GIS as a Tool for Assessing Volcanic Hazards, Vulnerability, and at Risk Areas of the Three Sisters Volcanic Region, Oregon

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Abstract

Active volcanoes give significant threats to the populations that live in their proximity. The Three Sisters Volcanic region is one of 9 threatening volcanoes within the Cascades volcanic arc. Eruptions are probable which makes it essential to complete hazard, vulnerability, and risk assessments so that proper planning, education and mitigation procedures can be implemented prior to the threat occurring. GIS provides a tool for extending hazard and vulnerability mapping to assist in the analysis of risk. Creating a procedure using GIS as an aid helps in automating the very complicated and lengthy processes of establishing a risk assessment. Responses to volcanic events can be better handled with an understanding of how communities will be affected.

Introduction

According to the global volcanism database of the Smithsonian Institution, the United States has 169 geologically active volcanoes (Ewert, Guffanti, and Murray, 2005). In a 2005 report by the National Volcano Early Warning System (NVEWS) the United States has 5 erupting volcanoes and 13 very high threat volcanoes (Ewert *et al*.). Ewert *et al*. explains United States volcanoes have produced many kinds of dangerous phenomena:

- Lava flows have buried communities
- Explosive eruptions have destroyed forests and killed people
- Debris avalanches and mudflows have clogged major river ways, damaged bridges, and swept bystanders to their deaths
- Noxious gas emissions have caused lung ailments
- Ash clouds have caused damage to aircraft and disrupted the lives of thousands of people

The potential for such threats to the nation's population, property, and infrastructure is significant and there is a need to study volcanic eruptive behaviors to help mitigate effects of these forces of nature (Ewert *et al*.).

On May 18, 1980 the United States experienced firsthand the damage that a volcanic eruption can cause. The eruption of Mount Saint Helens caused the death of 57 people. The Washington State Department of Game estimated that nearly 7,000 big game animals perished. Tens of thousands of acres of prime forest were destroyed. Furthermore, nearly 4 billion board feet of salable timber was destroyed

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by the Mt. St. Helen's lateral blast. The eruption caused over 2 million cubic yards of ash to fall onto Washington state highways and airports. In fact, ash removal costs reached $2.2 million and took over 100 weeks to complete in Yakima County. The ash also caused air transportation disruptions for up to two weeks as well as the closing of many highways and roads. It is also important to note more than 185 miles of highways, 15 miles of rails, and 200 homes were destroyed by the eruption (Tilling, Topinka, and Swanson, 1990).

Site Location

The Three Sisters volcanic center consists of three composite volcanoes including: North Sister, South Sister, and Broken Top. Throughout this region there are also mafic volcanoes that range from small cinder cones to large shield volcanoes (Scott, Iverson, Schilling, and Fischer, 2001).

Three Sisters is one of 9 threatening volcanoes within the Cascades volcanic arc (Ewert *et al*., 2005). The Cascades volcanic arc stretches from northern California, USA to British Columbia, Canada (Dzurisin, Lisowski, Wicks, Poland, and Endo, 2006).

As seen in Figure 1, the study area is defined as the area within 15 miles of one of the Three Sister volcanic centers. The area that will be reviewed includes portions of the following Oregon counties: Deschutes, Lane, and Linn.

Volcanic Events

Volcanism in the Three Sisters region has produced five large cones: North Sister, Middle Sister, South Sister, Broken Top, and Mount Bachelor (Dzurisin *et al*., 2006). The volcanic history of the Three Sisters region has been difficult to study because the last eruptions in the area occurred before written records. Thus, the eruptive history was derived from the study of geologic deposits and mapping in the area (Scott *et al*., 2001). Glacial erosion has also made detailed dating of the explosive history in the region difficult (Scott *et al*.).

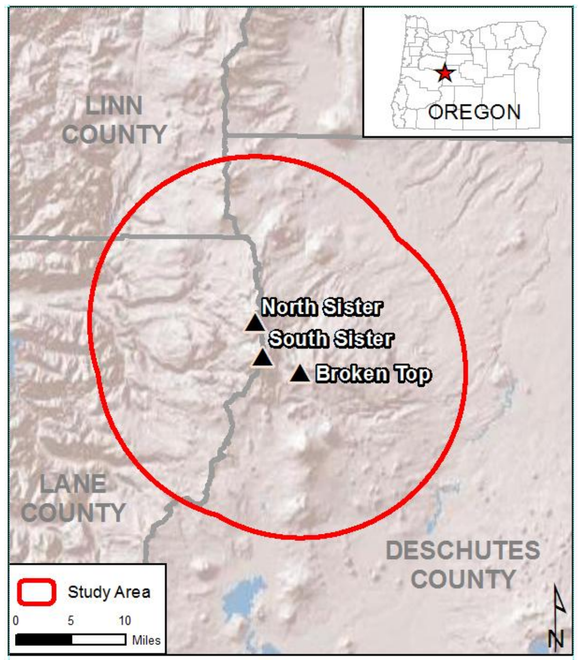

Figure 1. Site location with ESRI terrain background, summit locations and county boundaries.

Geologic mapping in the region suggests that during the past 700,000 years, there have been at least four explosive eruptions that produced significant pyroclastic flows that expanded to Bend, Oregon (Scott *et al*., 2001). Preliminary studies suggest there was an onset of volcanic periods between 12,000 and 30,000 years ago (Dzurisin *et al*., 2006). It is unlikely the volcanic center is capable of producing such a catastrophic explosion in the near future. This is due to the fact there is no evidence that there is enough magma present to drive such an eruption (Scott *et al*.).

The Three Sisters volcanic centers most recent eruption occurred nearly 2,000 years ago. These eruptions on South Sister produced small pyroclastic flows and tephra fallout. In the most significant expansions the tephra deposits extended 25 miles. These eruptions also produced lava flows, lava domes and small lahars (Scott *et al*., 2001; Dzurisin *et al*., 2006).

According to an Information Statement given by the USGS on April 11, 2007, the Three Sisters region is still being monitored. In 2001, satellite radar data revealed a 10 mile diameter area had risen about 4 inches. This uplift continued at an average of about 1 inch per year through 2004.

Field surveys and GPS receivers have confirmed the rate has slowed within the past two years to an average of about ½ inch. The uplift is most likely driven by intrusion of magma. The report explains the outcome or duration of the current intrusion is impossible to forecast. Intrusions require close monitoring because some lead to eruptions, but often only after weeks or months of intensifying unrest. The report concluded that scientists will work with the U.S. Forest Service to enhance monitoring networks as well as work with local agencies to develop a plan for responding to future volcanic events (USGS, 2007).

In the contents of this paper the term hazard will be defined as the probability for a point being affected by natural volcanic phenomena (Felpeto, Martí, and Ortiz, 2007). The term vulnerability will be discussed as Ewert *et al*. (2005) referred to it as those people and property threatened in regions of hazardous events. For the constraints of this project, risk will consider the possibility for loss of life and economic resources (Felpeto *et al*.). Thus, here risk will be used as the summation of hazards and vulnerability.

Methods

When faced with an environmental hazard, government officials, operation managers, scientists, environmental groups and landowners use formal or informal models to assess the possible outcomes. Given limited resources, time, and or expertise, pragmatic choices will be made so there are results with which to work. Therefore, it is important to use the most accessible and accurate data that is available (Renschler, 2005).

