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# Variations in population exposure and sensitivity to lahar hazards from Mount Rainier, Washington

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ABSTRACT

Although much has been done to understand, quantify, and delineate volcanic hazards, there are fewer efforts to assess societal vulnerability to these hazards, particularly demographic differences in exposed populations or spatial variations in exposure to regional hazards. To better understand population diversity in volcanic hazard zones, we assess the number and types of people in a single type of hazard zone (lahars) for 27 communities downstream of Mount Rainier, Washington (USA). Using various socioeconomic and hazard datasets, we estimate that there are more than 78 000 residents, 59 000 employees, several dependent-population facilities (e.g., child-day-care centers, nursing homes) and numerous public venues (e.g., churches, hotels, museums) in a Mount Rainier lahar-hazard zone. We find that communities vary in the primary category of individuals in lahar-prone areas—exposed populations are dominated by residents in some communities (e.g., Auburn), employees in others (e.g., Tacoma), and tourists likely outnumber both of these groups in yet other areas (e.g., unincorporated Lewis County). Population exposure to potential lahar inundation varies considerably—some communities (e.g., Auburn) have large numbers of people but low percentages of them in hazard zones, whereas others (e.g., Orting) have fewer people but they comprise the majority of a community. A composite lahar-exposure index is developed to help emergency managers understand spatial variations in community exposure to lahars and results suggest that Puyallup has the highest combination of high numbers and percentages of people and assets in lahar-prone areas. Risk education and preparedness needs will vary based on who is threatened by future lahars, such as residents, employees, tourists at a public venue, or special-needs populations at a dependent-care facility. Emergency managers must first understand the people whom they are trying to prepare before they can expect these people to take protective measures after recognizing natural cues or receiving an official lahar warning.

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## 1. Introduction

Swift, saturated debris flows originating on volcanoes (known commonly by the Indonesian term “lahars”) are significant volcanic hazards because of the long distances that they travel from their source, the high speed at which they travel, and their initiation with or without an eruption. Past lahar-related disasters have been well documented (Blong, 1984; Voight, 1990; Hall, 1992; Rodolfo, 1995; Blong, 1996; Newhall and Punongbayan, 1997; Crittenden, 2001; Annen and Wagner, 2003). Witham (2005) documents 29 937 deaths from lahars in the 20th century with the majority (23 080) from a disaster in Armero, Columbia, related to the 1985 eruption of Nevado del Ruiz. Although many communities throughout the world occupy lahar-prone areas downstream of volcanoes, loss of life and property damage from future lahars can be reduced if officials and at-risk populations understand and manage the risks associated with living and working in these areas.

Early efforts to assess societal risk to volcanic hazards focused on probabilistic loss estimates. For example, Fournier d'Albe (1979) characterizes risk as the product of the number of assets in a hazard zone, the proportion of those assets likely to be affected by a volcanic event, and the probability of that event. This probabilistic approach to risk is appropriate for estimating losses to individual assets (e.g., structures, infrastructure) when asset-fragility curves and hazard probabilities can be established (e.g., Alberico et al., 2002; Spence et al., 2004; Pomonis et al., 1999; Lirer and Vitelli, 1998; Taig, 2002) but fails to capture factors that influence individual risk, such as demographic sensitivity and adaptive capacity. The ability to evacuate, and therefore the probability of loss of life or injury, from an imminent lahar is not the same for all individuals in a hazard zone and will vary for each individual depending on demographic attributes (e.g., age, health, socioeconomic status and role) and knowledge (e.g., experience, perception, awareness, level of preparedness) (Wisner et al., 2004).

