GIS ANALYSIS OF THE EFFECT OF LAHARS FROM MOUNT RAINIER, WASHINGTON ON AREA WATER SOURCES

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By
Max R. Masters

NORTHWEST MISSOURI STATE UNIVERSITY
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EFFECT OF LAHARS ON AREA WATER SOURCES

GIS Analysis of the Effect of Lahars from Mount Rainier, Washington on Area Water Sources in King and Pierce Counties

Max R. Masters

Northwest Missouri State University

THESIS APPROVED

Thesis Advisor, Dr. Yi-Hwa Wu Date

Dr. Ming-Chih Hung Date

Dr. James C. Hickey Date

Dean of Graduate School, Dr. Gregory Haddock Date

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ABSTRACT

This project focused on the probable effects of three different magnitude lahars on the ground and surface water in the areas of King and Pierce Counties surrounding Mount Rainier. The data used for this project was acquired from King and Pierce Counties, the State of Washington, and the United States government. The goal was to use existing data that was available at little or no cost to promote the use of this model in other research projects or disaster mitigation planning. The vital piece of information, the three different magnitude lahar extents, was provided free of charge by the USGS as an output of LAHARZ; their mathematically advanced lahar inundation flow model. The three flow magnitudes, originally classified by the USGS as Case I, Case II, and Case III, were reclassified for this project as Extreme, Severe, and Moderate, to better illustrate the effect on the surrounding resources.

The primary concerns were possible impacts to critical aquifer recharge areas and salmon and aquatic organism habitat. The affected percentage of the total population in King and Pierce Counties based on the lahars ranged from 19.95% in Extreme flows, 16.61% in Severe flows, to less than 0.01% in Moderate flows. The percentage of critical aquifer recharge areas in the two counties affected by the Extreme lahar was 24.78%, Severe flows had 15.79% affected, while Moderate flows had 1.92% potentially contaminated. The salmon habitat in two counties was greatly affected by the Extreme

flow event with 41.73% of habitat affected. The Severe flow event still had a significant effect on the habitat with 25.09% affected. The Moderate flow event had a relatively small impact of 0.78%. The aquatic organism habitat was also greatly affected by the Extreme lahar with 72.32% potentially contaminated. The effect on aquatic habitat in the Severe lahar dropped greatly to 27.13%. The Moderate lahar affected 8.94% of the aquatic organism habitat. The model has the potential to be expanded and improved upon with the use of additional data, such as municipal water supply locations, that was not available for this research due to security concerns or costs associated with the acquisition.

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GLOSSARY OF TERMINOLOGY

Alluvial Fan

Alluvial fans are fan-shaped deposits of water-transported material (alluvium). They typically form at the base of topographic features where there is a marked break in slope. Consequently, alluvial fans tend to be coarse-grained, especially at their mouths. At their edges, however, they can be relatively fine-grained (United States Geological Survey 2000).

Census Tract

Census tracts are small statistical subdivisions of a county. Usually tracts have between 2,500 and 8,000 people and were originally created to be homogeneous with respect to population characteristics, economic status, and living conditions. Tracts do not cross county boundaries (United States Census Bureau 2009).

Cohesive Debris Flow

Cohesive flows exhibit behavior affected by the cohesion and adhesion of particles. Due to the high clay content, these flows have the capability of carrying large boulders and debris masses. These flows contain more than 3 to 5 percent of clay sediment (Scott *et al*. 1995).

Critical Aquifer Recharge Area

Ground areas with a critical recharging effect on aquifers used for potable water are identified and protected as Critical Aquifer Recharge Areas or CARA (United States Geological Survey 2000).

Noncohesive Debris Flow

Noncohesive flows are dominated by particle collisions. These flows are generally better sorted than the cohesive flows. These flows contain less than 3 to 5 percent clay sediment, which carries finer grained materials rather than boulders (Scott *et al*. 1995).

Lahar

Lahar is an Indonesian word that describes a mixture of water and rock fragments flowing down the slopes of a volcano and river valleys. When in motion a lahar looks like wet concrete that carries debris ranging from clay fragments to large boulders. The topography of a region determines the speed and depth of lahars (United States Geological Survey 2000).

LAHARZ

Menu-driven GIS program developed by the United States Geological Survey used to identify areas of lahar inundation. The program uses mathematical formulas and GIS data to create hazard zones (Schilling 1998).

Pyroclastic Flows

Pyroclastic flows are high-density mixtures of hot rock fragments and hot gases that move away from the volcanic vent at high speeds. Most pyroclastic flows consist of two parts: a basal flow of coarse fragments that moves along the ground, and a cloud of ash that rises above the basal flow (United States Geological Survey 1999).

Urban Area (Census Defined)

Urban areas are census block groups or blocks that have a population density of at least 1,000 people per square mile and surrounding census blocks that have an overall density of at least 500 people per square mile (United States Census Bureau 2009).

CHAPTER 1: INTRODUCTION

The thought of catastrophic volcanic eruptions near populated areas has been on the minds of many in the Pacific Northwest since the eruption of Mount Saint Helens on May 18, 1980 (United States Forest Service 2007). The Cascade Mountain Range, which runs from British Columbia, Canada to California, United States is home to fourteen active or potentially active volcanoes (United States Geological Survey 2003). Along with Mount Saint Helens, Mount Rainier raises much concern about the possibility of a large-scale eruption. The eruptive cycle of Mount Rainier might not result in an extreme eruption for another 800 years or more; however the mountain is capable of producing numerous non-volcanic events such as lahars, avalanches, and glacial floods (Scott *et al*. 1995).

A lahar from Mount Rainier poses the greatest current threat as it does not take a volcanic eruption to occur. Lahars can be formed by heavy rainfall, triggered by earthquakes, or simply the pull of gravity on the steep volcanic slopes (United States Geological Survey 2000). Although there is much research regarding the effects of large scale eruptions and their impacts on the surrounding area, there is little research illustrating the effects of lahars on water supplies for these areas. Lahars have the possibility to contaminate agricultural and domestic water supplies, which can create a long-lasting impact on the communities surrounding Mount Rainier. Lahars also reduce the capacity of streams, rivers, and lakes to convey and hold water due to the increased sediment deposits (Major *et al*. 2000). The diminished capacity of the waterways leads to further flooding and resource damage. Planning to mitigate these water supply concerns can be greatly enhanced by the use of GIS analysis in disaster management.

Catastrophic volcanic eruptions are not a common event in the written history of the United States. This lack of first-hand knowledge of the capabilities of eruptions along with socio-economic factors pushing development, particularly in the Cascade Range, has led to large-scale development near active volcanoes. More than 150,000 people live on deposits of lahars in the river valleys surrounding Mount Rainier (O'Dea 2007). Mount Rainier is within sight of the Seattle-Tacoma metropolitan area, which has a population that exceeds 3.2 million people (Figure 1). This presents some interesting issues when developing disaster mitigation plans. Previous USGS-sponsored studies of the volcano have focused on the problems associated with dense development around Mount Rainier, while avoiding another major threat, toxic flooding of domestic and agricultural water supplies (Hoblitt *et al*. 1998). The heavily glaciated peak of Mount Rainier has the potential to create massive lahars, slurry of mud, water, and vegetation, which would travel down the valleys surrounding the mountain at a high rate of speed. Previous lahars from Mount Rainier have reached the shores of Puget Sound, pushing out the shoreline approximately 117 square miles (Wood & Kienle 1990). The flood waters have the potential to cause a great loss of human life due to the speed at which it will travel. The lahars have the potential to overrun and destroy downstream dams creating further devastation (Scott *et al*. 1995).

Many variables affect the impact of the lahars on the human activities and economic costs, such as snow depth on the mountain, terrain, and the strength of the lahar-causing event. Water quality following a lahar event would be affected by the accumulation of organic debris and microorganisms in water bodies and critical aquifer recharge areas. A violent volcanic eruption would create high levels of sulfur, iron, and manganese, in water bodies on and around Mount Rainier in addition to the effects of the lahar (Hoblitt *et al*. 1998). As areas around Mount Rainier continue to be developed, due to its picturesque views and proximity to the Seattle-Tacoma metropolitan area, the effects of water supply contamination resulting from lahars will pose even greater threats.

This research strived to present interactive maps and analysis results to determine the areas that would be most adversely affected by a lahar event produced from either a volcanic or non-volcanic event. A combination of raster and vector data was used in the

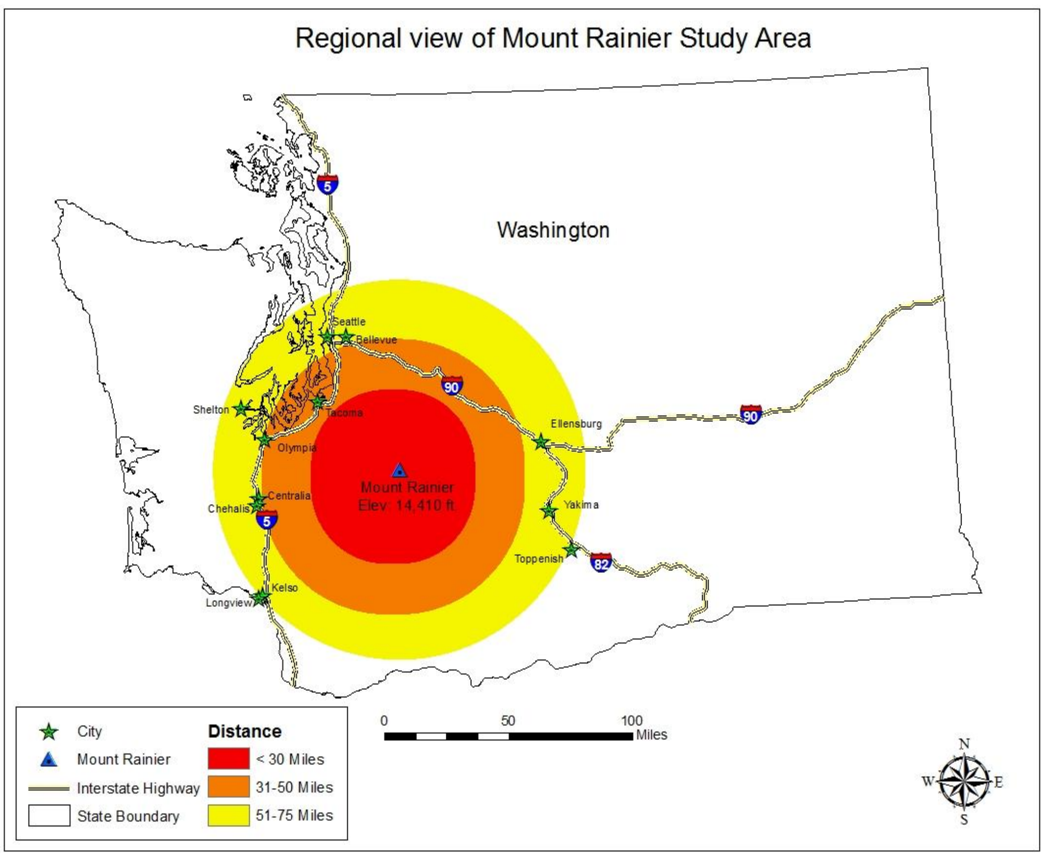

Figure 1: Distance from Mount Rainier, Washington to Surrounding Areas

analysis to determine possible outcomes of the event as variables were adjusted. Existing data were used in all models and analysis rather than the field collected data to reduce the cost. The overall goal of this research was to showcase the ability of GIS analysis in the identification of lahar hazards to water sources.

1.1 Research Background

The United States Geological Survey (USGS) had performed hazard analyses on Mount Rainier, with the most recent full study coming in 1998 (Hoblitt *et al*. 1998). These reports addressed concerns dealing with possible lahar flow locations (Figure 2) but did little in modeling the effect on local surface water and groundwater supplies. The focus of the hazard analysis was aimed at loss of life immediately following a violent eruption, rather than the lasting effects or the impact on surface and ground water. In research performed by the U.S. Geodynamics Committee (1994), potential hazards were identified, but supplemental maps and methodology were lacking.

Although previous studies of Mount Rainier focused on the immediate health and safety concerns associated with a lahar event rather than the longer term issue of water supply contamination that was the focus of this research, they did provide a strong foundation on which to base further research (Hoblitt *et al*. 1998; Iverson *et al*. 1998; Scott *et al*. 1995). The USGS-developed LAHARZ program provided detailed flow path information for this study (Schilling 1998). In-depth analysis of other volcanic regions (Prabaharan & Kanniah 2000) presented insight as to how to improve upon the existing Mount Rainier hazard analyses. The disaster following another Cascade volcanic eruption, Mount Saint Helens, also provided a basis to improve the Mount Rainier hazard analysis (United States Forest Service 2007). Watersheds surrounding Mount Saint Helens were seriously affected by the eruption, a trait that would carry over to a lahar event on Mount Rainier.

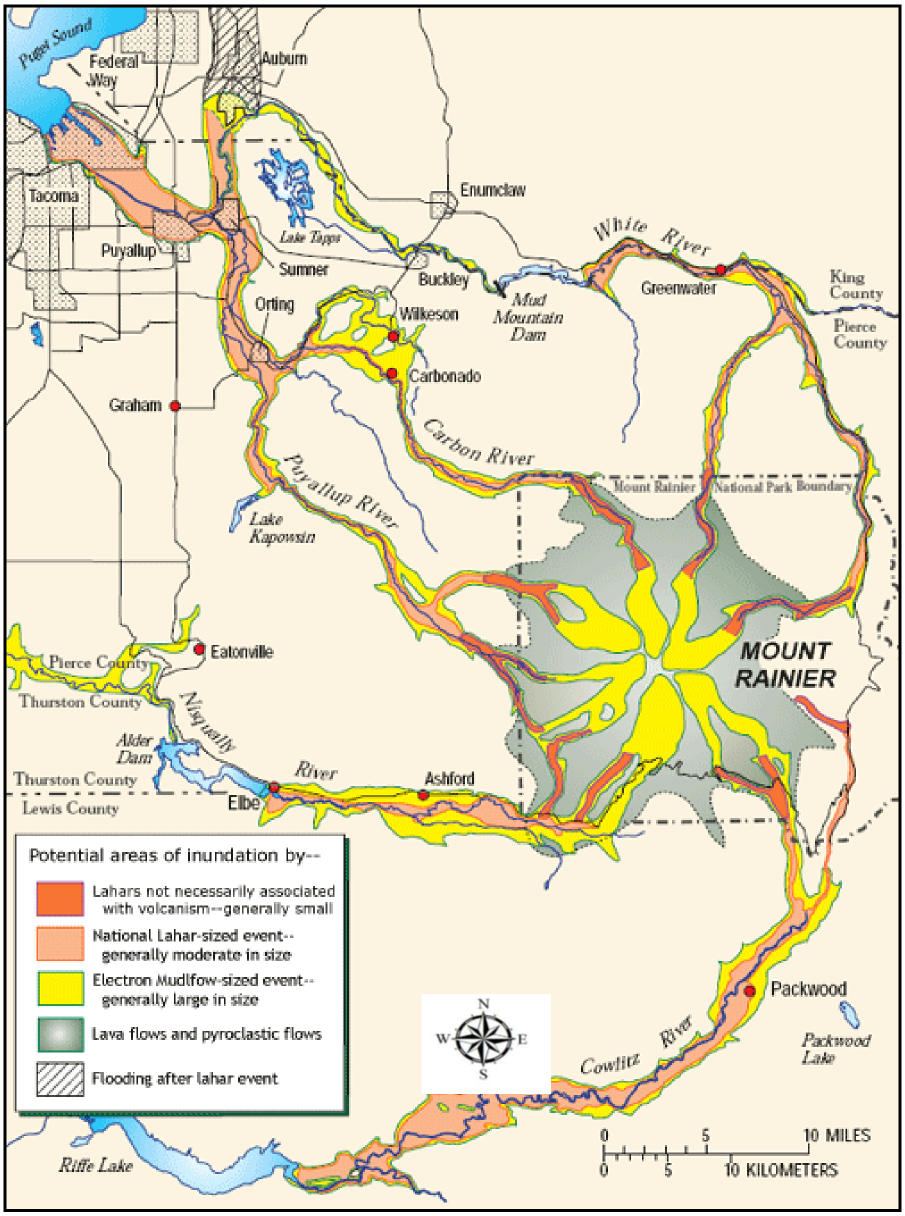

Figure 2: Hazard zones for lahars, lava flows, and pyroclastic flows from Mount Rainier (Source: Hoblitt *et al*. 1998)

The sheer size of Mount Rainier, the highest peak in the Cascade Range at 14,411 feet, along with its large mass of glacial ice cover also promotes the need for an improved hazard analysis (Figure 3). The region around Mount Rainier in King and Pierce Counties contains the necessary topographical features, such as major drainage valleys, that increase the destructive power of lahar events (Figure 4).