Hazard Discussion

Understanding hazards and their associated risk is important scientifically, economically and politically. The Three Sisters area presents a wide range of potential volcanic eruptions, styles, and hazards (Scott *et al*., 2001). The majority of the hazards are driven by the eruption of magma but debris avalanches and lahars can exist without eruptive activity (Scott *et al*.).

Tephra

Ash and rock fragments that are propelled into the atmosphere from a rush of expanding hot gas are called tephra. Large particle pieces (fist-sized up to 1 meter or more in diameter) will fall closest to vent while smaller ash particles can rise more than 30,000 feet and be carried tens to hundreds of miles away. Tephra can cause direct threats to life if deposit thicknesses are large enough to collapse structures. More often tephra causes hazards by decreasing visibility, irritating eyes and causing respiratory issues. Tephra clouds pose significant threats to aircraft because they interfere with the airplanes engines and filters (Scott *et al*., 2001).

Pyroclastic Flow

Pyroclastic flows are significant volcanic hazard. A pyroclastic flow is the mixture of hot rock fragments, ash and gas that flows down the sides of a volcano rather than rising into the atmosphere to produce tephra. If the mixture has a high density, made mostly of rock, the flow is controlled by topography. If the mixture has a lower density, fewer rocks and mostly gas, topography has little influence on the surge (Walder, Gardner, Conrey, Fisher, and Schilling, 1999). Most pyroclastic flows remain in valleys and travel no more than 6 miles (Scott *et al*., 2001). Pyroclastic events are dangerous because they travel at speeds of 30 to 90 miles per hour with temperatures greater than 570 degrees Fahrenheit (Walder *et al*.). These pyroclastic flows often will kill any living thing in its path as well as destroying all structures (Scott *et al*.).

Lahar

Lahars, like pyroclastic flows, contain volcanic rocks and mud. Lahars contain more water (Scott *et al*., 2001). Lahars move at speeds of nearly 10 miles per hour burying everything in their paths. Lahars can cause problems long after the original event. Lahars can inundate stream channels with sediment causing unstable paths and flooding (Walder *et al*., 1999).

Debris Avalanche

The steep sides of volcanoes can collapse causing landslides referred to as debris avalanches. Composite volcanoes are most susceptible to debris avalanches from volcanic unrest such as earthquakes or steam explosions (Scott *et al*., 2001). Avalanches can travel at speeds of 100 miles per hours up to 10 miles from collapse. Avalanche paths are greatly influenced by topography (Walder *et al*., 1999). Structures and objects in the path are often destroyed (Scott *et al*.). Deposits of debris avalanches can block tributary valleys causing unstable stream valleys and forming lakes (Walder *et al*.).

It is important to have tools for prediction and management for regions near volcano centers (Felpeto *et al*., 2007). The USGS has created a hazard-zone map showing areas likely to be affected by geologic events in the Three Sisters region as scene in Figure 2. In addition, the USGS has begun to distribute these hazard zones in ESRI shapefile format. Layer zones boundaries were determined by (1) past events at volcano, as interpreted from geologic mapping; (2) mathematical models used to determine the probable extent of lahars, pyroclastic flows and debris avalanches as understood from the study of volcanic events at other volcanoes; and (3) the judgment of the USGS from their experience of studying and observing of volcanic events (Scott *et al*., 2001).

Hazard Analysis

Figure 2 is broken into Proximal Hazard Zones, Distal Hazard Zones, and Regional Lava Flow Hazard Zone. According to Scott *et al*. (2001) the proximal hazard zone is defined as those areas subject to rapidly moving, devastating pyroclastic flows, debris avalanches and lahars. In addition, the proximal zone is also subject to lava flows and ballistic projectiles. The distal hazard zones are subdivided into three zones on the basis of the hypothetical lahar volumes and associated ranges of lahar probability. In general, because large lahars are less likely to occur than are small lahars, the distal hazard zones show the likelihood of lahar inundation decreases as distances from volcanoes and elevations above valley floors increase. For the purpose of the USGS created layers used in this analysis the small, medium, and large lahars were divided as 20 million, 100 million, and 500 million cubic meter hypothetical volumes respectively (Scott *et al*., 2001). The last zone included in the USGS hazard layer is the regional lava flow hazard zone. Scott *et al*. defines this as the area that could be affected by eruptions of mafic volcanoes. In this region hazards included: localized thick tephra fall, ballistic projectiles, pyroclastic flows near vents and lava flows that typically travel less than 15 kilometers.

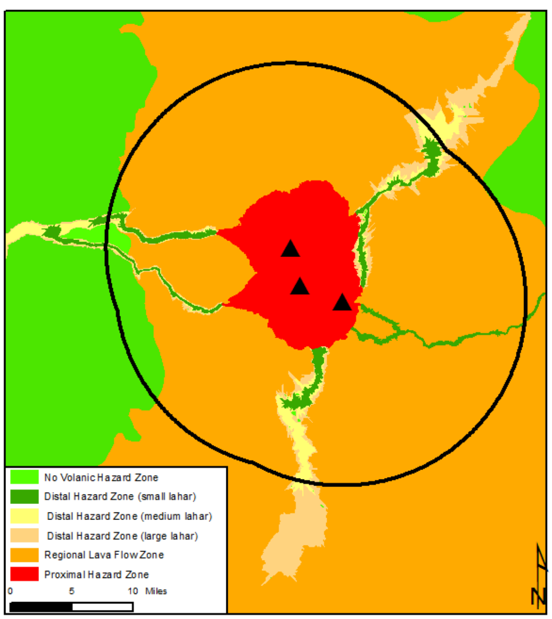

Figure 2. Hazard event probability map (no tephra hazard included) created by the USGS symbolized and defined by assigned hazard zones. See Figure 1 for site location details with site boundary in bold black outline.

When faced with an environmental hazard, government officials, operation managers, scientists, environmental groups and landowners use formal or informal models to assess the possible outcomes. Given limited resources, time, and/or expertise, pragmatic choices are made so that there are results to work with. Models are developed with a particular problem in mind (Renschler, 2005). This exact problem may or may not be the same reason that the program is being used in the future. Furthermore, models are often developed and tested using the best data that can be collected. However, often times when a model is being used it is based on the best data that can be obtained easily or at the moment. Thus, models should be used with critical mindsets or scaling (Renschler). Therefore, the volcanic hazard layer created by the USGS will be used for this study along with digitized layers based from the USGS's already created tephra hazard maps.

