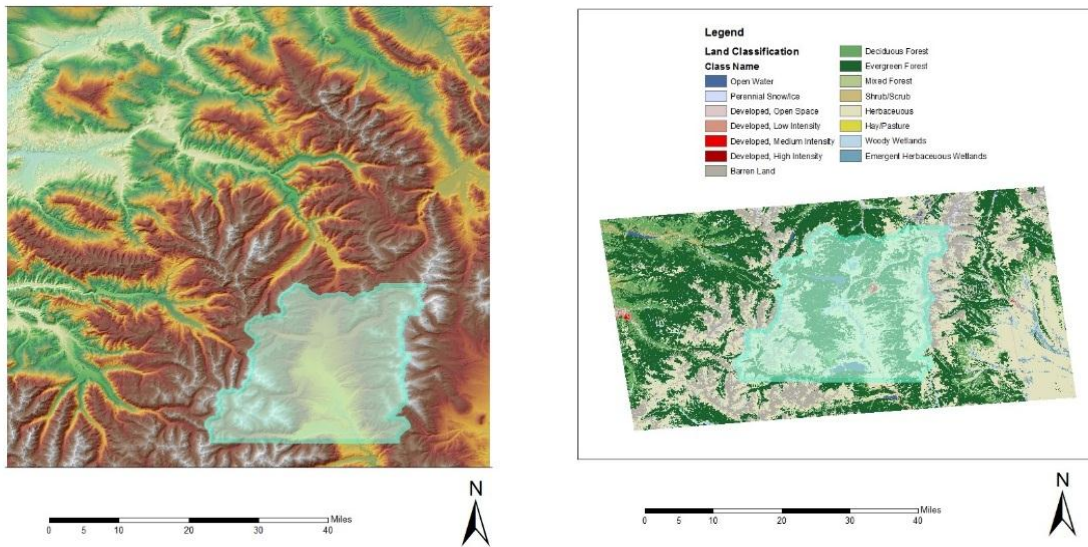

The script that was built for the model using Spyder and Python scripting was imported into a new ArcToolbox. Parameters that must be entered are the elevation data (raster layer), the land classification data (raster layer), the area of interest polygon (feature layer), and an ouptut for the results (raster layer). These parameters were set to the data acquired for Lake County and then the model is set to run.
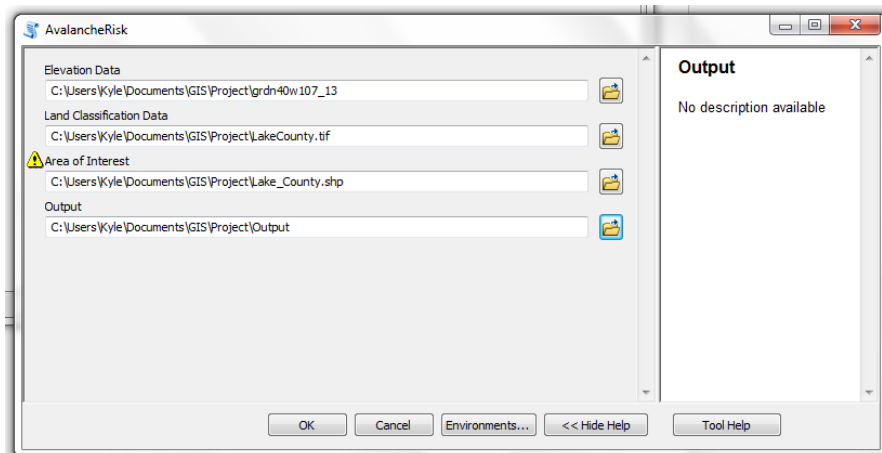
A raster layer containing values between zero and three is then produced. The original symbology is set to a stretched classification. However, the user may alter and display the data however they please depending on the purpose. In this example, a stretched classification ranging from high to low was used.