Considering the size of the active volcano, combined with the population density for the surrounding area, the urgency to develop an in-depth hazard analysis becomes apparent. Combining GIS technology with existing knowledge of the volcanic characteristics of the region, a quality set of hydrology lahar impact maps can be created to assist planners in disaster pre-planning and mitigation. Previous studies of Mount Rainier yielded stream networks that would be affected by a lahar, but the analysis lacked detailed information regarding the damage to water supplies (Hoblitt *et al*. 1998). The effect of lahars on the water supply for domestic, agricultural, and natural uses needs to be identified and examined further. How will domestic and agricultural supplies be affected by a lahar event? What mitigation strategies need to be developed to replace or protect damaged water supplies?

Previous research has determined flow locations and immediate disaster concerns; while less research has been focused on the lasting environmental and economic effects of a lahar (Iverson *et al*. 1998). This study filled the research niche created by the lack of GIS analysis of the potential long-term damage areas and the response issues associated with these areas.

Figure 3: Mount Rainer glacial coverage area. (Source: United States Geological Survey 2003)

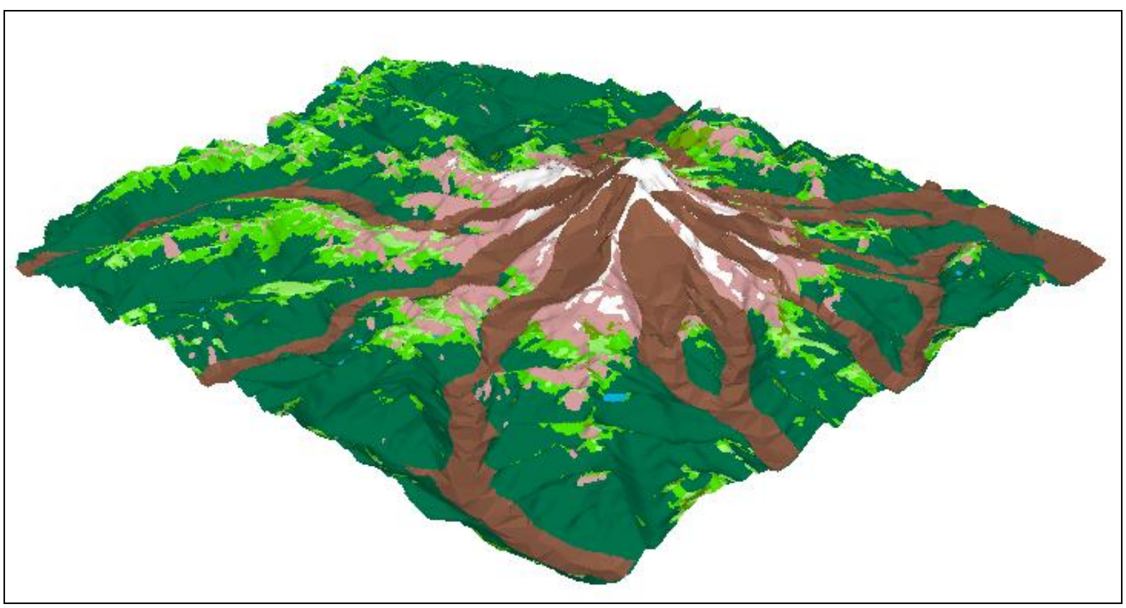

Figure 4: 3D Render of Mount Rainier area with potential lahar flow (Data Source: United States Geological Survey)

1.2 Research Objectives

The objective of this study was to expand upon previous lahar hazard research to identify long lasting effects that have been downplayed or avoided in other projects. Additionally, this research focused on readily available, low or no cost, data to insure the usability of the developed model. The primary objective involved the identification of potentially contaminated water supply areas surrounding Mount Rainier. Lahar flow routes determined by previous USGS LAHARZ analysis were used to determine the water supply and critical aquifer recharge areas that lay within the flow path. Lahars of different magnitudes included in the USGS study were also evaluated in order to determine the level of hydrological impact depending on the size of the lahar event (Schilling 1998).

Although numerous studies had been completed regarding disaster analysis of the Mount Rainier volcanic region, these studies failed to go into detail regarding the effects on water supply areas in the region (Hoblitt *et al*. 1998; Iverson *et al*. 1998; Scott *et al*. 1995). This research went beyond the initial disaster response to focus on more lasting affects to the area surrounding the volcano. An in-depth GIS analysis allowed different variables to be plugged into the process in order to better determine the critical aquifer recharge areas that might be affected by the lahar flow path. Also, GIS could be used well into the future as software continues to develop, allowing for more accurate models to be portrayed. GIS also helped reduce the cost of analysis as the need to evaluate every mitigation method in the field decreases with the addition of more accurate analysis data (Renschler 2005). The developed GIS model could also be used to evaluate other laharprone volcanic regions to determine areas of potential effect and methods to mitigate these areas.

1.3 Study Area

This study involved the spatial distribution of hazards related to a lahar event originating from Mount Rainier (Figure 5). The research was not limited to the region immediately surrounding the mountain; rather the full extent of the lahar flows within King and Pierce counties were examined. King and Pierce counties were chosen due to the higher population density in those areas and the availability of GIS data for those regions.

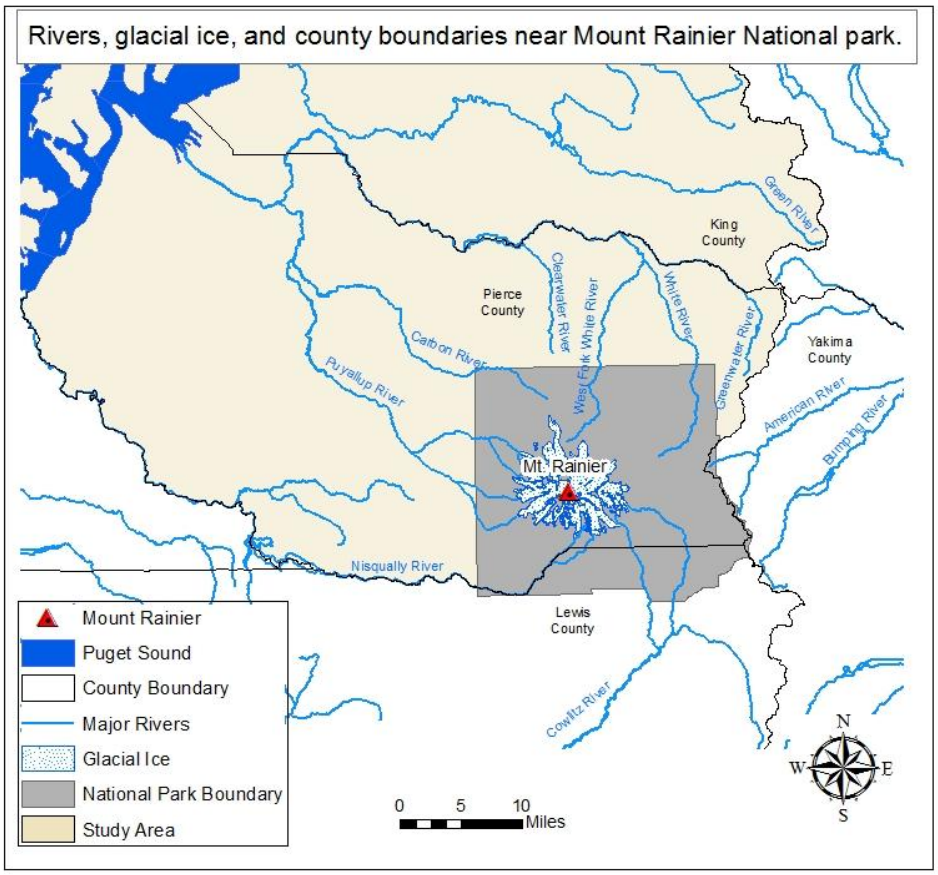

Figure 5: Mount Rainer region: rivers, glacial ice, and county boundaries.

CHAPTER 2: LITERATURE REVIEW

2.1 Mount Rainier History

Mount Rainier is an active volcano located in the northern portion of the Cascade Range, approximately 55 miles southeast of Seattle, Washington. During the past 10,000 years at least 60 lahar events of various sizes have originated on the 14,411 foot peak. Approximately 5,000 years ago, the Osceola Mudflow, which was ten times larger than any other Mount Rainier lahar event, traveled down the White River valley inundating 212 square miles before reaching suburban Seattle and the current Port of Tacoma (Figure 6) (Hoblitt *et al*. 1998).

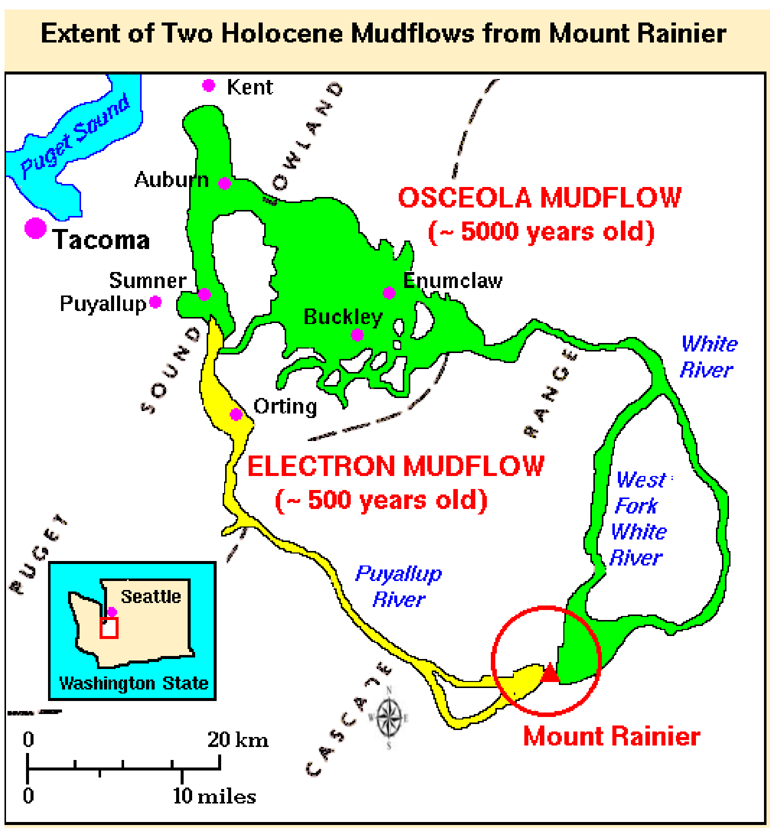

Figure 6: Areas inundated by the Osceola and Electron Mudflows originating from Mount Rainier. (Source: Sisson 1995)

The geology and topography of the Pacific Northwest are influenced by regional tectonics and prior glaciations, creating steep valleys and towering peaks. The fuel for the volcanoes in the Cascade Range is a result of the subduction of the Juan De Fuca Plate beneath the North America Plate (Barnhardt & Sherrod 2006).

While not the most active volcano in the Cascades, Mount Rainier has experienced a violent eruptive history. Mount Rainier first erupted roughly 500,000 years ago with the most recent eruption coming in the 1840s (Sisson 1995). The catastrophic Osceola Mudflow event of 5,000 years ago resulted from a collapse of a portion of the summit cone, similar to the May 1980 eruption of Mount Saint Helens, but on a much larger and more destructive scale. The Osceola Mudflow was at least 10 times larger than any other known Mount Rainier lahar event, covering an area of 212 square miles (Scott *et al*. 1995). The future danger of Mount Rainier lies in the high potential for destructive lahar events, rather than explosive eruptions. These mudflows with the consistency of wet concrete originate on the heavily glaciated summit area and flow down any one or more of the three major drainages originating on the mountain. The Puyallup, Nisqually, and White Rivers have all experienced lahar events in the destructive history of Mount Rainier (Barnhardt & Sherrod 2006).

Mount Rainier's relatively quiet years in written history have led to large-scale development on the slopes and valleys surrounding the peak. These developed areas include cities in the Seattle-Tacoma metropolitan area that are built on previous lahar and lava flows (Barnhardt & Sherrod 2006). The high probability of future lahar events is well known in the surrounding communities, many of which have developed mitigation plans for such an occurrence (Hoblitt *et al*. 1998).

2.2 Previous Lahar Events

Mount Rainier and the surrounding area have been affected by lahar events of different magnitudes and consistencies throughout the 500,000 year volcanic history of the mountain (Barnhardt & Sherrod 2006) (Table 1). The lahars originating on Mount Rainier occurred as a result of one or more of the following factors: eruptions, landslides, and excessive precipitation. The two types of debris flows, cohesive and non-cohesive, have drastically different origins, consistencies, and behavior. Cohesive debris flows contain more than 3 to 5 percent of clay-size sediment and maintain their consistency throughout the flow, which can extend up to 100 km from the summit. Cohesive flows do not correlate strongly with volcanic activity and tend to occur without warning, possibly resulting from earthquakes and changes in hydrothermal activity. Non-cohesive debris flows contain less than 3 to 5 percent of clay-size sediment and have a historical extent of up to 70 km. Non-cohesive debris flows are less destructive but much more common in the geologic history of Mount Rainier (Scott *et al*. 1995).