All geology and volcano related layers were gathered from the USGS. Figure 3 is a representation of the regional tephra-hazard maps created by the USGS. In Figure 3, the map on the left shows annual probability of deposition of 1 centimeter or more of tephra from any of the major Cascade Volcanoes. Also in Figure 3, the map on the right shows annual probability of deposition of a more major eruption causing 10 centimeters or more of tephra from any of the major Cascade Volcanoes. The darker the shade of pink in Figure 3, the higher the probability and higher hazard ranking. The USGS has already assigned numeric levels to each of the volcanic hazard layers but for the sake of consistency and statistical analysis for this study, these layers will be reassigned values as shown in Table 1. Hazard regions are not exact locations that can change from one side of the road to the other. For this reason, raster layers are going to be used. The USGS volcanic hazard event and tephra layers were converted to raster layers using ArcGIS

Desktop version 10.0. The inputs used for the conversion included cell sizes of 50 feet by 50 feet and cell values were determined by the value that covered the maximum area of each cell. The final step in creating the hazard raster layer in Figure 4 was used with the spatial analyst extension to add the tephra and the lahar raster layers together. Note, it is important in this analysis to make sure cells with no data are populated with a value of zero rather than having no data because the default of spatial analyst is to only show the sum of the cells with assigned values.

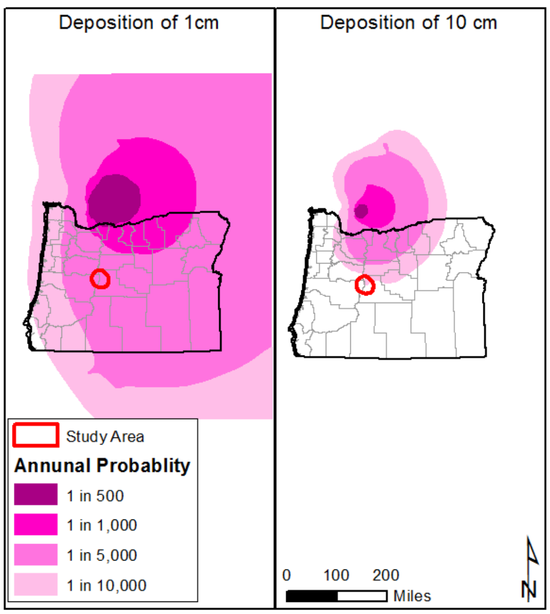

Figure 3. Tephra hazard map represented by layers by the USGS showing the annual probability of deposition of tephra from any major Cascade Volcanoes.

Vulnerability Discussion

For this paper, vulnerability is defined as the susceptibility of life, property or environment damage if a hazard were to occur (USGS, 2007). For this study, the NOAA Vulnerability Assessment Technique as described in their tool created for the North Carolina, New Hanover County Case Study was used. According to NOAA, vulnerability assessments describe the potential exposure of people and the built environment. The concept of vulnerability needs to incorporate the differential susceptibility and aspects of impacts to aid in risk mitigation (Hill and Cutter, 2001).

Table 1. Table showing attribute values assigned to vector data for GRID Code value classification in raster dataset.

Layer	Raster Value
No Volcanic Hazard Zone	0
Distal Hazard Zone (small lahar)	10
Distal Hazard Zone (medium lahar)	6
Distal Hazard Zone (large lahar)	4
Regional Lava Flow Zone	10
Proximal Hazard Zone	14
Tephra fallout 1 centimeter (1 in 500)	8
Tephra fallout 1 centimeter (1 in 1,00)	6
Tephra fallout 1 centimeter (1 in 5,000)	4
Tephra fallout 1 centimeter (1 in 10,000)	2
Tephra fallout 1 centimeter (<1 in 10,000)	0
Tephra fallout 10 centimeter (1 in 500)	7
Tephra fallout 10 centimeter (1 in 1,000)	5
Tephra fallout 10 centimeter (1 in 5,000)	3
Tephra fallout 10 centimeter (1 in 10,000)	1
Tephra fallout 10 centimeter (<1 in 10,000)	0

For this analysis, data layers were gathered for each of the vulnerability classes: critical facilities, environmental, economic and societal combined to create raster layers used for mitigation and risk analysis (Appendix A).

Each vulnerability vector layer was converted into a raster dataset by assigning attribute values to each feature. Next, the vector layers were converted to raster layers using ArcGIS Desktop version 10.0. The inputs used for the conversion included cell sizes of 50 feet by 50 feet and cell values were determined by the value that covered the maximum area of each cell. The final step in creating the individual vulnerability layers required use of the spatial analyst extension to add each individual defined feature raster layers together.

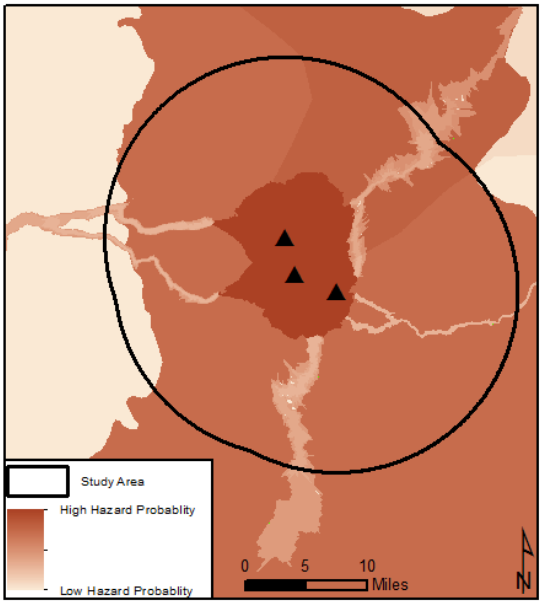

Figure 4. Volcanic hazard layer map created by the addition of USGS volcanic events and tephra deposition rasters. See Figure 1 for site location details.

As in the hazard raster layer creation, it was important in the vulnerability analysis to make sure no data cells were populated with zero rather than a no data input because the default of spatial analyst is to only show the sum of the cells only with values; any no data input values integrated with other values would result in no data output values.

Critical Facilities Analysis

This analysis focuses on determining the vulnerability of key individual facilities or resources. Focusing on critical facilities and structures allows for a more feasible study of important areas in a community (NOAA, 1999). As shown in Figure 5, critical facilities included: shelters, schools, hospitals, nursing homes, fire and rescue, police buildings, utilities, radio towers, major roadways, major waterways, major rails and government buildings (NOAA). Nursing homes, hospitals, schools and airport locations were gathered using the GNIS layer provided by the USGS. For major roadways a roadway network was obtained from the TeleAtlas. The roads were classified according to the FCC Codes as defined by TeleAtlas. Roads with FCC Codes beginning with A1 are considered to be a primary interstate. Roads whose FCC codes begin with A2 and A3 are defined as primary US and State Highways or Secondary State and County Highways respectively. In addition, roads with FCC codes beginning with A4 are considered local roads.

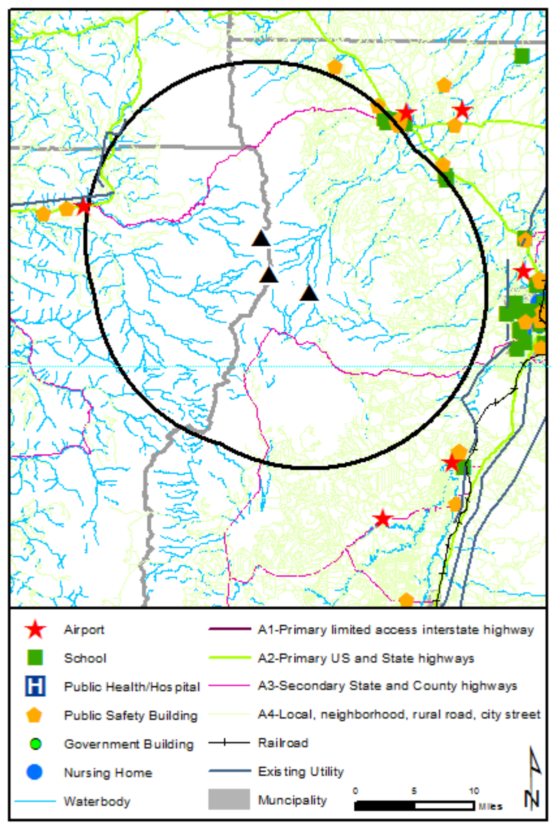

Figure 5. Critical facilities map showing the collected vector data. See Figure 1 for site location details with site boundary in bold black outline.