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Recent definitions frame risk more generally as the circumstances that pose danger to people and to the things they value (Stern and Fineburg, 1996) and methods to characterize risk vary to address specific issues (e.g., life loss, structural damage, financial loss) and risk-reduction strategies (e.g., evacuation, mitigation, insurance). This recognition of the need for multiple ways to characterize risk has led to an increase in efforts to assess and define the societal conditions that make individuals and communities vulnerable to volcanic hazards (Dibben and Chester, 1999; Chester et al., 2002; Dominey-Howes and Minos-Minopoulos, 2004; Degg and Chester, 2005). Vulnerability refers to the potential for damage or loss of a societal asset (e.g., individuals, buildings, infrastructure, economies) by a hazard and takes into account the societal conditions in and around hazard-prone areas that influence this potential, such as land use, types of structure, demographic patterns, economic conditions, cultural context, and political forces (Wisner et al., 2004). Vulnerability is often described in terms of the exposure, sensitivity, and adaptive capacity of a community and its assets to a hazard (Turner et al., 2003; Polsky et al., 2007). Exposure refers to hazard proximity, while sensitivity and adaptive capacity are characteristics of an individual, asset, or socioeconomic system. Sensitivity is exhibited by differential consequences from a single exposure (e.g., two structures with different building materials), whereas adaptive capacity (also referred to as resilience in some literature) is the ability of an individual or system to prepare for, withstand, and endure an extreme event (Turner et al. 2003; Polsky et al., 2007). For example, various types of people occupy lahar-prone areas (e.g., residents at their homes, employees at businesses, tourists at stores or recreational sites, commuters and shipping agents traveling through an area) and each group varies in their sensitivity and adaptive capacity because of differences in hazard awareness and ability to prepare for or respond to an extreme event.

Efforts to characterize societal vulnerability to volcanic hazards have taken various forms in recent years. Some research has focused on inventorying exposed assets, such as people and buildings (e.g., Pareschi et al., 2000; Thierry et al., 2007) and population-related studies in this realm have focused on multiple groups in single jurisdictions (Aguilera et al., 2004; Aceves-Quesada et al., 2007) or treat populations uniformly across several volcanoes (Lavigne, 1999; Ewert, 2007). Economic studies have included regional catastrophic loss-estimation methods to support financial insurance planning (Leung et al., 2003; Magill et al., 2006). An active area of social-science research focuses on understanding the societal context that influences risk, such as individual perceptions of volcanic hazards (Perry, 1990, Paton et al., 2008, Gregg et al., 2004, Lavigne et al., 2008; Dominey-Howes and Minos-Minopoulos, 2004; Gaillard and Dibben, 2008; Davis et al., 2006), community governance and social networks (Cronin et al, 2004), the dynamic societal pressures and root causes that create unsafe conditions (Dibben and Chester, 1999), psychological aspects of individual resilience (Miller et al, 1999; Paton et al., 2001) and sociopolitical aspects of community resilience (Tobin and Whiteford, 2002). Vulnerability to lahars can also be inferred by studying the societal conditions and pressures that affected preparedness and response efforts in past volcanic disasters, such as Nevado del Ruiz (Hall, 1992; Voight, 1990), Galeras (Cardona, 1997), Pinatubo (Crittenden, 2001), and Tungurahua (Lane et al., 2003).

To date, there has been little discussion in the volcano literature of how vulnerability varies because of the types of individuals in hazard-prone areas or on variations in population exposure among communities that share common volcanic hazards (e.g., far-reaching lahars). In this paper, we assess demographic and jurisdictional differences in population exposure and sensitivity to lahars and focus on communities downstream of Mount Rainier, Washington (USA). Our goal is to develop a usable description and assessment of population exposure and sensitivity for emergency managers who are responsible for educating and preparing at-risk populations near Mount Rainier. We overlay various population and volcano hazard data sets to assess the number and categories of individuals in lahar-prone areas of Mount Rainier in several communities. These calculations reveal regional patterns of community exposure and sensitivity to potential lahar inundation. We explore several aspects of vulnerability to lahar hazards including: (1) the distribution of populations within a hazard zone that includes all or part of several communities, (2) a method to determine which communities have greater exposure or sensitivity to lahars and (3) the relationship between land use within a volcanic hazard zone and unit-less indicators that describe relative community exposure. Information and methods presented here further the dialogue on understanding community vulnerability to lahar hazards and can be used by officials to identify individuals and communities that will need assistance in preparing for and responding to an event.