The major drainage systems originating on Mount Rainier are the historic flow paths of the previous lahars following the path of least resistance. Mount Rainier is drained by five major rivers (as shown in Figure 2 and Figure 4): the White River on the northeast of the peak, the Cowlitz River on the southeast, the Nisqually River on the southwest and the Puyallup/Carbon River system on the northwest. The White, Nisqually, Puyallup, and Carbon rivers flow into Puget Sound, while the Cowlitz River drains into the Columbia River (Scott *et al*. 1995).

Table 1: Previous lahar events with radiocarbon dating, affected drainage, and flow volume data (Source: Scott *et al*. 1995).

Flow	Age[1]	Drainage	Volume (km^3)
Broadly peaked flows that traveled a significant distance from the volcano			
Electron Mudflow	530-550	Puyallup	0.26
1,000 year old lahar	1,050-1,000	Puyallup	>0.30
Unnamed lahar (possible same as Round Pass Mudflow)	Same as below?	Puyallup	?
Round Pass Mudflow	2,170-2,710	Puyallup	?
Osceola Mudflow (probably includes Greenwater Lahar)	4,500-5,000	White River (main fork and west fork)	3
Greenwater Lahar (probably part of Osceola Mudflow)	?	White River (main fork)	?

[1] Years before 1950 in radiocarbon years.

2.3 Existing GIS Lahar Flow Models

GIS modeling of lahar flows can be evaluated using many different approaches. As GIS analysis and technology advance, the models associated with the analysis also advance. While many models existed for lahar hazard mapping, three of the most commonly used GIS models were: FLOW3D, TITAN2D, and LAHARZ, all of which had their advantages and disadvantages.

The FLOW3D model calculated changes in velocity as a block slides across a digital elevation model. The path was traced in small increments of time until the object stops, the termination point of the flow. In order to display an estimate of the extent of the affected area a large number of blocks were included in the model for calculation (Sheridan *et al* 2004). According to Sheridan *et al.* (2004) there were several limitations to this model. A major limitation was the inability of the model to work with the interaction of multiple blocks moving down the slope. There was also a lack of input and output parameters associated with the model, mainly the lack of source volume, flow thickness, and deposit thickness options. Despite its input limitations the model displayed field-verifiable lahar events well.

The TITAN2D model, a freely-available geophysical mass-flow model developed at the University of Buffalo, allowed for additional inputs that were lacking in the FLOW3D model; mainly source volume and flow thickness. The primary outputs of this model were flow depth and momentum, while secondary outputs included flow velocity and inundation areas. This program modeled the entire flow rather than the individual blocks as in the FLOW3D model (Sheridan *et al* 2004). A limitation of this model was the environment within which the program operates. The model, while it ran independent of any GIS program, requires Digital Elevation Models (DEM) created from an open-source GIS program known as the Geographic Resources Analysis Support System (GRASS) (Sheridan *et al* 2004).

The LAHARZ model, developed by the USGS, was a model designed for automated mapping of lahar hazard inundation zones. This menu-driven program ran from within ArcINFO. The advanced analytical properties of LAHARZ allowed for the input of multiple lahar volumes, producing a separate lahar inundation zone for each volume. LAHARZ utilized depressionless DEMs to assist in the determination of lahar inundation zones. The LAHARZ menu allowed for numerous variables to be input, but a more advanced understanding of hydrology, topography, and lahar properties was required to achieve the full functionality of the program (Schilling 1998). A downside of the LAHARZ model was the requirement of the ArcINFO environment in order for the analysis to be performed.

All three of the studied lahar-hazard mapping models utilized different aspects of GIS in order to arrive at the similar result of lahar inundation areas. The different variables in each of the models required a level of knowledge beyond that of most disaster response personnel and GIS users. This limitation could lead to inaccurate analysis results, which can skew disaster response plans. Another limitation of the current lahar-hazard identification models was the intense computing power required for the advanced equations. For example, both the TITAN2D and FLOW3D models allowed for multiple processors to be utilized in order to cut down on the processing time (Sheridan *et al* 2004). While GIS data for volcanoes within the United States were readily available, data for many volcanoes lying outside the United States were sparsely available and much more generalized, creating problems with the established GIS models that required the data for inputs to achieve the desired results. Although there were variances in the results for each of the methods the common thread was the ability to use GIS for in-depth disaster mitigation and hazard analysis.

Another emerging trend in GIS modeling was the use of satellite imagery in volcanic hazard analysis. The data available from this method were generally at a much lower spatial resolution than the freely available USGS DEMs, but it could utilize an additional data source for less studied volcanic regions, allowing the use of the previously mentioned models for hazard analysis (Kerle & Oppenheimer 2002).

Mount Rainier’s vicinity to the Seattle-Tacoma metropolitan area combined with its non-volcanic triggered lahar events in the past have resulted in a large amount of data being available for analysis in different hazard mapping models. This allowed GIS users beyond the federal government level access to quality information that can be used in disaster mitigation. Rather than performing the in-depth lahar inundation area analysis for each disaster scenario, disaster response analysts can instead focus on the effects of the inundation on specific resources.

The LAHARZ program created the most well defined hazard areas that matched well with field-checked lahar paths on and around Mount Rainier (Iverson *et al* 1998). This study utilized the data created from LAHARZ for the area surrounding Mount Rainier (Schilling *et al* 2008). The output created a set of GIS layers that allow for the creation of volcanic hazard maps to identify areas and resources that may be affected by a lahar event. The ability to use USGS generated lahar inundation boundaries eliminated a major concern regarding a lack of advanced understanding of the underlying aspects of lahar events and allow for more of a detailed post-lahar analysis.

CHAPTER 3: CONCEPTUAL FRAMEWORK AND METHODOLOGY

3.1 Lahar Magnitude Descriptions

The USGS LAHARZ data was presented in three cases, or magnitudes. The following lahar cases are listed in order of decreasing magnitude and increasing frequency (Table 2). Case 1, hereafter known as Extreme, flows have occurred about once every 500 to 1000 years. Most of the historic Extreme flows have reached some part of the Puget Sound lowlands. These flows tend to originate from debris avalanches of weak, chemically morphed rock. Although large in size, a magmatic eruption is not required for an Extreme flow event. Case 2, hereafter known as Severe, lahars have typically occurred once every 100 to 500 years. Some Severe events have inundated flood plains well beyond the volcano. Severe flows have low clay contents, with the most common cause of this event being the melting of snow and glacial ice by hot rock fragments during a volcanic event. Although volcanic events are the most common cause of a Severe flow, non-eruptive origins are possible. The most recent Severe flow, in 1947, was the result of torrential rains combined with the release of water stored in glacial ice. Case 3, hereafter known as Moderate, flows are small but occur frequently, with events every 1 to 100 years. These flows are not triggered by volcanic eruptions. Moderate events are mostly restricted to the slopes of Mount Rainier, and rarely go beyond the National Park boundary. Each of the lahar magnitudes may reach farther than their historic counterparts due to increased deforestation along the flow paths creating hydraulically smoother topography (Hoblitt, *et al* 1998).

Table 2: Lahar occurrences, probability, and common origin

Lahar Magnitude	Occurrence	Annual Prob.	Common Origin
Extreme – Case I	500-1000 yrs	0.1% - 0.2%	Debris avalanche of chemically altered rock.
Severe – Case II	100-500 yrs	1%	Melting snow by volcanic rock fragments.
Moderate – Case III	1-100 yrs	10%	Sudden release of water stored by glaciers.

3.2 Description of Data

The primary goal of the data collection portion of the project was to obtain the necessary GIS data at little or no cost. The majority of the data were readily available from various state and federal agencies while a small portion of the data was acquired from Pierce County for a minimal fee.

The 2009 full color ortho-imagery used for a visual comparison of the lahar and stream location data was downloaded from the Natural Resource Conservation Service's Data Gateway site on a county-wide basis.

The federal government provided a wealth of information for the project. Most importantly the USGS was responsible for the lahar inundation area locations that were created as a result of the LAHARZ project. The National Park Service provided the boundaries for Mount Rainier National Park, the location of Mount Rainier, and the county boundaries surrounding Mount Rainier. The National Oceanic and Atmospheric Administration in partnership with the USGS provided critical Chinook salmon habitat locations and the western Washington hydrology network which included watershed, stream, and lake information necessary for the project. The U.S. Census Bureau provided population statistics, city locations, and metropolitan area boundaries that were necessary to determine an estimated affected population.

Two Washington counties, King and Pierce, had GIS data available that was important for the analysis of the affected water supplies. Both counties provided critical aquifer recharge areas in shapefile format that was used to determine underground aquifer areas that were at risk of contamination from lahar events.

3.3 General Methodology

The research methodology for this project revolved around GIS analysis of existing and newly created data to produce a working model to determine the effects of lahar events on Mount Rainier area water supplies. The key components of the GIS model revolved around the expanded analysis of existing LAHARZ data. Three magnitude lahars available from the USGS analysis of Mount Rainier were input in order to determine the areas affected in differing flows (Hoblitt, *et al* 1998). The lahar inundation layers developed by the LAHARZ program were then added to the base map to determine flow locations, rather than reproducing flow models using inferior technology and geological knowledge.

In order to expand on previous model research the USGS LAHARZ lahar inundation areas were added to the GIS in order to determine flow locations. Since the lahar areas were originally created in a line shapefile, a conversion was performed in order to create a polygon shapefile to determine inundated streams, critical Chinook salmon habitat, and aquifer recharge areas. After trying different options a select by location query was performed to select the inundated water supply areas. A multiple ring buffer was applied to the potentially contaminated critical aquifer recharge areas in each magnitude lahar to attempt to better illustrate the affected populated areas. Rather than clipping the layers based on the lahar inundation area boundaries, any stream segment, critical Chinook salmon habitat, or critical aquifer recharge area that had the potential to be inundated by the lahar event was exported to an effected area shapefile. This process was performed a total of three times to each affected layer in order to encompass the three different magnitude lahar events provided by the LAHARZ data.

The hydrology layer, including domestic and agricultural water supplies and the salmon populated streams was added to the analysis to determine the areas of potential hydrological contamination. The hydrology areas that were within the flow path were selected and exported, with the affected domestic and agricultural water supplies being exported separately from the affected aquatic habit (fish and aquatic organisms) streams. The aquatic habit areas will also be greatly affected in the alluvial fan areas of the inundated streams, due to the increased sediment load. Also critical aquifer recharge areas intersected by the lahar flows were exported.

Next, a population density raster was created, reclassified, and analyzed, along with the critical aquifer supply areas that were affected, to determine the population centers that will possibly need to find alternate water sources. Some areas will have only a portion of their water supply affected, while others may have their entire supply affected. This project identified population centers that may need to find additional water sources, whether the entire water supply is affected or only a portion. Due to United States Department of Homeland Security concerns all municipality water supplies are not readily available in a GIS format, as a result critical aquifer recharge areas were used in this research. The U.S. Census population data will also be used to show the estimated number of people directly in the lahar path. A ranking system was used, with areas with a higher population density receiving a higher rank and those with a lower density receiving a lower rank.

Finally, two approaches were used to create the final maps. The affected critical salmon habitats and water bodies were added to the map along with the three different magnitude lahars to show the affects to surface water. In a separate process the reclassified population density raster and critical aquifer recharge areas were input into the raster calculator to determine the areas that would potentially need to find alternative water sources. Separate risk maps were created, with a focus on the effect to the human population and critical aquifer recharge areas, and a second showing affected salmon fisheries and aquatic habitat impacts.

The ultimate goal of the research methodology associated with this project was to determine those surface and ground water areas with the greatest potential risk of contamination in the case of a lahar event from Mount Rainier. Figure 7 illustrates the process of the research framework. The resulting maps are provided in the analysis results section as a visible depiction of the areas affected by the lahar.

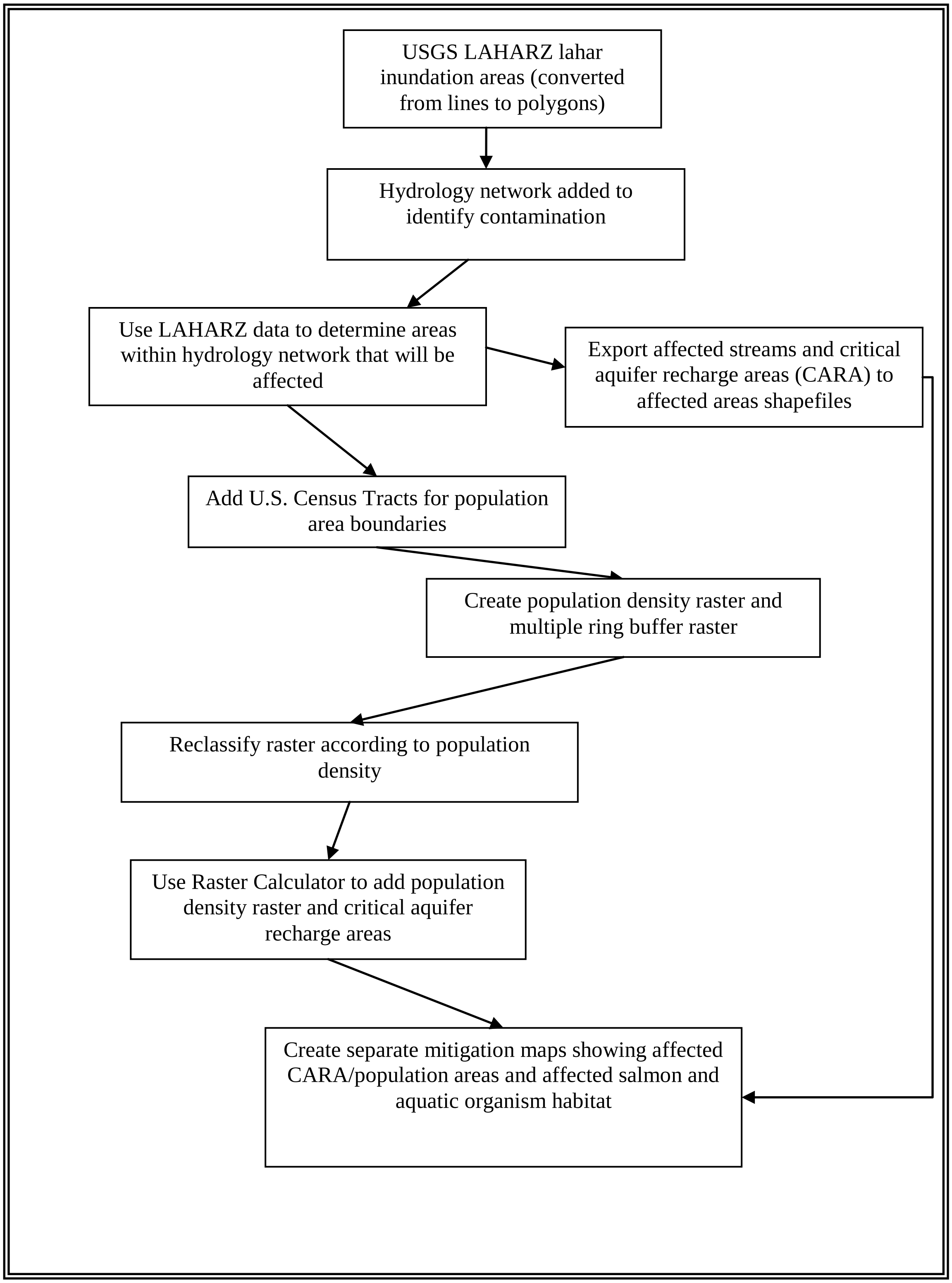

Figure 7: Research Framework

3.4 Data Reclassification and Data Creation

Due to the creation of raster data in the cases of population density and critical aquifer recharge areas, raster reclassification was performed in order to prepare the data for insertion into the Raster Calculator.