Furthermore, any other classifications such as driveways, highway entrance ramps and recreational vehicle trails were not considered for this analysis. Waterways were defined by the Oregon Department of Natural Resources waterbody layer and all features were considered. Railways were defined by the ESRI Streetmap layers. City boundaries were gathered from the Oregon Department of Transportation. Existing major utility lines were collected from the Digital Chart of the World Data that was originally created for the Defense Mapping Agency but is now incorporated as an ESRI product.

The first step in converting the vector data of the critical infrastructures into a raster dataset was to assign values to each attribute as shown in Table 2. Similar to the volcanic hazard regions, critical infrastructure vulnerability goes beyond the exact location of the building; for this reason, each vector layer was buffered by the values in Table 2 before being converted to raster. As described previously, the next step included converting each vector layer to raster layers. The sum of each of these layers depicts the final critical infrastructure vulnerability layer (Figure 6).

Environmental Analysis

This analysis has two parts: first, to identify potential for secondary environmental impacts and second, to identify critical natural resources (NOAA, 1999). Secondary impacts occur when natural hazard events create new hazards such as toxic releases or hazardous spills. Therefore, it was necessary to locate key sites where hazardous and/or toxic materials exist (NOAA). In this region critical environmental resources included areas marked off as wildlife refuges, old growth forests, and surface water intakes.

The original format of this data can be seen in Figure 7. Data was collected for forested areas by the OregonGAP analysis program.

Table 2. Table showing attribute values assigned to vector data for GRID Code value classification in raster dataset as well as buffer distance given to each facility for the creation of the raster layer.

Layer	Raster Value	Buffer Distance (ft.)
Airport	5	50
Public Health Building/Hospital	5	50
Public Safety Building	5	50
Government Building	5	50
Schools	5	50
Nursing Homes	5	50
Primary Interstate (Streets FCC Codes A1*)	5	50
Primary US and State Highway (Streets FCC Codes A2*)	4	50
Secondary State and County Highway (Streets FCC Codes A3*)	3	50
Local road (Streets FCC Codes A4*)	2	50
Railroad	5	50
Waterbody	5	20
Utilities	5	50
Municipality	10	0

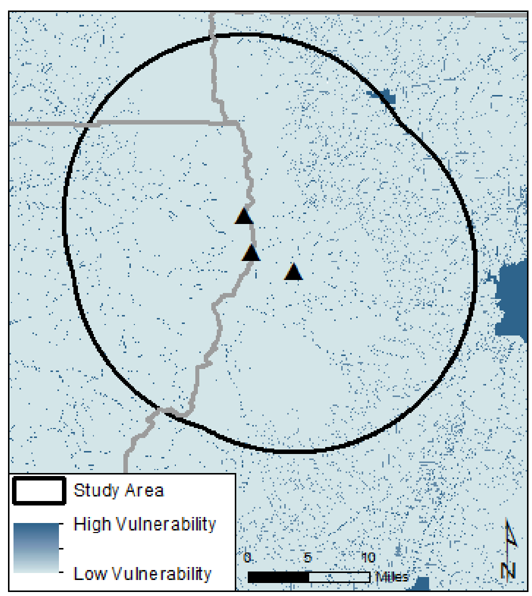

Figure 6. Critical infrastructure vulnerability raster layer map created by the addition of various critical infrastructure locations. See Figure 1 for site location details.

A national dataset of public lands was obtained from the Conversation Biology Institute (CBI) and was used to determine federal lands. These lands are owned by the Federal government and may include wildlife refuges, national parks and national forests. Toxic release/hazard spill sites were obtained from the Oregon Department of Environmental Quality's Environmental Cleanup Site Information (ECSI) database. The ECSI data was imported based on coordinate values for each site in ArcGIS Desktop to create a shapefile.

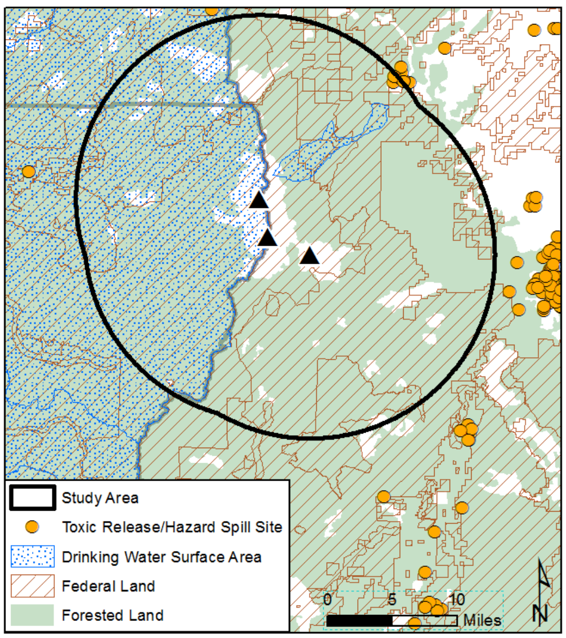

Figure 7. Environmental concern map showing the collected vector data. See Figure 1 for site location details.

The first step in converting the vector data of the environmental layers into a raster dataset was similar to the other vulnerability assessments. To begin it was necessary to assign values to each attribute as shown in Table 3. The toxic release/hazard spill sites are point locations; therefore, each point was given a 50 foot buffer similar to those point locations in the critical infrastructure analysis. Vector layers were then converted to raster layers and finally added together to create the environmental vulnerability layer in Figure 8.

Table 3. Table showing attribute values assigned to vector data for GRID Code value classification in raster dataset.

Layer	Raster Value
Toxic Release/Hazard Spill Site	5
Drinking Water Surface Area	5
Federal Land	5
Forested Land	5

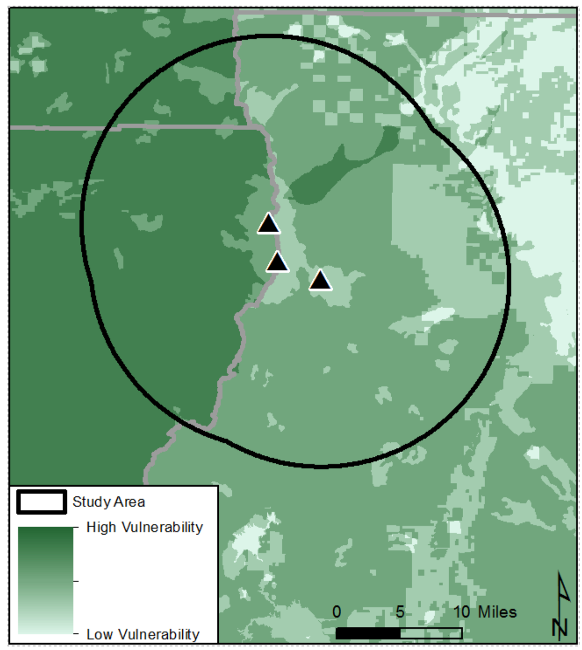

Figure 8. Environmental vulnerability raster layer map created by the addition of various environment layers. See Figure 1 for site location details.