## 2. Regional setting and study area

Mount Rainier, Washington (USA) (Fig. 1) is an active volcano that is quiescent, yet has generated at least 60 lahars of various sizes over the past 10000 years and will likely produce more in the future because of its steep slopes and large volume of water stored in its 25 glaciers (Hoblitt et al., 1998; Vallance et al., 2003; Walder and Driedger, 1994). Although some Mount Rainier hazards (e.g., ballistic projectiles) extend only a few kilometers beyond its National Park boundary (Fig. 1), past lahars have traveled tens of kilometers from the summit (Vallance et al., 2003). Increasing urbanization of the lowlands near Puget Sound and downstream of Mount Rainier makes it one of the areas in the United States at greatest risk from a lahar flow (Scott and Vallance, 1995). Of all Mount Rainier hazards, a lahar that reaches Puget Sound is the greatest threat to communities that are downvalley of the volcano (Hoblitt et al., 1998), hence our focus on lahars in this study of population exposure.

During the past several thousand years, Mount Rainier lahars reached the Puget Sound lowland on average at least once every 500 to 1000 years. Smaller lahars that did not reach the lowland occurred more frequently. Based on this record of past lahars, there is approximately a 1-in-10 chance of a lahar reaching areas of significant human development in the Puget Sound lowland during an average human lifespan (Driedger and Scott, 2008). The great majority of previous lahars were initiated by the swift melting of snow and ice during volcanic eruptions. Such lahars in the future will be preceded by volcanic events that will warn of impending lahar activity. In addition to meltwater-driven events, lahars can be caused by landslides, which can be triggered when magma intrudes into a volcano and destabilizes it, by large earthquakes, or by spontaneous slope failure of weak, chemically-altered, clay-rich rock. Recent studies suggest that the Puyallup and, to a lesser extent, the Nisqually Valleys are the only areas on Mount Rainier prone to such events (Finn et al., 2001; Sisson et al., 2001). Regardless of whether lahars originate from landslides or by rapid production of meltwater, they hold the potential for affecting areas of significant human development. Efforts to reduce societal risk from Mount Rainier lahars include lahar detection and warning systems in river valleys, multi-agency response plans (Pierce County Department of Emergency Management, 2008), hazard assessments (Hoblitt et al., 1998; Schilling et al. 2008), and education efforts (Driedger and Scott, 2008; Driedger et al., 1998; Driedger et al., 2005). Although much has been done to develop warning systems and awareness programs for hazards associated with Mount Rainier and other U.S. volcanoes, less has been done to understand societal vulnerability to these hazards, specifically the potential impacts to people (Aster et al., 2007).

This study of population exposure to lahar hazards focuses on the 18 cities and 9 unincorporated communities within four Washington counties (King, Lewis, Pierce, and Thurston) that include land within a Mount Rainier lahar-hazard zone (Fig. 1). Incorporated cities and unincorporated towns are delineated by city limits and census-