The population density raster was created from a study area Census tracts shapefile that was displayed using nine natural breaks based on the population field. Following the conversion of the Census tracts shapefile to a ten meter cell-size raster the population data needed to be divided by the number of cells in each tract in order to calculate the population density per ten meter unit. This created a somewhat odd looking result of fractions of a person per ten meter unit, but allowed for a better representation of the affected population. The raster created in the conversion was then reclassified based on nine natural breaks to create a more useable scale to assist in raster calculations (Table 3). Lower populations received a lower ranking while higher populations received a higher ranking. This was done to illustrate the greater impact an affected water supply would have on higher populations.

The multiple ring buffer areas surrounding each of the potentially contaminated critical aquifer recharge areas for the three different magnitude lahar events were converted to a raster and reclassified according to distance from the aquifer area (Table 4). The multiple ring buffer shapefile was converted to a ten meter resolution raster based on a one mile, two mile, and three mile buffer. The newly created buffer raster was reclassified in order to place a greater emphasis on areas lying nearer to potentially contaminated recharge areas.

Table 3: Reclassification of values from population raster.

Original Value Persons/ Census Tract	Persons/ per 10m Cell	Reclassified Value
425-1378	0.000130-0.012539	1
1379-2331	0.012539-0.038339	2
2332-3284	0.038339-0.076392	3
3285-4237	0.076392-0.120845	4
4238-5190	0.120845-0.172604	5
5191-6143	0.172604-0.246171	6
6144-7096	0.246171-0.367121	7
7097-8049	0.367121-0.775351	8
8050-9002	0.775351-1.696486	9

Table 4: Multiple Ring Buffer Reclassification.

Buffer Distance (miles)	Reclassified Value
1	30
2	20
3	10

CHAPTER 4: ANALYSIS RESULTS AND ISSUES

4.1 Research Issues and Problems

Many of the problems discovered during this study revolved around the lahar models used in previous analysis and the attempts to recreate that data. Near the beginning of the research an attempt was made to create depressionless digital elevation models (DEMs) in order to duplicate lahar flow locations. The size of the study area combined with the topology of the area made creation of depressionless DEMs difficult and processor intensive. While prior research has focused on the effects of lahars on man-made and natural features there were issues with the availability of the previously created GIS data. The results of previous studies were well documented in professional journals but the associated GIS data was not freely available. This was unfortunate due to the extreme complexity of some of the previous models that prevented the replication of the modeling process and results. Starting this level of advanced GIS research from scratch is cost prohibitive and would have resulted in an inferior analysis model. Also, much of the contact information for the researchers on previous projects was outdated resulting in the inability to search for additional GIS data that could have been utilized in this project.

The only data readily and freely available online was a result of the USGS LAHARZ program analysis of Mount Rainier. While the LAHARZ program uses a higher level GIS program than was used in this project, the data was exported into shapefiles which allowed for their inclusion in this project. This method of using previously created data allowed for the research to focus on areas that had not previously been evaluated, such as water supply concerns, rather than attempting to recreate data without the proper tools necessary to develop a quality model.

Another issue associated with the project was the availability of free or low-cost GIS data to use for additional analysis inputs. Of the four counties in the Mount Rainier area only two, King and Pierce Counties, provided GIS data at little or no cost. While it would have been ideal to include Yakima and Lewis Counties in the GIS analysis, cost concerns and available data forced the change in focus to only include analysis for Pierce and King Counties.

Data consistency created minor problems during the course of the project. Data from Pierce and King Counties contained similar information but in different database structures that had to be evaluated before analysis could be conducted. Discovering these differences during the early stages of the research allowed a more complete analysis of the project data, rather than being forced to conduct analysis on a county by county basis.

Using data from different agencies created some display issues while attempting to create visual representations of the analysis data. The county-level data was created at a larger scale than the USGS data which presented alignment issues when displayed together. Primarily the USGS hydrologic network line data matched up poorly to the ortho-imagery for the counties in the study area. The stream locations from the USGS data were simplified and as a result matched poorly to the ortho-imagery. The issues were resolved for the most part by relying more heavily on county-level data to maintain scale consistency.

Data from the U.S. Census Bureau created some technical issues that needed to be resolved before the population density information could be added to the map. The census tracts that were used for population density did not include any population information in GIS form. The tract shapefile only contained tract numbers and polygon boundary information. Additional tables were downloaded from the Census Bureau website that contained population information associated with the tract numbers in order to import the population data into the GIS.

There was also issue stemming from the use of U.S. Census data was the issues related to determining population density. Population density information was not readily available in a people-per-square-mile format which would have been ideal for this project. Instead Census tracts were used, which showed population statistics at a sub-county level.

Initially all relevant project data related to the lahar inundation zones was converted from vector to raster format for use in the raster calculator. While this was relevant for the affect on population portion of the model, it was not necessary to determine affected salmon and other aquatic species habitat. After much time was spent creating and reclassifying these rasters it was determined that the same result could be achieved by selecting any critical salmon habitat or body of water that was intersected by the three different lahar cases.

4.2 Analysis Results

The analysis results were broken down by lahar event in order to keep the results separate according to the magnitude of the event. Also, direct human impact results (critical aquifer recharge areas) were separated from critical salmon habitat and aquatic organism impact results. This was done in order to show that mitigation plans could be developed separately for the two project focuses based on the needs of the analyst. The data below is presented by lahar magnitude, first by critical aquifer recharge areas and affected population, then by critical salmon habitat, and finally by aquatic organism impact. The Extreme, Severe, and Moderate lahars were also displayed against the historic Osceola and Electron mudflows to illustrate how the predicted flows compare to the historic events. The analysis results are also summarized below illustrating the percentage of potentially contaminated Critical Aquifer Recharge Areas (CARA) within King and Pierce Counties, population, critical salmon habitat, and aquatic habitat affected within the study area by each of the three magnitude lahars (Table 5).

The base data used for each of the lahar events started with the critical aquifer recharge areas, Census-based population, critical salmon habitat, and aquatic habitat areas. The critical aquifer areas and population statistics were only for the study area of Pierce and King Counties, the critical salmon habitat was a statewide shapefile, and the aquatic habitat areas were pulled from watersheds surrounding Mount Rainier. The critical aquifer recharge areas located within Pierce and King Counties (Figure 8) cover 375,236.2 acres. The population within the study area totaled 2,422,781 people, broken down by Census Tracts (Figure 9). The State of Washington contains 1,820 miles of critical salmon habitat, with approximately 658 miles lying within the study area, which contains 1,724.77 miles of aquatic habitat in the watershed surrounding Mount Rainier in the study area (Figure 10).

Table 5: Analysis Results Summary.

LAHAR EVENT	% AFFECTED CARA IN KING AND PIERCE COUNTY	% POPULATION	% SALMON HABITAT	% AQUATIC HABITAT
Extreme	24.78%		41.73%	72.32%
Extreme 1-mile		9.63%		
Extreme 2-mile		14.70%		
Extreme 3-mile		19.95%		
Severe	15.79%		25.09%	27.13%
Severe 1-mile		7.92%		
Severe 2-mile		12.32%		
Severe 3-mile		16.61%		
Moderate	1.92%		0.78%	8.94%
Moderate 1-mile		<0.01%		
Moderate 2-mile		<0.01%		
Moderate 3-mile		<0.01%		

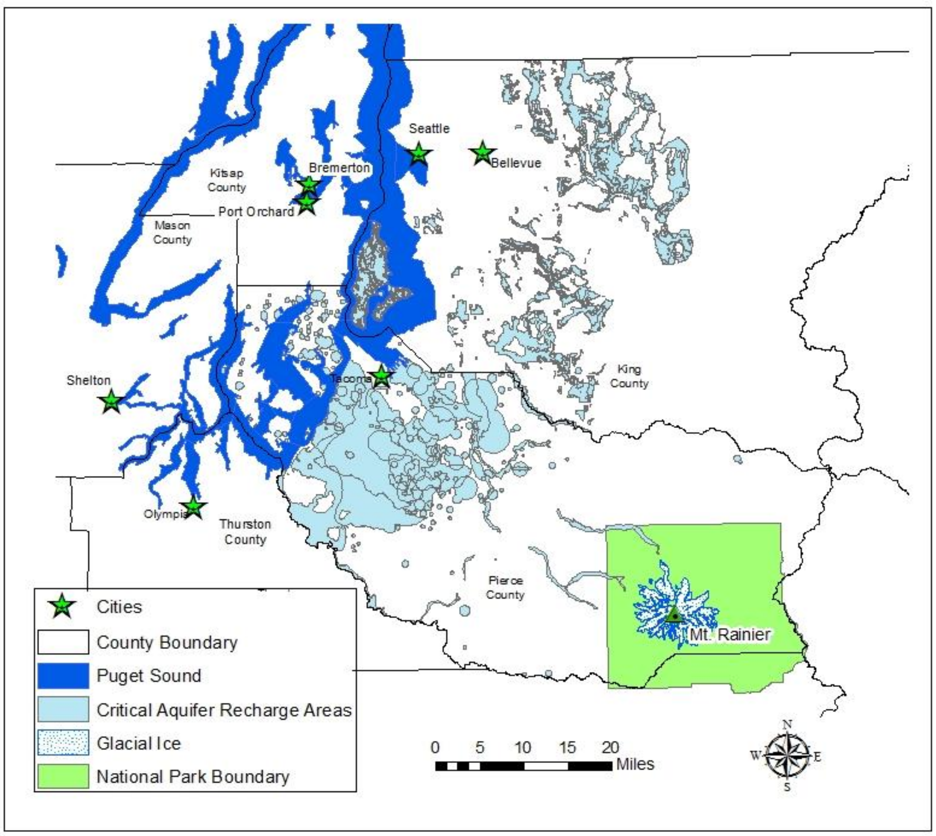

Figure 8: Critical Aquifer Recharge Areas in Pierce and King Counties.

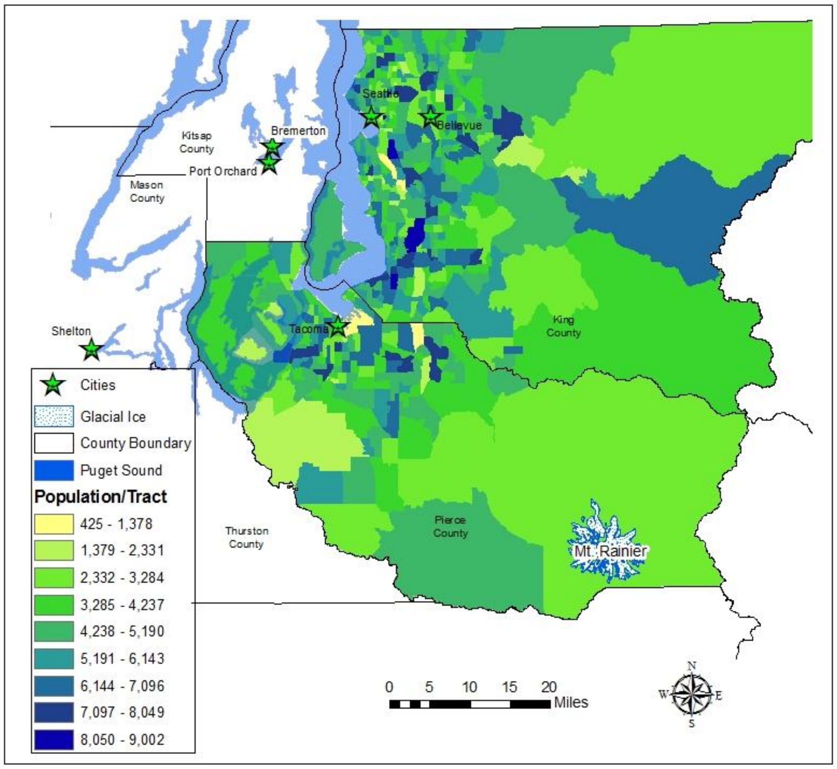

Figure 9: Population statistics for Pierce and King Counties.

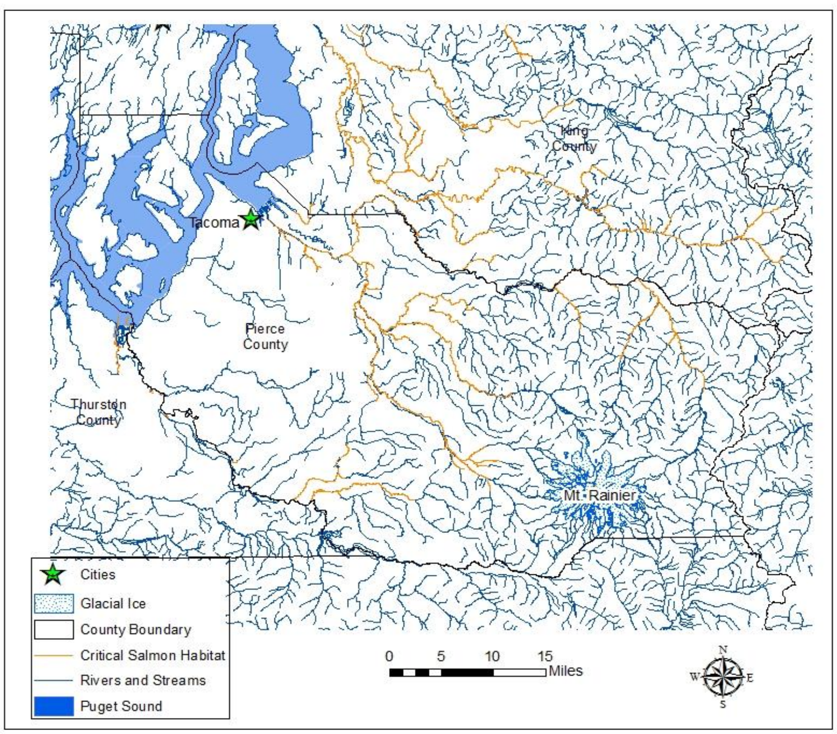

Figure 10: Rivers, streams, and critical salmon habitat near the study area.

The Extreme lahar has the farthest reaching impact to human populations and critical aquifer recharge areas based on the magnitude of this event. An Extreme lahar event has the potential to cover 225,503.94 acres, of which 156,519.56 acres (69.41%) lay within the study area. Its inundation zone shares 63,384.29 acres (40.50%) with the historic Osceola and Electron mudflows within the study area (Figure 11).