Identifying separations between classifications allows one to mask areas that have no risk of avalanches occurring, such as open water lakes.
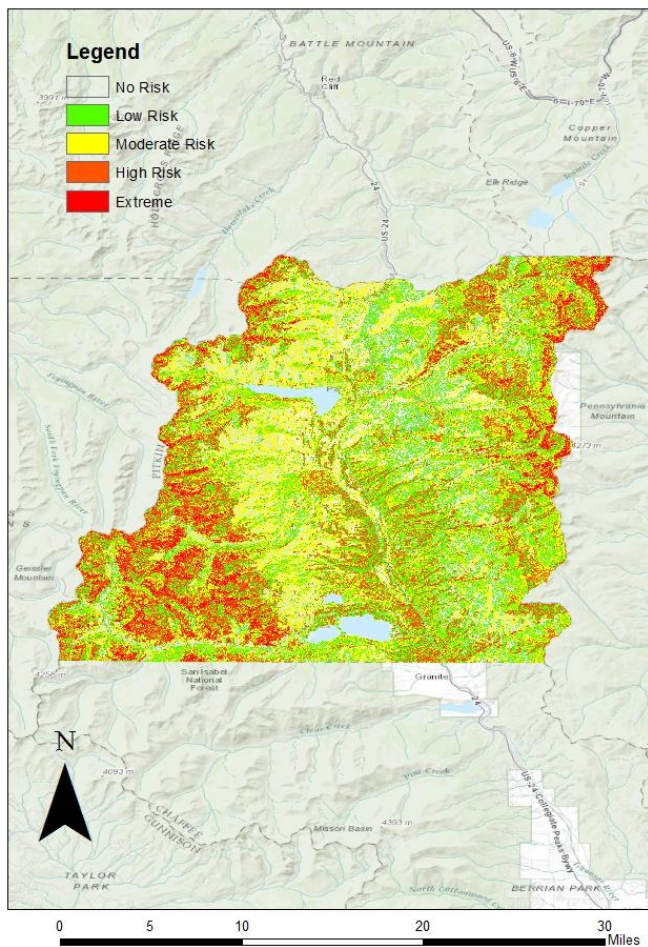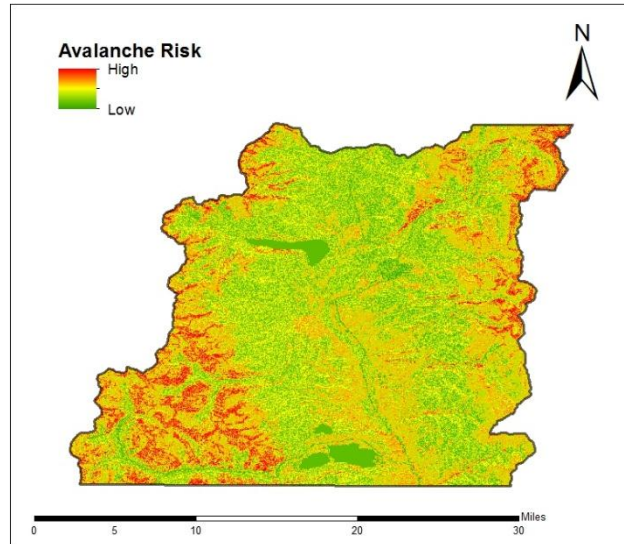
Various thresholds can be set that will determine where this separations will occur. For example, the image on the left has been classified to have breaks occurring at values of 1, 1.5, 2, and 2.5, thus separating the data into five distinct classifications.

Analyzing the results of the Lake County example, one can identify areas of safety near the waterbodies including both the lakes and the streams, and as well as throughout the majority of the valley. Along the edges of the county, in the mountains, the risk of avalanche increases dramatically as one would expect.

Conclusion

While interpreting the results of this model, it is important to keep in mind the limitations of this model. This model serves to only create a scale upon which to judge one areas terrain's likelihood to slide upon another areas terrain's likelihood of sliding. The estimation of the importance or contribution of a variable is based upon an approximation made using reasoning and prior research. The likelihood assigned to each value or class during the reclassification stage are also just approximations. Without further research done on the contribution of each variable, all values derived from such model should be used only for comparison and generalizations and not as quantitative values.

Information derived from this model can be used as an input for further research. One tool in particular that would be of interest regarding avalanche modeling is the D-Infinity Avalanche Runout tool within the TauDEM Toolbox. The D-Infinity Avalanche Runout tool is used to identify an avalanches affected area and a possible flow path length to each cell within the affected area (Utah State University Hydrology Department, 2015). The tool utilizes a Pit Filled Elevation Grid that can be produced from the elevation data available as well as a D-Infinity Flow Direction Grid. The Avalanche Source Site Grid can be created by determining a threshold for avalanche risk, for example a 2.25 on the three point scale. Cells above the threshold will receive a positive value and be used as avalanche source sites, whereas all other cells will receive a value of zero and not be used. A raster indicating avalanche runout paths is the created.

For further specifications in the coefficient, it is required to gather historical information such as the slope, aspect, land cover, etc. for previous avalanches and to collect information for future slides, a database could be created that could be used to provide more precise values. Instead of arbitrarily selecting coefficients based on reasoning, a statistical regression could be performed and coefficients could be precisely selected and updated as more information becomes available. Also, the likelihood assigned to each condition within each variable could be more precisely estimated.

Data created by this model can be used with other available layers, such as a layer displaying the roads in the area, and areas that lie within at risk terrain can be avoided or appropriately monitored to increase safety and awareness. The applications of this model are endless and easily customized. By making the script for this model available, the coefficients and reclassification variables can be easily reassigned dependent on the final purpose of the analysis. Further research is required and through sharing on Hydroshare, a model can be produced in the future that will increase the efficiency in which professionals or researchers can identify avalanche risks.

Citations

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