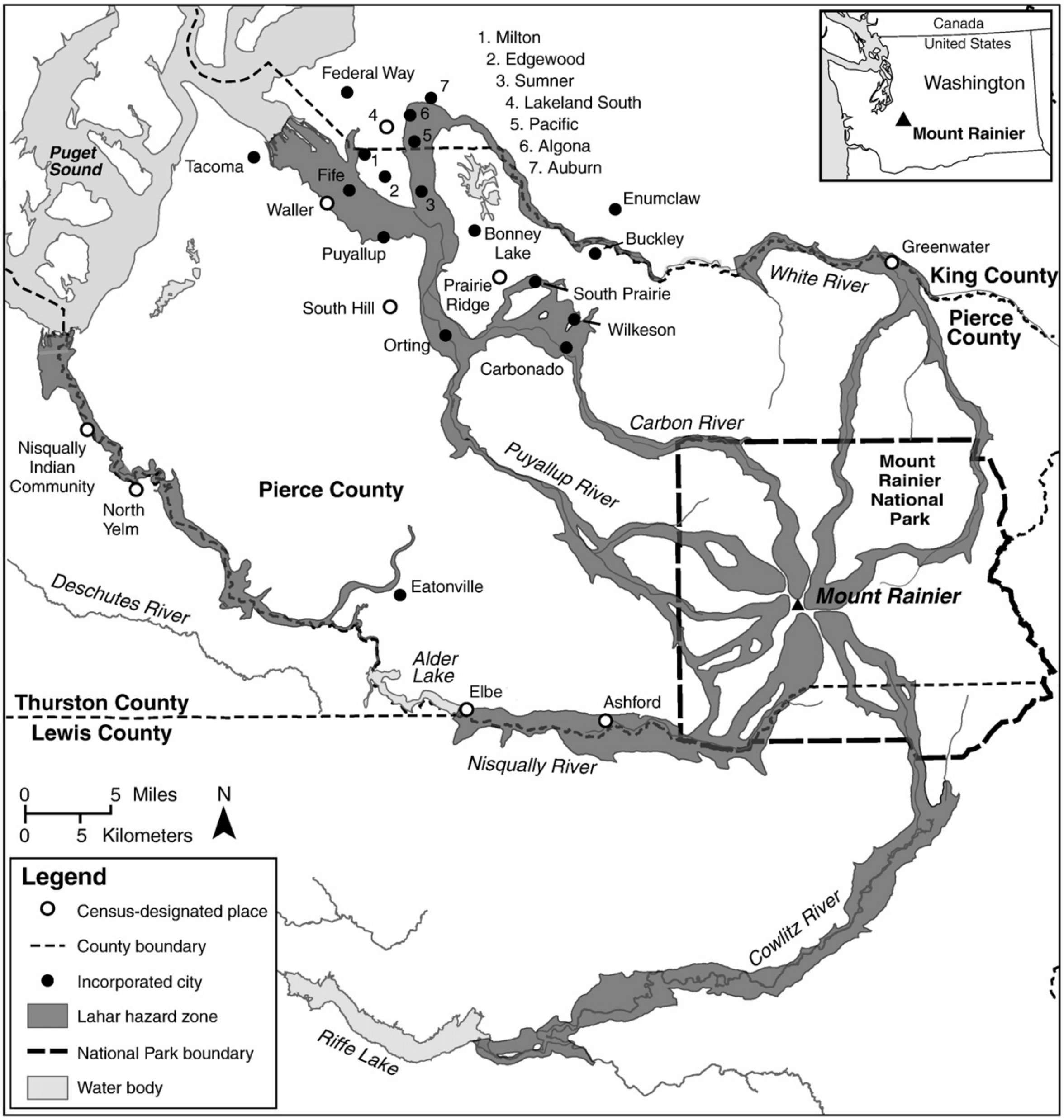


**Fig. 1.** Map showing counties, incorporated cities, and unincorporated (i.e., census-designated) places within a lahar-hazard zone on and near Mount Rainier, Washington.

designated-place boundaries, respectively, of the 2000 Census Bureau (Office of Financial Management, 2009). The delineation of the Mount Rainier lahar-hazard zone used in this study is based on the behavior of the Electron Mudflow (noted as a "Case 1" scenario in Hoblitt et al., 1998, and Schilling et al., 2008). The Electron Mudflow traveled along the Puyallup River (Fig. 1) approximately 500 years ago and was the result of a slope failure on the west flank of Mount Rainier. It was one of the largest lahars of the past several thousand years and is therefore considered to be a characteristic flow for identifying probable inundation areas from future lahars that could significantly impact downstream communities. Additional hazard zones for smaller, more likely, lahars that impact areas closest to the volcano are also described in Hoblitt et al. (1998) and Schilling et al. (2008). The Electron Mudflow, with no known evidence of an accompanying eruption (Sisson and Vallance, 2009), illustrates how some rare but significant lahar events can occur without precursory volcanic activity. Upstream reports of advancing lahars or signals from the lahar detection system may serve as the only warning for some downstream communities in the event of rare lahars that are not accompanied by volcanic unrest or activity (Driedger and Scott, 2008; Hoblitt et al., 1998).