Economic Analysis

The purpose of this section focuses on identifying major economic centers that could have impacts on the local community (NOAA, 1999). In this study economic vulnerabilities were limited to: natural resource and mining locations, agricultural land, industrial centers and any Fortune500 companies (NOAA).

According to CNNMoney Fortune (2011) there are only two Fortune500 companies in Oregon: Nike and Precision Castparts. The addresses of these two companies were gathered and georeferenced to create a shapefile. Mining locations were gathered using the GNIS layer provided by the USGS. For land of value in particular: agricultural and industrial land, a zoning layer was collected from the Department of Land Conservation. Areas zoned as agricultural, industrial, natural resource and commercial were considered to be of economic vulnerability and land of significant value for the constraints of this paper. As discussed above, these were the layers gathered to determine areas of economic vulnerability and can be seen in Figure 9.

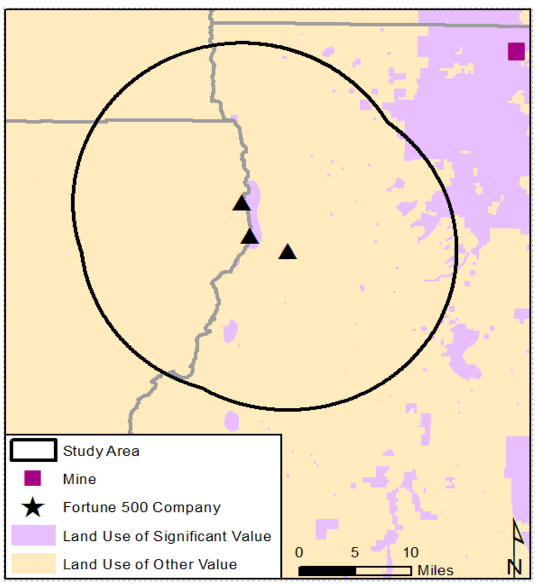

Figure 9. Economic areas of concern map showing the collected vector data. See Figure 1 for site location details.

The first step in converting vector data of the economic analysis into a raster dataset was to assign values to each attribute as shown in Table 4. Similar to the critical infrastructure analysis, many of the economic vulnerabilities go beyond the exact location. For this reason, both the Fortune500 companies and mine locations were buffered by 50 feet before being converted to raster. The vector layers were then converted to raster layers. The final step taken to create the economic vulnerability layer in Figure 10 was to use the spatial analyst extension to add the individual raster layers together.

Table 4. Table showing attribute values assigned to vector data for GRID Code value classification in raster dataset as well as buffer distance given to each facility for the creation of the raster layer.

Layer	Raster Value
Land Use of Significant Value (Zoning codes as: Agricultural, Natural Resource, Commercial, and Industrial)	10
Land Use of Other Value (Zoning code as: Coastal, Forestry, Public Lands, Non Resource, Residential, Urban, and Water)	0
Fortune 500 Business Location	5
Mines	5

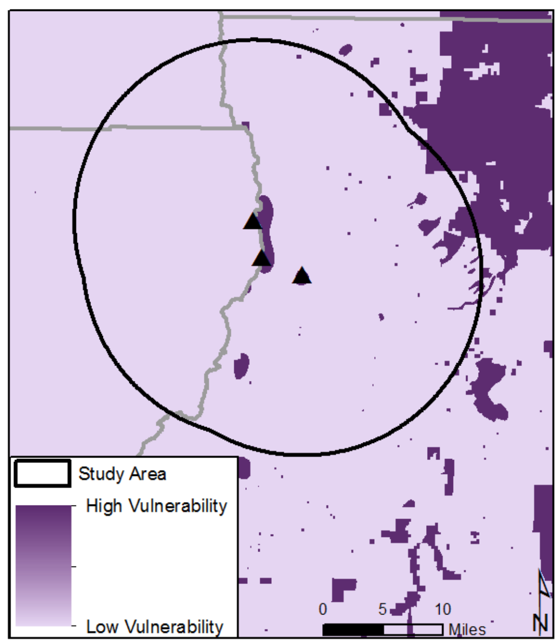

Figure 10. Economic vulnerability raster layer map created by the addition of raster classification layers. See Figure 1 for site location details.

Societal Analysis

This section helps to identify special considerations where individual resources are minimal and personal resources for dealing with hazards can be extremely limited (NOAA, 1999). In this study special consideration areas were defined as follows:

- Minority populations may indicate possibility of language or cultural barriers.
- Senior citizen population (over age 65) indicates possible mobility or cultural considerations.
- Single parent households may indicate special child care considerations.
- Rental areas indicate areas where households that may not have insurance for possessions (NOAA).

For the societal vulnerability analysis, 2000 Census data was used. Demographic data was summarized on the tract level. Although the 2010 census data has been completed, the summarized demographics were not yet available on the ESRI download site. ESRI had both the block geospatial shapefiles and the summary files that could be joined with shapefile for analysis.

The percentages for the senior citizen and minority vulnerabilities were found for each tract group by taking the total count of persons in consideration, dividing it by the total population and then multiplying the result by 100. Note, all considerations that were considered non-white were incorporated into the minority populations. The percentages for rental households and single parent household vulnerabilities were found for each tract group by taking the count of households in the considerations, dividing it by the total number of households and then multiplying the result by 100. For each societal factor the percentages were divided into 5 equal interval classes based on an interval that would include the highest percentage of each vulnerability. This analysis included census tract data for the four counties of: Lane, Linn, Deschutes, and Jefferson. Therefore, each vulnerability was divided into unique classes (Figure 11) that are relative to its maximum and minimum values in the region.

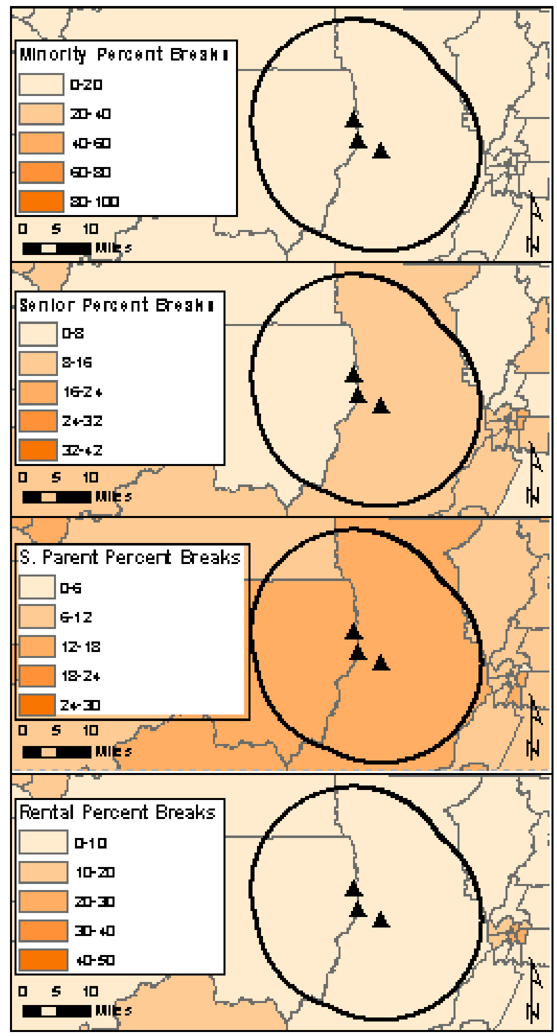

Figure 11. Societal areas of concern maps showing the collected census vector data. See Figure 1 for site location details. Study Area is in thick black outline on each map.