The Extreme lahar encompassed 92,975.95 acres of critical aquifer recharge areas. Any critical aquifer recharge area that came in contact with the lahar was exported as an affected aquifer (Figure 12). The percentage of the total critical aquifer recharge areas in Pierce and King Counties that was contaminated equaled 24.78%.

The vicinity within one mile of the Extreme lahar affected critical aquifer recharge areas contained 233,286 people or 9.63% of the Pierce and King County population (Figure 13). The Population/CARA raster was an output of the Raster Calculator. Potentially contaminated critical aquifer recharge areas within the Extreme lahar were buffered to better illustrate the potentially affected population. Buffer rings of one mile, two miles, and three miles were applied and reclassified as rasters for use (Table 4). The population rankings in the population raster were classified according to the values in Table 3. The resulting Population/CARA raster contained any population of a ten meter cell that resided within the buffers applied around the potentially contaminated critical aquifer recharge areas. For example a value of “31” in the output raster corresponds to a population value of 0.00013-0.012539 people per hundred square meters that lies within a mile of a potentially contaminated critical aquifer recharge area.

The vicinity within two miles of the Extreme lahar affected critical aquifer recharge areas contained 356,303 people or 14.70% of the Pierce and King County population (Figure 14). The vicinity within three miles of the Extreme lahar affected critical aquifer recharge areas contained 483,287 people or 19.95% of the Pierce and King County population (Figure 15).

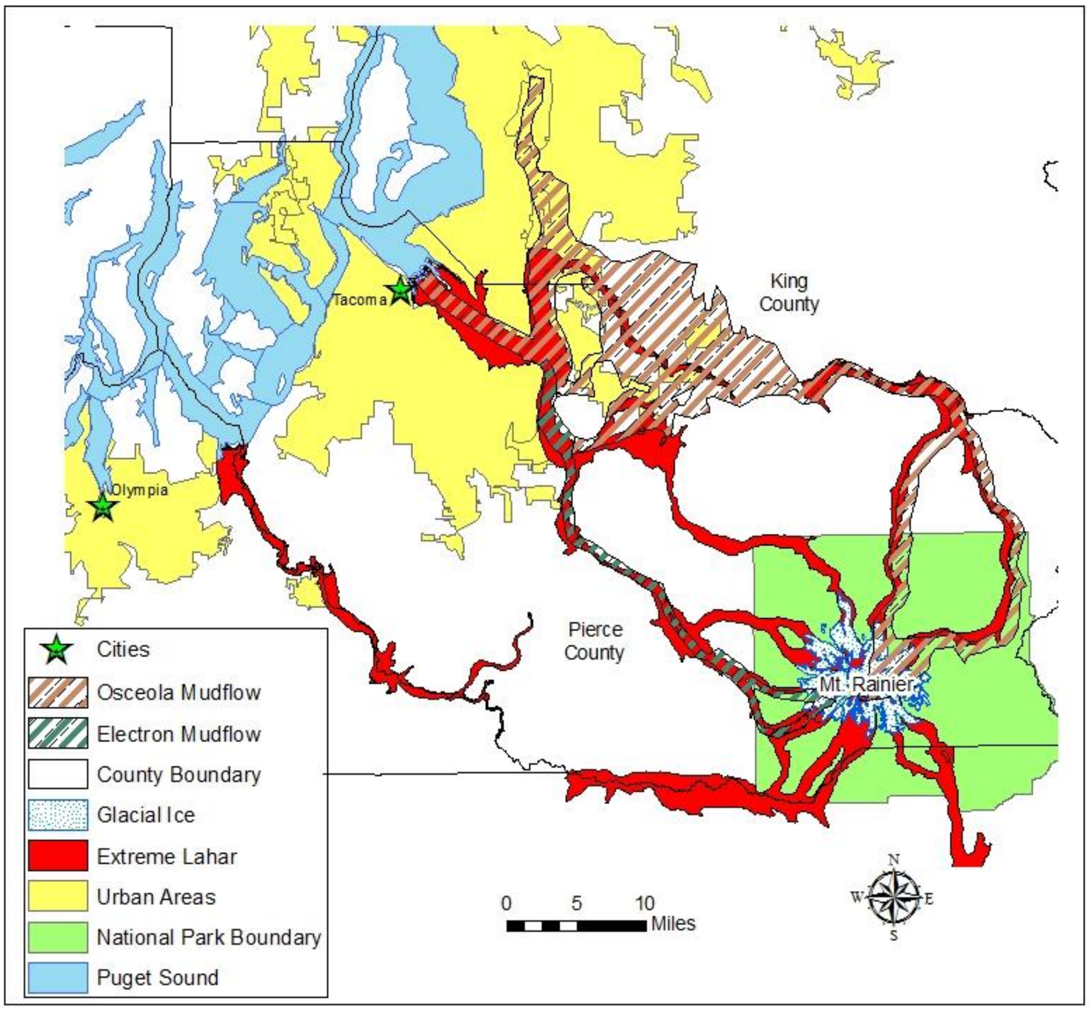

Figure 11: Extreme lahar extent compared with historic Osceola and Electron Mudflows.

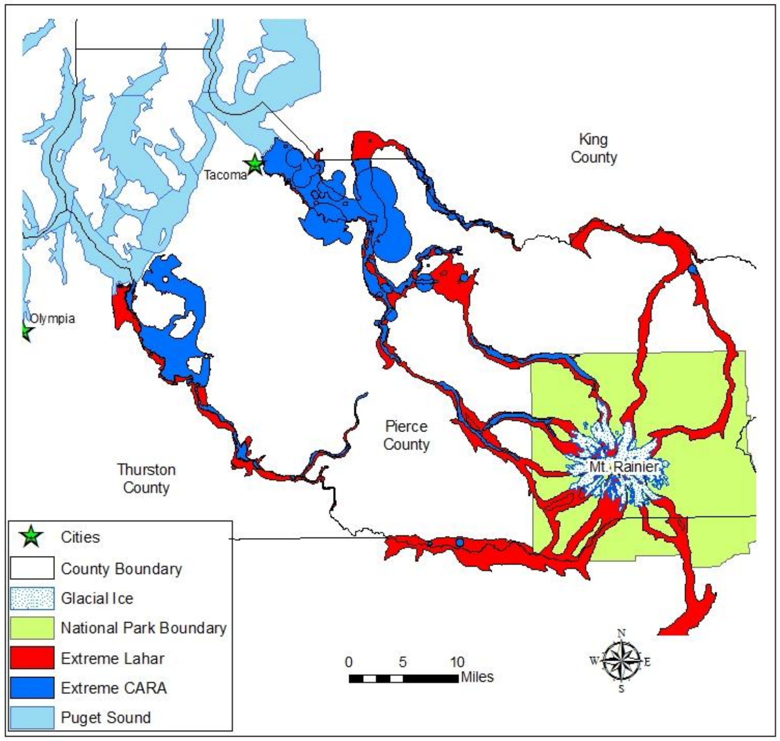

Figure 12: Critical Aquifer Recharge Areas (CARA) affected by the Extreme lahar.

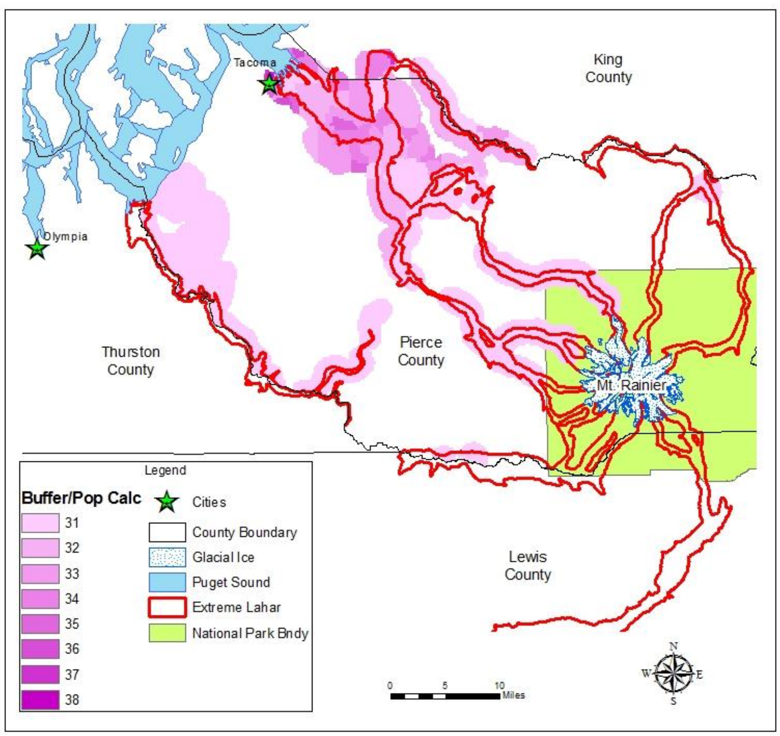

Figure 13: Population areas within one mile of possibly contaminated critical aquifer recharge areas within an Extreme lahar.

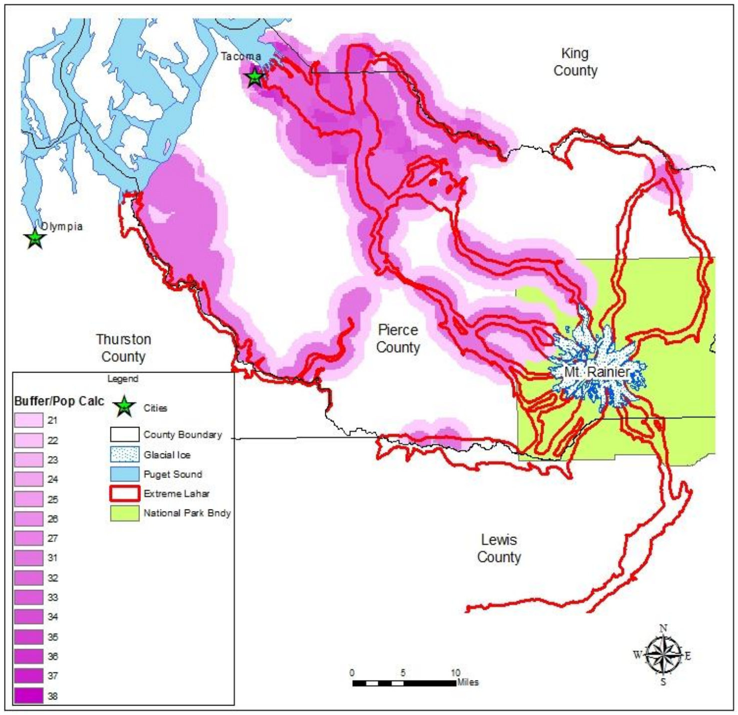

Figure 14: Population areas within two miles of possibly contaminated critical aquifer recharge areas within an Extreme lahar.

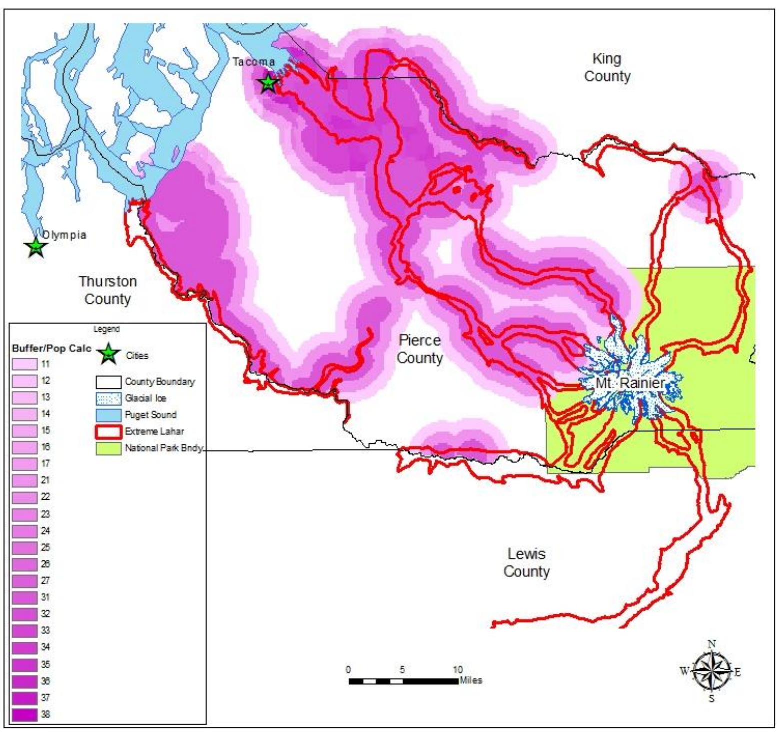

Figure 15: Population areas within three miles of possibly contaminated critical aquifer recharge areas within an Extreme lahar.

The Severe lahar is a medium impact event that has the potential to cover 81,114.19 acres, of which 54,942.54 acres (67.73%) lay within the study area. Its inundation zone shares 27,724.29 acres (50.50%) with the historic Osceola and Electron mudflows within the study area (Figure 16).

The Severe lahar encompassed 59,253.53 acres of critical aquifer recharge areas. Any critical aquifer recharge area that came in contact with the lahar was exported as an affected aquifer (Figure 17). The percentage of the total critical aquifer recharge areas in Pierce and King Counties that was contaminated equaled 15.79%.

The vicinity within one mile of the Severe lahar affected critical aquifer recharge areas contained 191,887 people or 7.92% of the Pierce and King County population (Figure 18). The Population/CARA raster was an output of the Raster Calculator. Potentially contaminated critical aquifer recharge areas within the Severe lahar were buffered to better illustrate the potentially affected population. Buffer rings of one mile, two miles, and three miles were applied and reclassified as rasters for use in the raster calculator (Table 4). The population rankings in the population raster were classified according to the values in Table 3. The resulting Population/CARA raster contained any population of a ten meter cell that resided within the buffers applied around the potentially contaminated critical aquifer recharge areas.

The vicinity within two miles of the Severe lahar affected critical aquifer recharge areas contained 298,575 people or 12.32% of the Pierce and King County population (Figure 19). The vicinity within three miles of the Severe lahar affected critical aquifer recharge areas contained 402,427 people or 16.61% of the Pierce and King County population (Figure 20).