The lahar-hazard zone shown in Fig. 1 identifies areas that could be affected by lahars generated in the various drainage valleys of Mount Rainier, based on the behavior of the Electron Mudflow. It is not meant to imply that all delineated areas would be inundated by a future lahar; typically a single lahar is confined to one drainage valley (e.g., Puyallup River). The west flank of Mount Rainier, including the Puyallup and Nisqually river valleys, is considered to have the greatest potential for generating large landslides that become significant lahars because of higher amounts of hydrothermally weakened rock at high altitudes (Driedger and Scott, 2008). Also, the areas in the identified lahar-hazard zone are not equally at risk from inundation; areas in stream bottoms and closer to the volcano are more likely to be impacted than areas on the periphery of the zone or increasingly distant from the volcano. The lahar-hazard zone used in this study is a guide for emergency planning and is not a prediction for a future flow, because the actual inundation extent, depth, and speed of a future lahar will be determined by topography and the volume of material entrained in the flow. Therefore, even if another Electron-sized lahar were to occur, some areas will be affected by lahar-impact forces while others receive lahar-related flooding. Finally, the lahar-hazard zone used in this study does not include other hazards associated with volcanic activity of Mount Rainier, including lava flows, pyroclastic flows, ash fall and flooding, nor does it include post-lahar sedimentation of areas downstream of deposits that follow lahar events for decades to centuries.

## 3. Methods

### *3.1. Population and asset exposure in lahar-prone areas*

We use the amount and percentage of six variables—developed land, residents, employees, public venues, dependent-population facilities, and parcel values—to describe the variation in population exposure to lahar hazards among the 27 communities and four counties. We chose these variables because they are all indicators of human occupation of lahar-prone areas and are data that U.S. jurisdictions are encouraged to collect as they develop local and State hazard mitigation plans (Federal Emergency Management Agency, 2001). Calculating the number and distribution of individuals and assets in lahar-prone areas shows officials where risk and warning education may be most needed and where, in the absence of evacuations, losses could be greatest. Knowing the percentages of communities' assets that are in a lahar-hazard zone helps us understand the relative impact of losses. For example, if community A has 500 individuals in a lahar-hazard zone (representing 10% of the local population) and community B has 100 individuals in a lahar-hazard zone (representing 95% of the local community), then community A may have higher losses from a lahar, but community B may experience greater relative impacts and have fewer available resources during recovery. Social disruption may be more significant in community B, even though the number of deaths or affected individuals is less than in community A.

Analyses were completed using geographic-information-system (GIS) software to overlay geospatial data representing population counts, land-cover classification, administrative boundaries, and lahar-hazard zones. If GIS-based population polygons overlapped hazard polygons, final population values were adjusted proportionately based on the spatial ratio of each sliver within or outside of the lahar-hazard zone. Exposure inventories are based on the presence of people and assets in hazard zones; they are not engineering-based loss estimates for any particular facility or mortality estimates for any community. These inventories cannot be considered loss forecasts because other factors that influence evacuation potential and mortality are excluded from this study, such as risk perception, level of preparedness, and adaptive capacity during a response (Alwang et al., 2001; Pelling, 2002; Turner et al., 2003). Population-exposure inventories are loss estimates only if one assumes that all individuals in lahar-prone areas are unaware of lahar risks, are unaware of what to do if warned of an imminent threat (either by natural cues or official announcements), and fail to take protective measures to evacuate. This assumption is unrealistic, given the high number of hazard awareness efforts in the Mount Rainier region (e.g., Driedger and Scott, 2008; Driedger et al., 1998; Driedger et al., 2002; Driedger et al., 2005).

To calculate the amount and percentage of developed land within the lahar-hazard zone of each community, we used a subset of the 2001 National Land Cover Database (NLCD) (Homer et al., 2004). NLCD products are coded by automated techniques from Landsat Thematic Mapper (TM) digital satellite imagery (30-m grid cells or pixels) and verified with field visits. We assumed that population exposure to lahar hazards increases with increased amounts and percentages of developed land within lahar-prone areas (Wood, 2009). We focused on three NLCD 2001 classes that characterize developed land:

(1) High-intensity developed pixels, which contain more than 80% of impervious surfaces and typically represent heavily built-up urban centers, large buildings, and abundant paved surfaces, such as runways and interstate highways;
(2) Medium-intensity developed pixels, which contain 50 to 79% of impervious surfaces and typically represent single family housing units; and
(3) Low-intensity developed pixels, which contain 21 to 49% of impervious surfaces and typically represent single family housing units with the addition of roads and associated trees (National Oceanic and Atmospheric Administration Coastal Services Center, 2007).