The census vector data were then converted into a raster dataset with the assigned values from Table 5. The final step in creating the societal vulnerability layer in Figure 12 included using the spatial analyst extension to add each individual societal raster layers together, as was done for the creation of every other vulnerability layer.

Table 5. Table showing attribute values assigned to vector data for GRID Code value classification in raster dataset.

Layer	Raster Value
Minority: Class Break 5 (Percent 80-100%)	5
Minority: Class Break 4 (Percent 60-80%)	4
Minority: Class Break 3 (Percent 40-60%)	3
Minority: Class Break 2 (Percent 20-40%)	2
Minority: Class Break 1 (Percent 0-20%)	1
Senior Citizen Age 65 and Up: Class Break 5 (Percent 0-8%)	5
Senior Citizen Age 65 and Up: Class Break 4 (Percent 8-16%)	4
Senior Citizen Age 65 and Up: Class Break 3 (Percent 16-24%)	3
Senior Citizen Age 65 and Up: Class Break 2 (Percent 24-32%)	2
Senior Citizen Age 65 and Up: Class Break 1 (Percent 32-40%)	1
Single Parent Household: Class Break 5 (Percent 0-6%)	5
Single Parent Household: Class Break 4 (Percent 6-12%)	4
Single Parent Household: Class Break 3 (Percent 12-18%)	3
Single Parent Household: Class Break 2 (Percent 18-24%)	2
Single Parent Household: Class Break 1 (Percent 24-30%)	1
Renter Household: Class Break 5 (0-10%)	5
Renter Household: Class Break 4 (10-20%)	4
Renter Household: Class Break 5 (20-30%)	3
Renter Household: Class Break 5 (30-40%)	2
Renter Household: Class Break 5 (40-50%)	1

Risk Discussion

The final stage of analysis in this study was the creation of the risk layer (Figure 13). The sum of the comprehensive vulnerability and hazard layers created a raster that depicted inherent risk. Some data manipulation was needed before combining all layers. First, all layers had to be in raster format. All layers had to have the same extent as well as same cell size. In addition, as in the creation of the hazard and vulnerability layers it was necessary to make sure no data cells were populated with zero rather than a no data value.

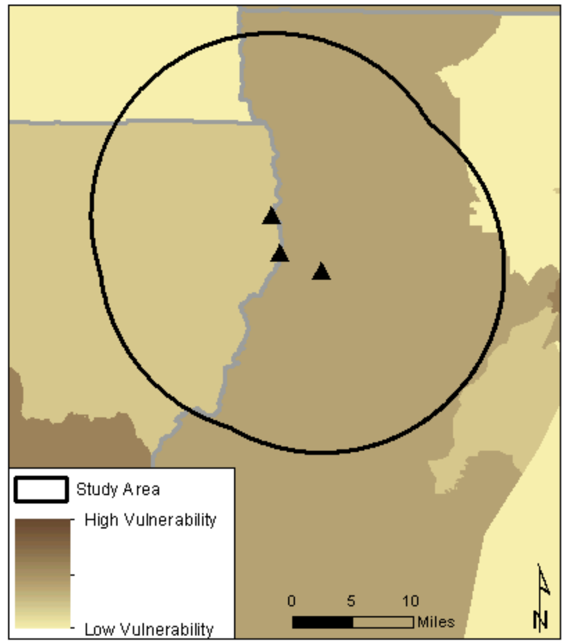

Figure 12. Societal vulnerability raster layer map created by the addition of various census raster classification layers. See Figure 1 for site location details.

This risk layer is beneficial to city planners. It shows areas with the least risk that would be best suited for future development. Furthermore, this layer would also be useful to emergency response teams so that they know where to focus resources in the case of a volcanic event. This layer could also be used to educate the community so that residents can better understand the risks associated to their surroundings.

Analysis

Although the risk layer created during this analysis is beneficial as a macro overview of areas at risk for the Three Sister Volcanic region, it was still necessary for more analysis to be done to point out specific areas of concern for mitigation purposes. According to NOAA (1999), mitigation is the effort to lessen the effect that natural hazards have on surrounding populations and property. The first stage of this analysis was to identify the areas that had higher probability of volcanic hazards to occur. The second stage was to identify those considerations that were considered to be vulnerable to those hazards.

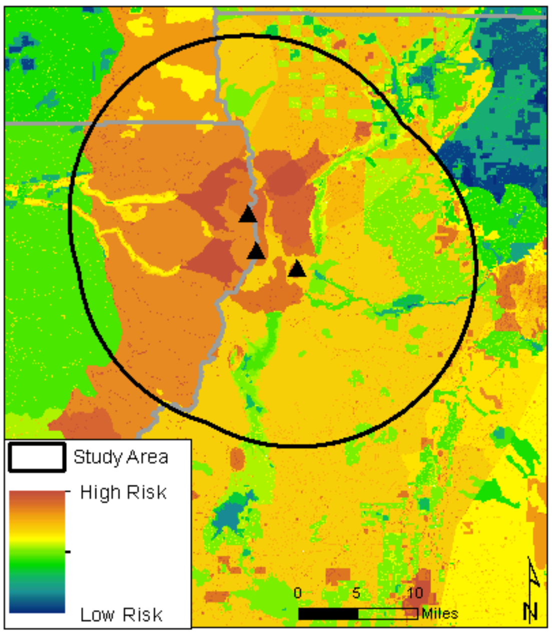

Figure 13. Risk raster layer map created by the addition of all vulnerability classification raster layers (critical infrastructure, environment, economic and societal) and volcanic hazard raster layer. See Figure 1 for site location details.

After creating hazard and vulnerability layers, these rasters were multiplied using the spatial analyst extension. Multiplying allowed areas where no hazard or vulnerability existed to remain a zero implying no need for mitigation efforts for these regions. Furthermore, areas where both hazards and vulnerabilities existed would result in higher values which allowed for classification of data to recognize those areas where mitigation efforts might be focused. One constraint of this analysis is that all areas in this region are at risk of at least a tephra deposit. However, this does work for the benefit of being able to pin point which vulnerabilities to focus on. For the investigation of which considerations are of the gravest concern and should be focused on for mitigation were the multiplied layer was classified in the ESRI ArcMap software by natural breaks. ESRI software uses the Jenks optimization method for this classification. The method is designed to determine the best arrangement of value in different classes by seeking to minimize each class's average deviation from the class mean while also maximizing each class's deviation from the means of other groups. Simply put, it attempts to reduce the variance within classes and maximize the variance between classes. Comparing those values that fall within the highest natural break to the original vector data for each of the critical infrastructure, environmental, economic, societal vulnerability analyses allows for better understanding which considerations should be focused on in areas of high hazard rankings for mitigation efforts.