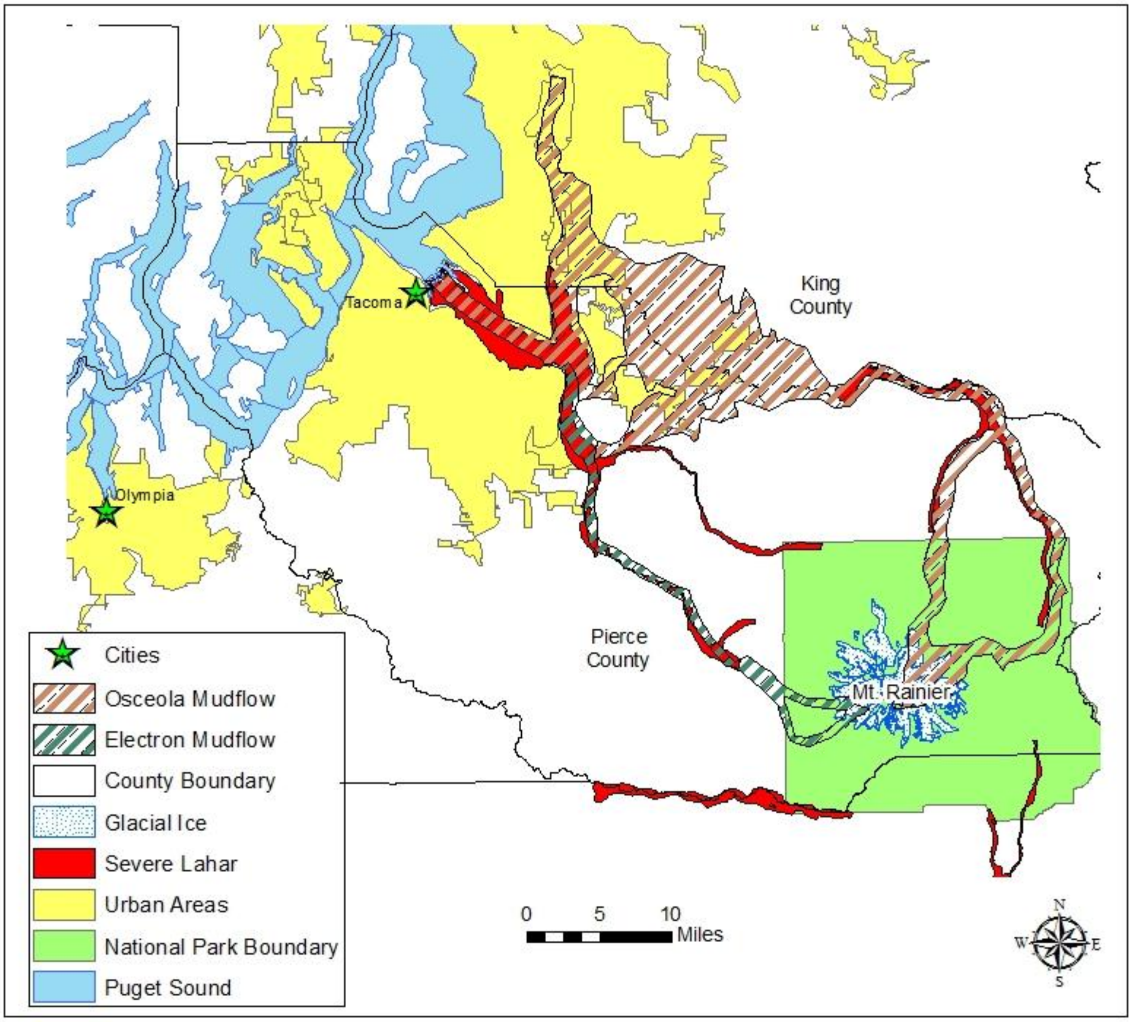

Figure 16: Severe lahar boundaries compared with historic Osceola and Electron Mudflows.

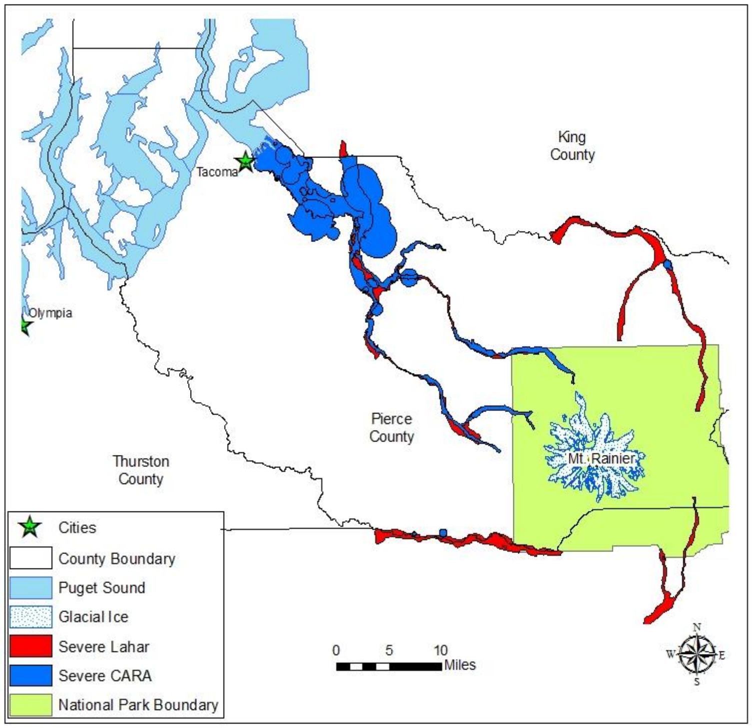

Figure 17: Critical aquifer recharge areas (CARA) affected by a Severe lahar.

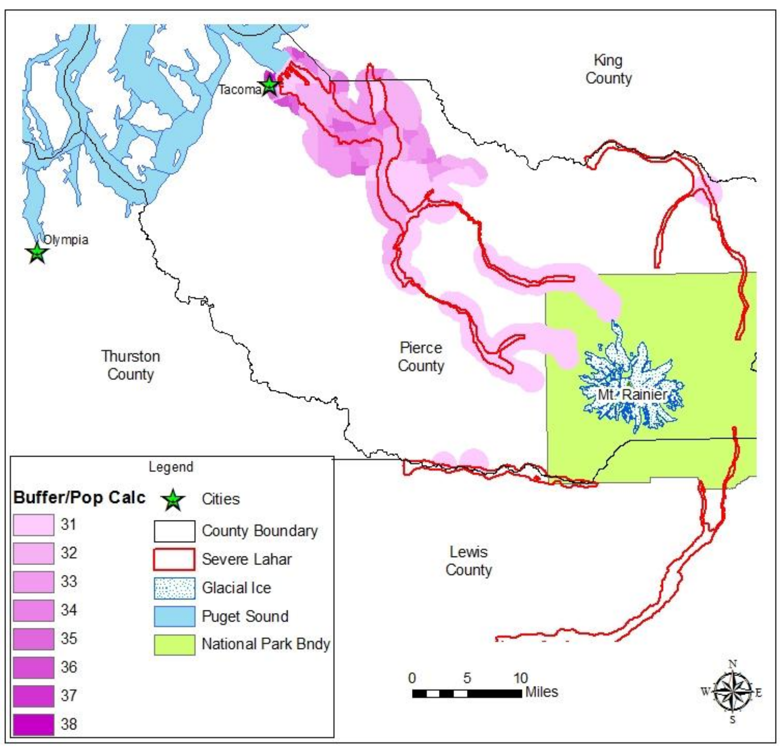

Figure 18: Population areas within one mile of possibly contaminated critical aquifer recharge areas within a Severe lahar.

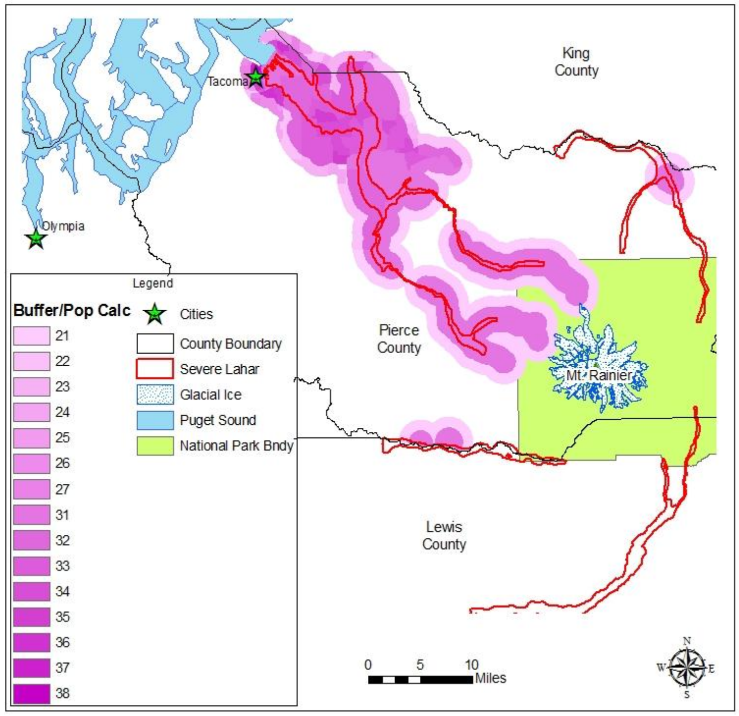

Figure 19: Population areas within two miles of possibly contaminated critical aquifer recharge areas within a Severe lahar.

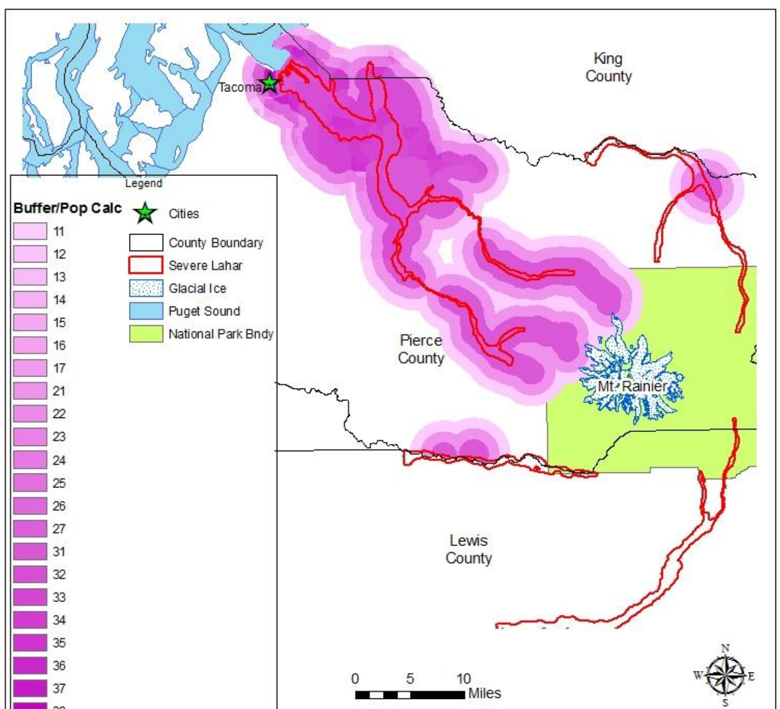

Figure 20: Population areas within three miles of possibly contaminated critical aquifer recharge areas within a Severe lahar.

The Moderate lahar (Figure 21) is a relatively low impact event that has the potential to cover 14,880.76 acres, of which 13,628.57 acres (91.59%) lay within the study area. These lahar events are fairly common but have little effect on the surrounding population. Its inundation zone shares 13,628 acres (27.55%) with the historic Osceola and Electron mudflows within the study area (Figure 22).

The Moderate lahar encompassed 7,204.58 acres of critical aquifer recharge areas. Any critical aquifer recharge area that came in contact with the lahar was exported as an affected aquifer (Figure 23). The percentage of the total critical aquifer recharge areas in Pierce and King Counties that was contaminated equaled 1.92%.

The vicinity within one mile of the Moderate lahar affected critical aquifer recharge areas contained 655 people or less than 0.01% of the Pierce and King County population (Figure 24). The Population/CARA raster was an output of the Raster Calculator. Potentially contaminated Critical Aquifer recharge areas within the Moderate lahar were buffered to better illustrate the potentially affected population. Buffer rings of one mile, two miles, and three miles were applied and reclassified as rasters for use in the raster calculator (Table 4). The population rankings in the population raster were classified according to the values in Table 3. The resulting Population/CARA raster contained any population of a ten meter cell that resided within the buffers applied around the potentially contaminated critical aquifer recharge areas.

The vicinity within two miles of the Moderate lahar affected critical aquifer recharge areas contained 1,433 people or less than 0.01% of the Pierce and King County population (Figure 25). The vicinity within three miles of the Moderate lahar affected critical aquifer recharge areas contained 2,217 people or less than 0.01% of the Pierce and King County population (Figure 26).

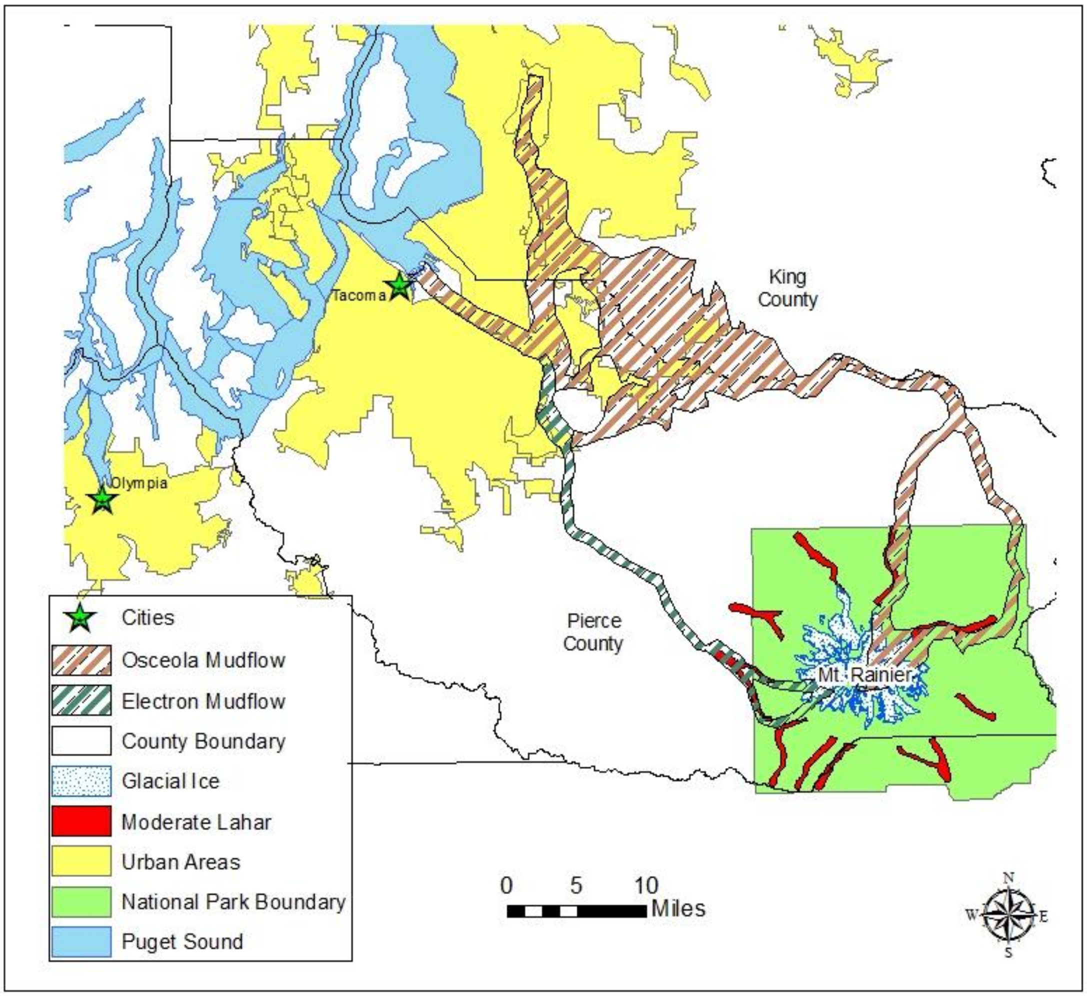

Figure 21: Moderate lahar extent compared with historic Osceola and Electron Mudflows.