The number and type of residents in the lahar-hazard zone were assessed by overlaying and calculating the union of geospatial layers representing the lahar-hazard zone, community boundaries and block-level population counts compiled for the 2000 U.S. Census (U.S. Census Bureau, 2008). Demographic characteristics can amplify an individual's sensitivity to hazards (Morrow, 1999; Ngo, 2003; Cutter et al., 2003; Laska and Morrow, 2007); therefore, we calculated the number of residents in lahar-prone areas according to ethnicity (Hispanic or Latino), race (American Indian and Alaska Native, Asian, Black or African American, Native Hawaiian and other Pacific Islander, and White—either all alone for each race or in combination with one or more other races), age (individuals under 5 and over 65 years in age), gender (female-headed households with children and no spouse present), and tenancy (renter-occupied households). These counts do not imply that all individuals of a certain group will exhibit identical behavior; variations in individual adaptive capacity and local situations modify the influence of these demographic sensitivities.

The number and type of employees in lahar-prone areas were determined by overlaying the lahar-hazard zone and the 2008 InfoUSA Employer Database (InfoUSA, 2008). Our counts serve as approximations because we were unable to field verify the locations and attributes of the 108 182 businesses within the four counties of the study area. North American Industry Classification System (NAICS) codes for businesses in the InfoUSA Employer Database were used to characterize employee type, as well as to identify dependent-population facilities and public venues. Dependent-population facilities contain individuals who would require evacuation assistance (e.g., hospitals, psychiatric and substance abuse hospitals, adult residential care and nursing homes, child-day centers, schools, correctional facilities). Public venues attract transient populations that may have limited volcanic-hazard awareness and include aquariums, botanical gardens, casinos, colleges and universities, fairgrounds, historical places, libraries, museums, overnight accommodations, parks, religious organizations, shopping centers and malls, sporting facilities, theaters, and zoos. The number of facilities and transient nature of populations at these locations precluded exact population counts; therefore, we limit discussion to the number of public venues and dependent-population facilities.

The amount and percentage of total tax-parcel value (land and content value in 2008 U.S. dollars) in lahar-hazard zones of each community was based on 2008 county data received from each of the four counties. Parcel values are useful for understanding the spatial distribution of people and community assets because high parcel values indicate human occupation while parcels with no or low value indicate less developed areas. Communities also rely on property taxes for social services (e.g., law enforcement, schools) and reductions in property values can affect these services, which then hamper long-term disaster recovery and can lead to individuals leaving a community.

After compiling population and asset distributions relative to the lahar-hazard zone for the 27 communities, we performed simple linear regressions to test the predictive power of the amount of land in lahar-prone areas as an indicator of the number of community assets in these areas (i.e., does more land in the hazard zone mean there are more people in the zone?). The independent variable is the area of land within community boundaries regardless of NLCD classification. The dependent variables we tested are the community assets described previously (i.e., developed land, residents, employees, dependent-care facilities, public venues, and parcel values). A significant statistical relationship between land area and the specific asset is assumed if the statistic probability is less than 5% (i.e., $p<0.05$). Similar tests were conducted to test the predictive power of the percentage of land in lahar-prone areas as an indicator of the percentage of community assets in these areas.

### 3.2. Composite indices of community exposure

We developed two composite indices to compare community exposure to lahars for the 31 geographic units (i.e., 18 incorporated cities, 9 unincorporated census-designated places, and the remaining unincorporated land in the 4 counties). The indices were derived for each geographic unit from the amounts and percentages of six variables—developed lands, residents, employees, public venues, dependent-population facilities, and total tax-parcel values. Each composite index was created by normalizing values in the six categories to the maximum value found within that category. Normalizing data to maximum values creates a common data range of zero to one for all six categories and is a simple approach for comparing disparate datasets. The six normalized values in each community were added, resulting in a score that ranged between zero and six for each of the 31 geographic units. Each geographic unit has two composite indices—one summarizing the number of assets in lahar-prone areas and another summarizing the percentage of total community assets in lahar-prone areas. The two indices are unit-less, relative values to help us compare the 31 geographic units but they have no absolute meaning for a community. We calculated a final score for each of the 31 geographic units by normalizing each of the composite indices to maximum values (yielding a common data range between zero and one for the two indices) and then adding the two indices, resulting in values ranging between zero and two. Normalizing the two composite indices is needed to eliminate weighting bias between the indices; this bias can occur because of differences in the distribution of values within each index.