Critical Infrastructure Mitigation

Figure 14 illustrates the resulting raster layer from multiplying the hazard layer with the critical infrastructure vulnerability raster layer. The areas deserving the greatest concern would be the municipalities. The only municipality that is within the study area is the City of Sisters, however the larger urban area of Bend is approximately 2 miles from the study boundary and should be mentioned and considered for mitigation purposes. These communities should focus on education of potential hazards.

In addition, within the study area, other areas of concern would be major roadways. Where major commute routes fall within lahar flood zones, alternative routing should be preplanned. Finally, this information provides an overview of the potential for future development in areas that are not at risk. In addition, it can show where emergency response facilities should be built in relation to high risk areas.

Environmental Mitigation

The multiplication of the environmental vulnerability raster layer and the hazard layer is represented in Figure 15. When comparing this layer to the original vector data the areas of greatest concern are those areas that are mapped as drinking water surface intake areas. One method of mitigation for this region would be to make sure there would be bottled water or filtered water options for citizens that receive water from wells within those areas.

Although not present in the immediate study area, one other area of concern would be the secondary environmental hazards that are present if a disaster were to happen near an already environmental sensitive area such as toxic release and hazard spill areas. These sites should have education trainings and assessments done to identify methods of mitigation in a volcanic event.

Economic Mitigation

Figure 16 illustrates the resulting raster layer from multiplying the hazard layer with the economic vulnerability raster layer. The areas deserving greatest concern would be areas that were zoned to have economic value.

Areas of most concern are zoned as

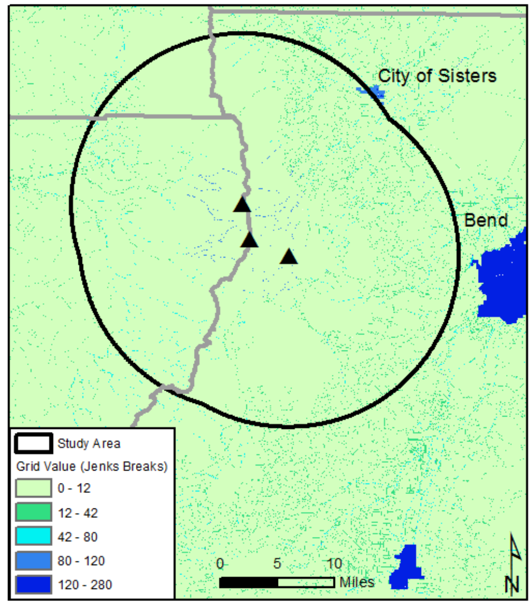

Figure 14. Critical infrastructure mitigation raster layer map. Areas with higher values require the most consideration for mitigation efforts. See Figure 1 for site location details.

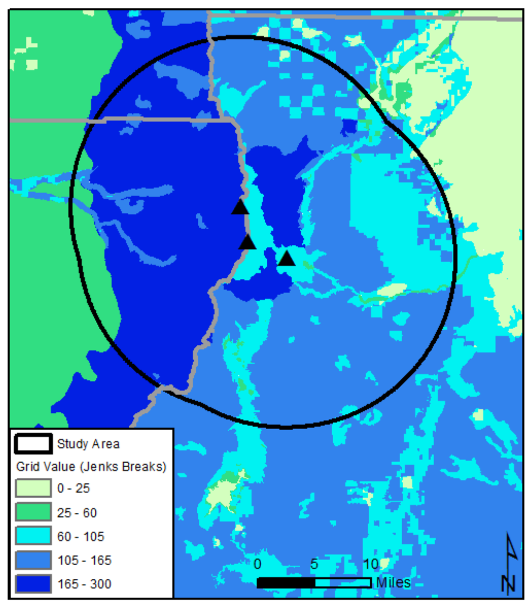

Figure 15. Environmental mitigation raster layer map. Areas with higher values require the most consideration for mitigation efforts. See Figure 1 for site location details.

areas of natural resources by the Department of Land Conservation. This information provides an overview of the potential for future development in areas that are not at risk. This is mainly due to the fact there are no Fortune500 companies or mines in the region.

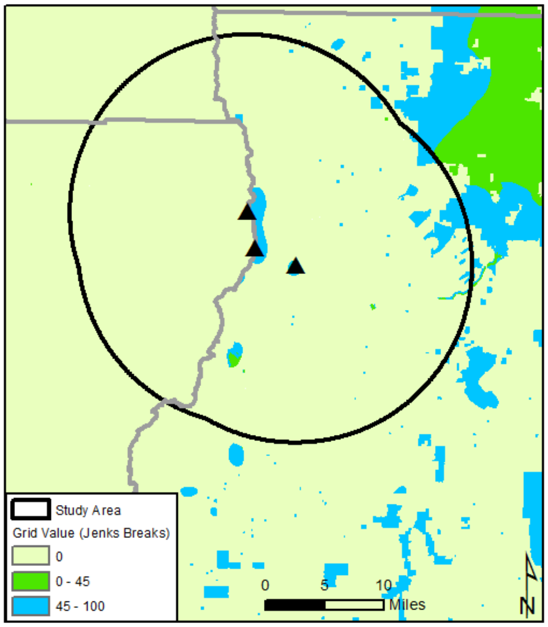

Figure 16. Economic mitigation raster layer map. Areas with higher values require the most consideration for mitigation efforts. See Figure 1 for site location details.

Societal Mitigation

The multiplication of the societal vulnerability raster layer and the hazard layer is represented in Figure 17. When comparing this layer to the original Census vector data, the vulnerabilities of greatest concern are the regions are senior citizen populations and single parent households. Although the Census data shows population at risk, it still leaves wide geographical areas of these vulnerabilities.

One could suggest a further study of the Census blocks rather than the tracts, to get a clearer picture of population concerns. Once these areas are identified, the communities should offer special hazard mitigation education. Information could be delivered through schools, community centers and business centers. Special evacuation plans need to be in place for the senior citizen populations with mobility needs. In addition, efforts should be made to help single parents that will have limited resources for child care needs.

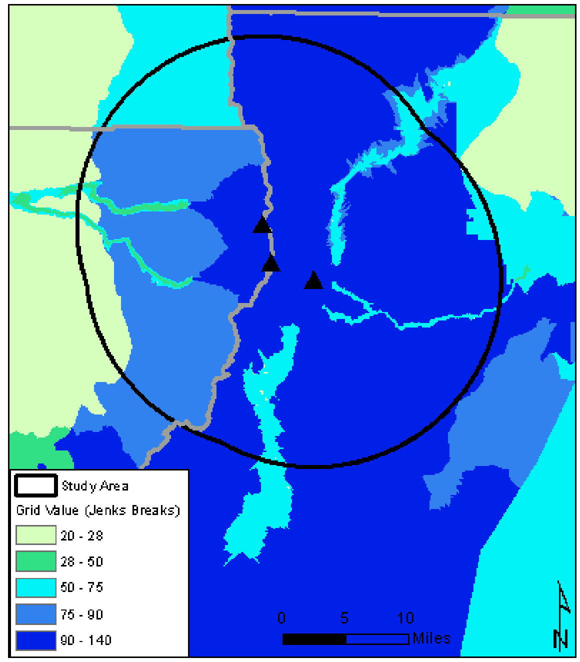

Figure 17. Societal mitigation raster layer map. Areas with higher values require the most consideration for mitigation efforts. See Figure 1 for site location details.