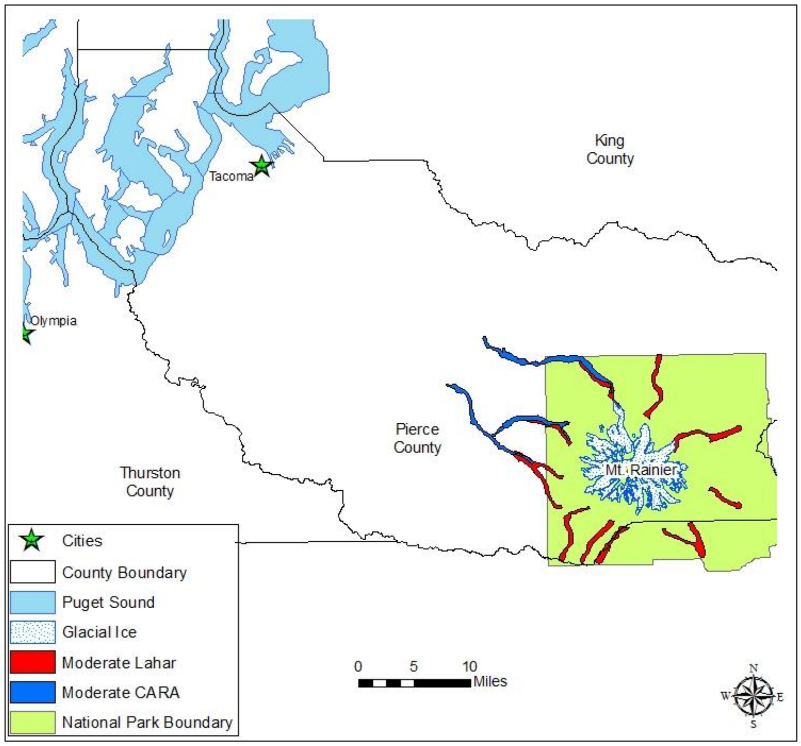

Figure 22: Critical aquifer recharge areas (CARA) affected by a Moderate lahar.

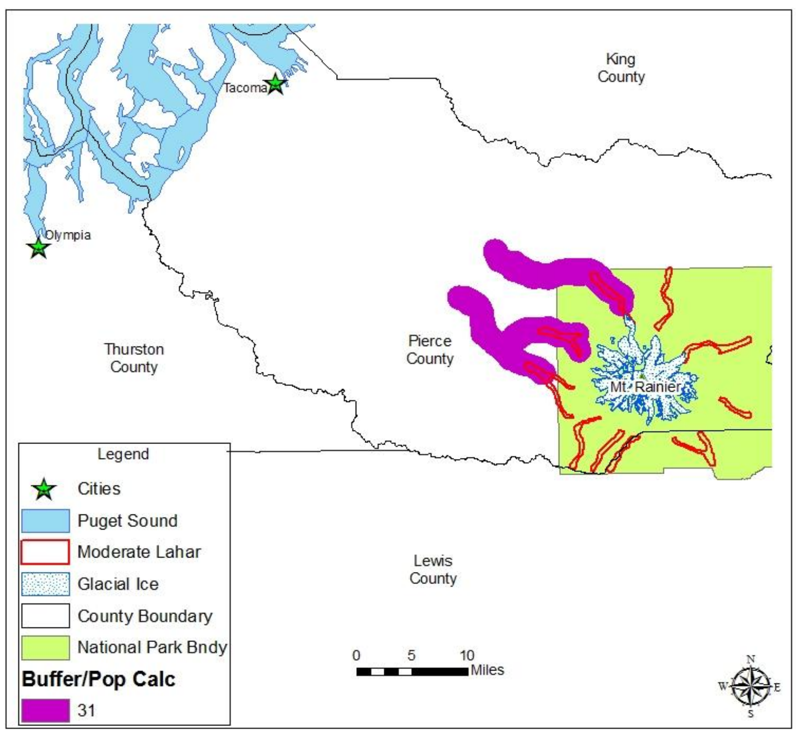

Figure 23: Population areas within one mile of possibly contaminated critical aquifer recharge areas within a Moderate lahar.

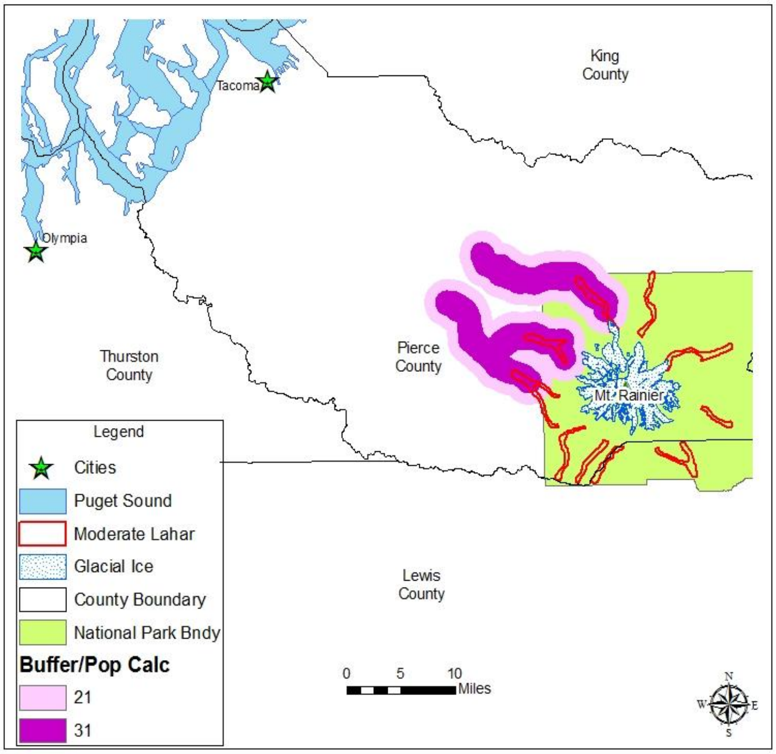

Figure 24: Population areas within two miles of possibly contaminated critical aquifer recharge areas within a Moderate lahar.

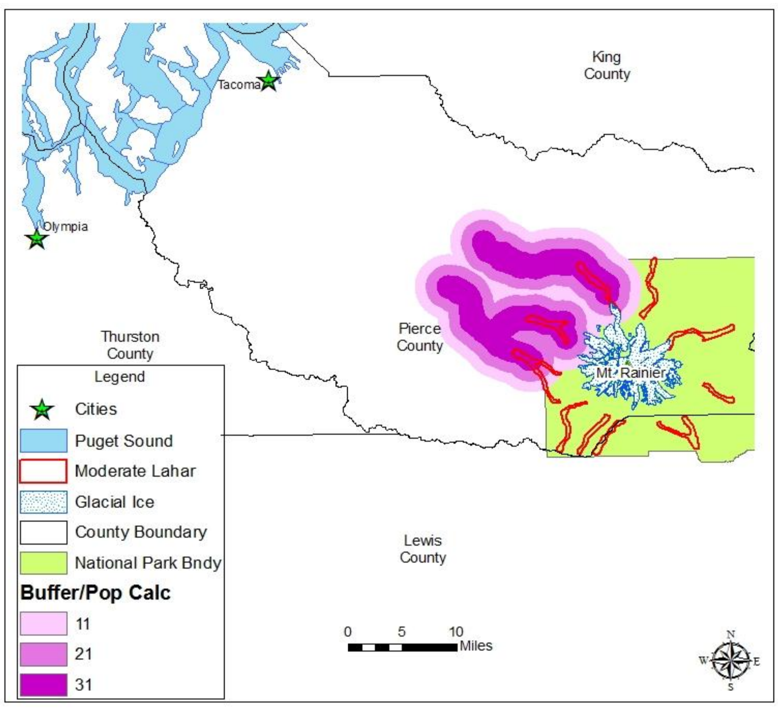

Figure 25: Population areas within three miles of possibly contaminated critical aquifer recharge areas within a Moderate lahar.

An Extreme lahar would have a devastating effect on critical salmon and aquatic organism habitat in the study area (Figure 26). Of the 658 miles of critical salmon habitat in the study area, 274.57 miles, or 41.73%, would be inundated by an Extreme event. Of the 1,724.77 miles of aquatic habitat in the study area, 1,247.34 miles, or 72.32%, would have the potential to be affected by this lahar.

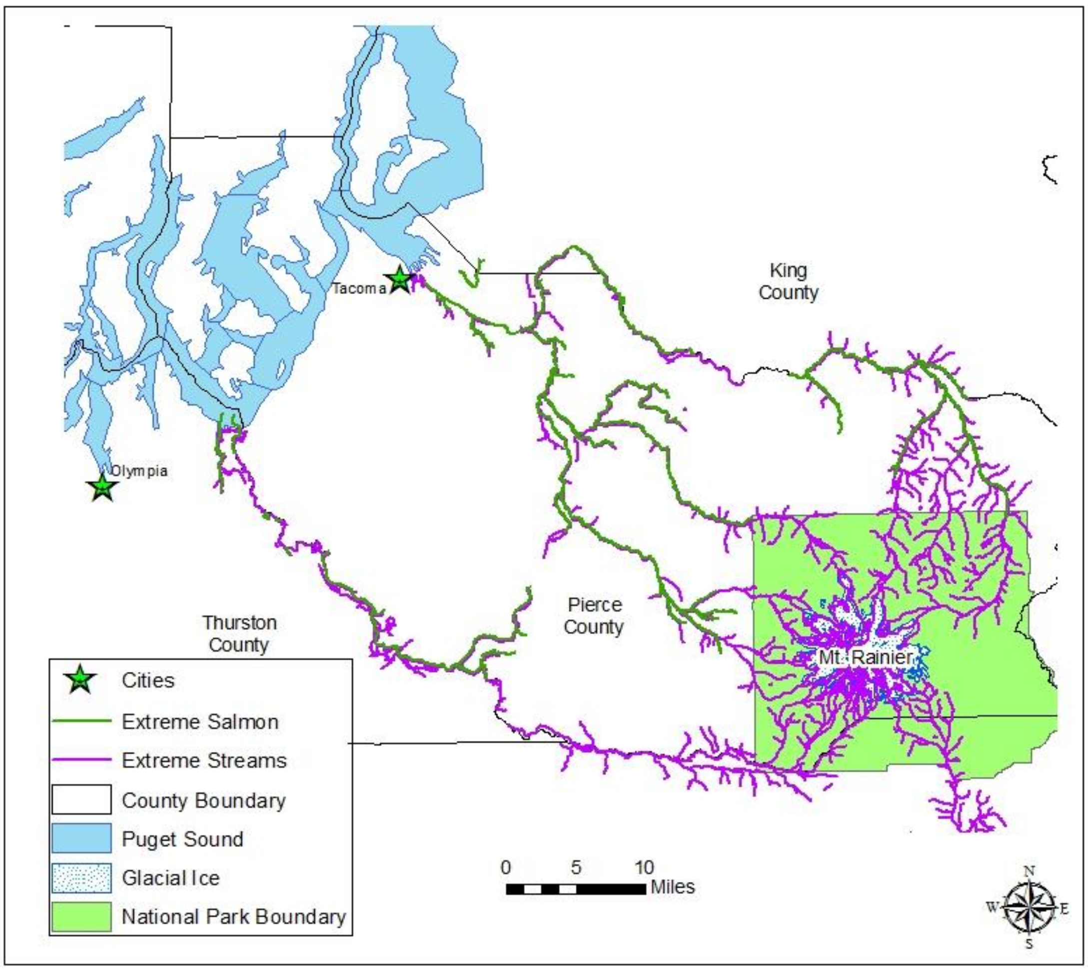

Figure 26: Extreme lahar affected critical salmon and aquatic organism habitat.

A Severe lahar would have the potential to affect a relatively large expanse of critical salmon and aquatic organism habitat (Figure 27). Of the 658 miles of critical salmon habitat in the study area, 165.11 miles, or 25.09%, would be inundated by a Severe event. Of the 1,724.77 miles of aquatic habitat in the study area, 467.96 miles, or 27.13%, would have the potential to be affected by this lahar.

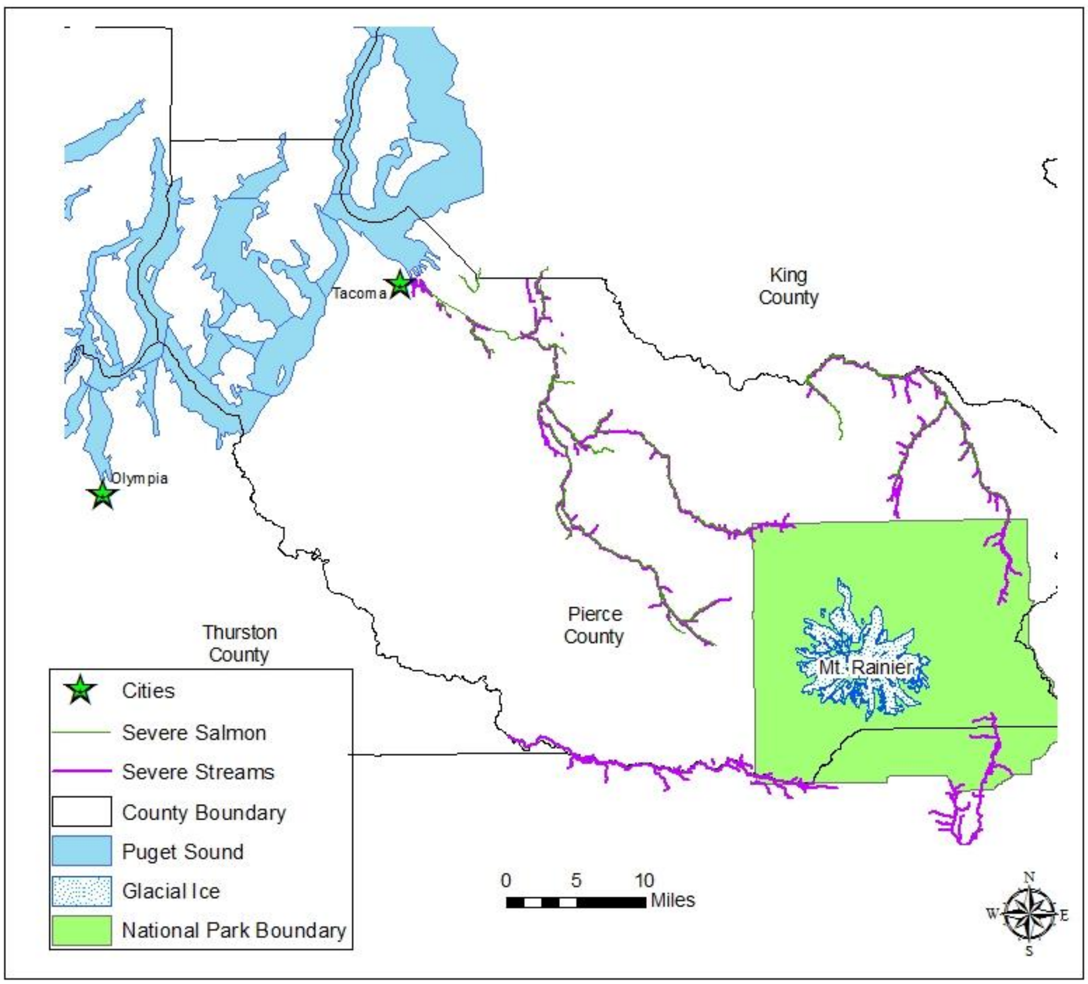

Figure 27: Severe lahar affected critical salmon and aquatic organism habitat.