Results

The analysis of risks, hazards, and vulnerabilities in the Three Sisters Region using GIS helped identify where future hazard mitigation projects should be focused. In reviewing the volcanic hazard analysis, it is import to focus on minimizing impacts from the hazards in the following order: pyroclastic flow areas, debris avalanches, tephra fallout areas and lahars. Furthermore, it should go without saying that mitigation efforts should be prioritized according to proximity to high-risk areas. In addition, considerations of high vulnerability should also warrant mitigation efforts.

In the Three Sister region, the urban areas of Bend and the City of Sisters should have emergency response procedures in place in the event of a volcanic eruption. In association with this, the municipalities and critical infrastructure of major commuter routes should have planned detours and reroutes in place before an emergency. Another vulnerability that should be mitigated is drinking water in the area. This includes the number of waterways in the area and the amount they contribute to the drinking water in the west side of the study area. Consideration for land that is zoned as natural resource should be incorporated into city planning and facility emergent management plans should be required in these areas. Finally, the study of the societal vulnerabilities in the region identified that single parent households and senior citizens are at risk in the Three Sisters Volcanic Area. In conclusion, communities in high hazard areas or areas with significant vulnerabilities should be offered special hazard mitigation education.

Conclusions

The Three Sisters Volcanic region is one of 9 threatening volcanoes within the Cascades volcanic arc. With planning, education and mitigation done before an eruption, hazards, vulnerabilities and risks can be assessed before an event occurs. The creation of a procedure using GIS helps in automating the very complicated and lengthy processes of creating a risk assessment. Responses to volcanic events can be better handled with an understanding of how communities will be affected.

Suggestions for Future Analysis

The study area for this project was focused on the proximity surrounding the volcanic center, future studies might focus on communities such as the City of Sisters or Bend that are near volcanic regions to better anticipate what the denser population areas will need to know to respond to volcanic events. The data incorporated in this study included data that was easily accessible and free. County data or field verified data in the region would more accurately portray the hazards, vulnerabilities and risks in the region.

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For all geospatial data see Appendix A.

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USGS. 2007. Three Sisters Vicinity - Information Statement, April 11, 2007. Retrieved February 8, 2008 from http://vulcan.wr.usgs.gov/Volcanoes/Sisters/WesternUplift/information_statement_04-11-07.html.
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Appendix A. Geospatial Data.

Data Name	Source / Website	Date Published / Date Collected
	Source	**Date Published**
	Website	**Date Collected**
Base		
State Boundary	Oregon/Washington Bureau of Land Management	1/1/2001
	http://oregon.gov/DAS/EISPD/GEO/alphalist.shtml	3/9/2011
County Boundaries	Oregon/Washington Bureau of Land Management	9/1/2007
	http://oregon.gov/DAS/EISPD/GEO/alphalist.shtml	3/9/2011
Municipality Boundaries	Oregon Department of Transportation	10/8/2009
	http://oregon.gov/DAS/EISPD/GEO/alphalist.shtml	3/9/2011
Three Sister Summits	USGS Geographic Names Information System	5/1/2009
	http://gis.oregon.gov/DAS/EISPD/GEO/alphalist.shtml	3/13/2011
Hazard		
USGS hazard shapefile for Three Sisters	USGS Cascade Volcano Observatory	1/1/1986
	http://geopubs.wr.usgs.gov/open-file/of99-437/of99-437map.pdf	2/24/2011
Tephra	USGS Cascade Volcano Observatory	1/1/1986
	http://geopubs.wr.usgs.gov/open-file/of99-437/of99-437map.pdf	2/24/2011
Societal Vulnerability		
Census data	US Census	1/1/2000
	http://arcdata.esri.com/data/tiger2000/tiger_statelayer.cfm?sfips=41	3/29/2011
Critical Facilities Vulnerability		
Hospitals	USGS Geographic Names Information System	5/1/2009
	http://gis.oregon.gov/DAS/EISPD/GEO/alphalist.shtml	3/13/2011
Schools	USGS Geographic Names Information System	5/1/2009
	http://gis.oregon.gov/DAS/EISPD/GEO/alphalist.shtml	3/13/2011
Airports	USGS Geographic Names Information System	5/1/2009
	http://gis.oregon.gov/DAS/EISPD/GEO/alphalist.shtml	3/13/2011
Government Buildings	Homeland Security Infrastructure Program TechniGraphics Inc	2/2/2008
	http://gis.oregon.gov/DAS/EISPD/GEO/alphalist.shtml	3/13/2011
Fire Buildings	Homeland Security Infrastructure Program TechniGraphics Inc	9/19/2008
	http://gis.oregon.gov/DAS/EISPD/GEO/alphalist.shtml	3/13/2011
Police Buildings	Homeland Security Infrastructure Program TechniGraphics Inc	12/30/2009
	http://gis.oregon.gov/DAS/EISPD/GEO/alphalist.shtml	3/13/2011
Major roadways	ESRI Streetmap	1/1/2003
	ESRI Basedata CDs	3/9/2011
Major waterways	ESRI Streetmap	1/1/2007
	ESRI Basedata CDs	3/9/2011
Utilities	Defense Mapping Agency	1/1/2000
	http://data.geocomm.com/	3/27/2011
Major rails	ESRI Streetmap	1/1/2007
	ESRI Basedata CDs	3/9/2011
Economic Vulnerability		
Mines	USGS Geographic Names Information System	5/1/2009
	http://gis.oregon.gov/DAS/EISPD/GEO/alphalist.shtml	3/13/2011
Oregon Zoning	Department of Land Conservation and Development	5/1/1986
	http://gis.oregon.gov/DAS/EISPD/GEO/alphalist.shtml	3/29/2011
Fortune 500 companies	CNN Fortune 500	5/3/2010
	http://money.cnn.com/magazines/fortune/fortune500/2010/states/OR.html	3/29/2011
Environmental Vulnerability		
Wildlife Public Land	Conservation Biology Institute	1/20/2001
	http://databasin.org/protected-center/features/PAD-US-CBI	1/1/2011
Forested Land	Oregon GAP Analysis Program	3/13/2011
	http://gis.oregon.gov/DAS/EISPD/GEO/alphalist.shtml	1/1/1993
Known Hazard/Toxic Sites	Oregon Department of Environmental Quality	3/20/2011
	http://www.deq.state.or.us/lq/ECSI/ecsi.htm	2/28/2011
Drinking Water Intake Sites	Oregon Department of Environmental Quality	3/13/2011
	http://gis.oregon.gov/DAS/EISPD/GEO/alphalist.shtml	9/15/2003