A Moderate lahar would have a relatively minor affect to critical salmon and aquatic organism habitat (Figure 28). Of the 658 miles of critical salmon habitat in the study area, only 5.16 miles, or 0.78%, would be inundated by a Moderate event. Of the 1,724.77 miles of aquatic habitat in the study area, only 154.12 miles, or 8.94%, would have the potential to be affected by this lahar.

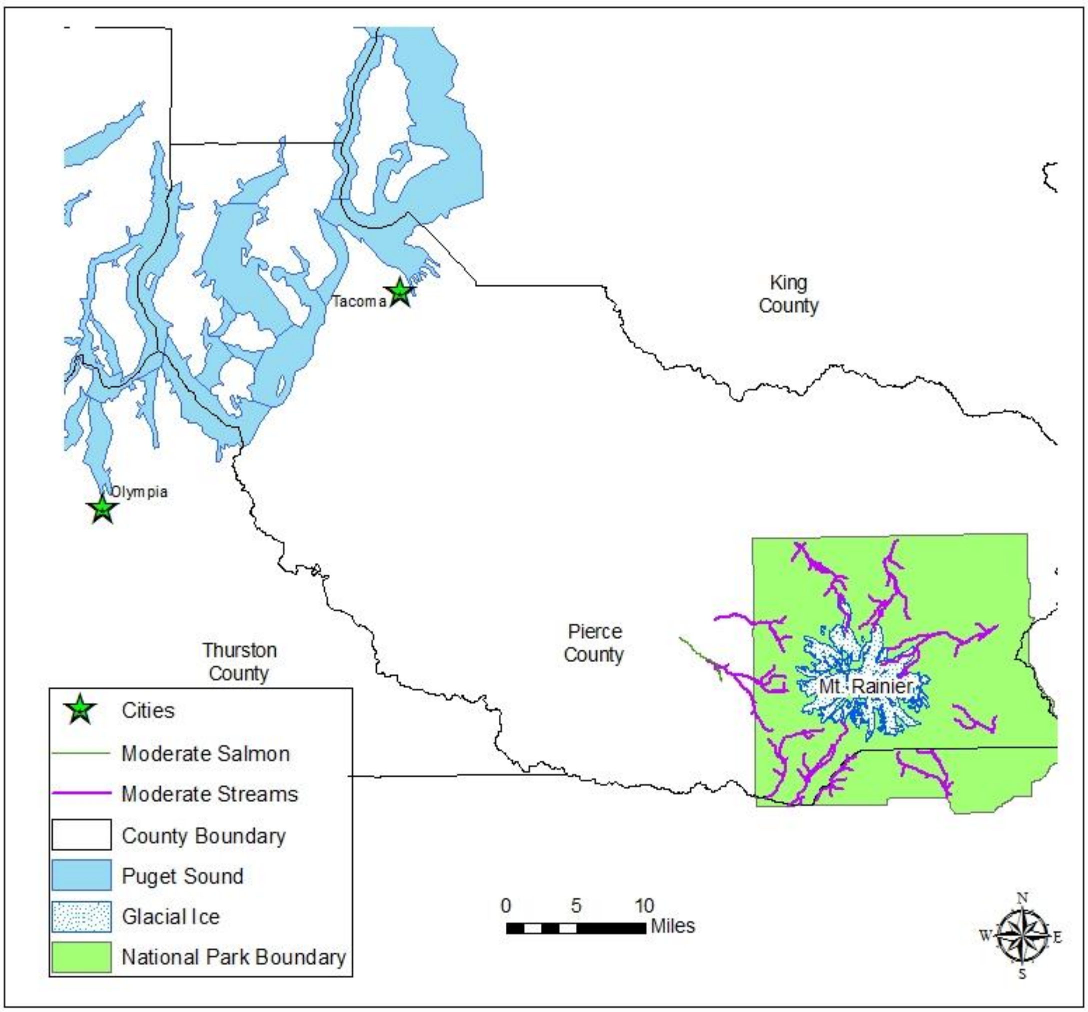

Figure 28: Moderate lahar affected critical salmon and aquatic organism habitat.

4.3 Analysis Issues

A major issue that was encountered in trying to reach the desired analysis results was related to differing projections between the many shapefiles, coverages, and feature classes. Much of the smaller scale data, such as statewide hydrological networks, was displayed in a Geographic Coordinate System format; while the larger scale data, such as Census tracts, was displayed in a Projected Coordinate System. This created problems when the data was clipped or exported between the differing coordinate systems, resulting in display, alignment, and accuracy issues. This was resolved by re-projecting all analysis data into NAD 1983 UTM Zone 10N which was the native projection of the Census tracts.

The extent of some of the project data, specifically the stream network, was the basis for another issue in the analysis process. The stream network that was acquired for this project was for the entire western half of Washington, an extent well beyond that needed for this research. Initially the stream network was clipped to the Pierce and King County boundaries for input into the model. This clip had the unintended result of eliminating segments of streams that were partially in the study area. A new approach was used to select any stream segments within 1 mile of the county boundaries. This allowed for segments that skirted the boundary of a county, or jumped in and out of a county to be included in the analysis. This also allowed for any stream segment that was touched by a lahar event to be included in the study, rather than only those portions of streams directly within the lahar boundary. Rather than using watersheds to determine areas of potential contamination, the stream network was used to illustrate the inundated areas. If watersheds were used the differences between the three magnitude lahars would have been more difficult to illustrate, as a moderate lahar would have the potential to contaminate a river that would carry contaminants dozens of miles beyond the inundation zone. Also the lahar inundation areas do not travel up tributaries within a watershed, so identifying potentially contaminated watersheds could have illustrated a more widespread contamination than actually would occur.

Getting the population statistics necessary for the analysis was difficult. No-cost Census population data is not readily available. Rather, many portions of the data exist in different table formats and shapefiles. There was no quick fix available to mitigate this problem. Multiple tables and shapefiles were downloaded and modified in order to achieve the desired result. Also the Census Tract population statistics were not the ideal format for measuring affected population. A more preferred method would have been using commercially available population density information that presents information based on people per square mile. This would have helped to arrive at a more detailed and possibly more accurate representation of affected population. But the goal of this research was to use as much no-cost data as possible to be applicable to the largest audience.

CHAPTER 5: CONCLUSION AND FUTURE RESEARCH

5.1 Research Summary

The goal of this research was to expand upon previous studies in the Mount Rainier vicinity in order to answer questions that were overlooked or downplayed in those studies. The analysis was performed using all low or no-cost data in order to illustrate the possibilities of the research being used by organizations where obtaining GIS at a high cost is not an option. The research relied heavily on agencies that have produced data specific to their disciplines in order to avoid recreating data without the necessary knowledge. Rather than focusing on the scientific basis as to why a lahar would reach a certain extent, the research aimed to use existing scientific data to achieve results focusing on different areas of impact.

The magnitude of the lahar events was determined by USGS studies regarding the size and frequency of lahars originating on Mount Rainier. Although there could be a nearly infinite number of variables used to determine the size of a lahar, these three cases used for the analysis were the result of field-checks and scientific analysis of previous lahar events performed by USGS personnel. While many different magnitude lahars exist, the three cases gave a good basis to determine the effects on area resources without spending weeks or months on size variables.

Buffers of the three magnitude lahars in one, two, and three mile intervals, were used to better estimate the impact of a potentially contaminated critical aquifer recharge area on the surrounding population. This method was used to illustrate that the water contaminated by a lahar event has the potential to affect a greater portion of the population than that inundated by the lahar.

The Extreme lahar event had devastating effects on critical aquifer recharge areas, human population, and salmon and aquatic habitat. The Severe lahar had a much smaller area affected but still had the potential to affect wide stretches of critical aquifer recharge areas and salmon and aquatic habitat. The Moderate lahar did not go much beyond the Mount Rainier National Park boundary. This event would affect a small number of critical aquifer recharge areas and also a much smaller population area since the area directly around the park is sparsely populated. By studying any stream segment or critical aquifer recharge area that was intersected at some point by the lahar event, potentially contaminated areas were more readily identified. Selecting recharge areas that had the potential to be contaminated by lahar inundation allowed for disaster mitigation plans to be developed for an important natural resource that was not previously associated with lahar research. While previous research focused on the immediate damage to the area directly within the lahar path, this research expanded beyond the initial damage within the lahar path to show farther reaching long-term population and hydrological effects resulting from prolonged water contamination.

The salmon and aquatic organism habitat portion of the analysis produced some staggering results. An Extreme event has the potential to contaminate over 40% of the critical salmon habitat and over 72% of the aquatic organism habitat in King and Pierce counties. The pollutants that would be carried by a large-scale lahar would have far reaching affects to the salmon fisheries and other aquatic organisms, a problem that has no feasible mitigation strategy. These areas were identified in this project in order to identify concerns beyond the human population that need to be considered.

This research illustrated that low or no-cost data could be utilized in new ways to arrive at results more directly tied to the long lasting effects of lahar events. Also all the analysis was completed using the lowest ArcGIS license level, further reducing potential costs to disaster mitigation agencies.

5.2 Research Problems and Limitations

A limitation that presented itself throughout the research was the inability to accurately create additional lahar inundation areas. Without advanced knowledge in volcanic geology it would not be prudent to create modified lahar inundation areas. Also the USGS provided lahars were field checked in order to determine accurate boundaries, while GIS created lahar inundation zones would not be field checked due to distance from the study area and lack of geological field experience. This limited the analysis results to the pre-defined USGS lahar boundaries.

The Department of Homeland Security regulations regarding the availability of municipality water supply data presented a major limitation for the research (United States Department of Homeland Security 2004). Without the location of ground and surface water supplies for settlements surrounding Mount Rainier, critical aquifer recharge areas had to be used instead. While this did provide areas of potential groundwater contamination, there was no way of knowing if that particular aquifer would actually have an effect on the surrounding population. The location of an aquifer in relation to an area of population concentration does not guarantee that the population will need to find an alternative water source. The ability to locate municipal water supply areas would provide a more detailed affected population number for analysis. What this research did was determine a population area within the boundary of a potentially contaminated aquifer.

Larger bodies of water were not examined for potential contamination in this project. For example, an Extreme lahar has the potential to reach the Port of Tacoma and spill into Puget Sound. The size of Puget Sound prevented it from being included in this research as it would have been extremely difficult without advanced hydrological knowledge to understand the effects of the contaminates flowing into a body of water that covers over 1,020 square miles (Lincoln 2000).

Another limitation to the research performed for this project was the inability to determine the severity of impact to an aquifer or stream. While the analysis identified areas that had the potential to be affected there was no known way to determine the extent of the damage the lahar would have on the water supply. Areas that were identified as potentially contaminated by the three lahar cases could have ranged from minimal lasting effects to extremely destructive, long lasting effects. Without advanced hydrological models developed specifically for each lahar example the degree of impact to the water supply cannot be readily quantified.

5.3 Impact of Project Research

The impact of this project's research lies in the ability of the analysis to be performed on readily available data. Rather than focusing on areas that needed field data collected, existing data was used to arrive at new results. This illustrates the ability of

GIS analysis to utilize existing data and create multiple hazard area identification maps without stepping into the field. While this does not replace the need for field checks in disaster mitigation projects it does provide a methodology for users to perform analysis at a much lower cost and at a faster rate.

Also the research identified critical aquifer recharge areas that have the potential to become contaminated by a lahar event. Previous research focused on the effect on surface water immediately following the event, with little attention paid to the lasting effects of groundwater contamination.

5.4 Future Research Opportunities

The advantage of using little or no cost data allows for the further improvement of the research model by anyone with access to GIS software and GIS-related knowledge. Many different variables could be evaluated to show impact to other resources surrounding Mount Rainier. The analysis could also be expanded to other volcanic regions provided the necessary base data exists to perform the analysis. This model could be further expanded to illustrate damage resulting from other natural disasters such as floods and tsunamis.

Government agencies in the Mount Rainier area would have addition resources to obtain free GIS data. Also, local and regional government agencies would have access to exact municipal water supply locations to develop a better model for showing affected population areas as a result of a lahar event. Access to municipal water supply data, such as lake or river intake locations, would allow for a more detailed study of potential surface water resource contamination. These government agencies would be much better equipped to illustrate the necessary mitigation strategies involved in the search for alternative water supplies.

Ranking the contamination to water supplies based on the severity of the contamination would be a useful expansion on this research. This would allow for the development of more detailed hazard mitigation plans based on the likelihood of a certain aquifer or water supply area being contaminated beyond an acceptable level. The USGS National Water Information System website could be used to determine baseline data for water quality in the areas surrounding Mount Rainier. Gauging stations in the area watersheds monitor surface and ground water quality on a daily, monthly, and annual basis, depending on the location (USGS 2011). In addition, municipalities would also have water quality data from their intakes available to help determine the extent of a lahar contamination.

Potential users with advanced geological and volcanic knowledge would be able to create additional lahar flow models to better suit the differing needs of communities and organizations surrounding Mount Rainier. For example, a geologist would be able to determine what magnitude lahar would need to occur in order for a community or resource of interest to be affected. This portion of the research could also be applied to other volcanic regions and is limited only by the data available to the researcher.

Economic impact is another future research opportunity that could be a spin-off of this research. Rather than focusing on the population impact of a lahar event, the economic damage resulting from the destruction of a large portion of the salmon fisheries, contamination to agricultural water supplies, and damage to timber areas could be examined. This could help Federal and State agencies determine the possible aid packages that would need to be available based on different magnitude lahars. Economic impacts would be much more far reaching than water contamination and would require advanced statistical analysis.

Many aspects of this project could be modified in order to meet a user's specific needs. The project could be used to determine affects to numerous natural resources, such as the extent of forest resource damage or the potential contamination of Puget Sound. Also there are hydroelectric dams that surround the Mount Rainier area, which would allow the research to be expanded to include the size of a lahar event necessary to destroy or overflow dammed water supplies affecting power generation for the surrounding communities.

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