## 4. Results

The following section details population diversity and spatial variations in population exposure to lahars associated with Mount Rainier, Washington. We first report on results and trends among 27 communities and four counties in the amount and percentage of various population groups and assets in the lahar-hazard zone, including developed land, residents, employees, dependent-population facilities, public venues, and parcel values. Next, we report on statistical tests designed to test the predictive power of land-cover data as an indicator of population distributions. Finally, we summarize composite indices of population exposure and trends in regional vulnerability to lahars.

### 4.1. Population and asset exposure in lahar-prone areas

Approximately 10% of the land in the Mount Rainier lahar-hazard zone is classified as developed (5% low-intensity, 3% medium-intensity, and 2% high-intensity) with the remainder classified as forest (44%), ice/snow (8%), wetlands (8%), pasture, hay, and cultivated crops (7%), shrub/scrub (7%), open-space developed (5%), barren land (4%), grassland (3%), and open water (3%). The amount (Fig. 2A) and percentage (Fig. 2B) of developed land (cells classified as low-, medium- or high-intensity developed) in lahar-prone areas vary considerably among the 27 communities and four counties. The three largest areas of developed land in the lahar-hazard zone are in the unincorporated areas of Pierce County (1630 ha), City of Tacoma (1504 ha), and the City of Puyallup (1190 ha), but these lands represent low to moderate percentages of the total land of each jurisdiction (5%, 14% and 54%, respectively). Several communities (e.g., Ashford, Carbonado, Fife, Greenwater, Orting, and Wilkeson) have relatively low amounts of developed land in the lahar-hazard zone, but these lands are all of the developed land for each community. Only a few communities (e.g., Pacific, Fife, and Sumner) are above the third-quartile values for both amount and percentage of developed land in the lahar-hazard zone. Third-quartile (75th percentile) values are reported in Fig. 2 bar-graphs to identify the top 25% of the communities in a certain category and are shown instead of standard deviations because several datasets have non-normal distributions, based on D'Agostino normality tests at 95% significance (i.e., $\alpha=0.05$) (Zar, 1984).

Approximately 78 049 people live in the lahar-hazard zone, representing approximately 3% of the total residential population of the four counties. The number (Fig. 2C) and percentage (Fig. 2D) of residents in the lahar-hazard zone vary significantly across the four counties. The City of Puyallup has the highest number of residents in the lahar-hazard zone (17 459 residents), but this number is only a portion of the entire city population. Conversely, other towns (e.g., Fife, Orting) have much smaller exposed populations, but they represent the entire residential population. Twenty-one percent of the residents in lahar-prone areas live outside of the incorporated cities and unincorporated towns within the four counties. Similar to land-cover results, there are several areas with high numbers but relatively low percentages of total residents in the lahar-hazard zone (e.g., City of Auburn and the unincorporated areas of Pierce County), while other areas have low numbers and high percentages of residents in lahar-prone areas (e.g., Algona, Pacific, Ashford, Carbonado, Elbe, and Wilkeson). Only the cities of Fife, Orting, and Sumner have both high numbers and high percentages of their residents in the lahar-hazard zone (denoted by these cities having values above the third-quartile values in both categories).

Demographic characteristics of residents vary in the lahar-hazard zone and these differences may make certain individuals less able to prepare or respond to a lahar. These demographic sensitivities are not based on extensive studies of the residents in the Mount Rainier lahar-hazard zone, but instead on the established social-science literature on hazard preparedness to and disaster impacts from various extreme events (e.g., earthquakes, tornadoes, hurricanes). Relative to national percentages of race and ethnicity, the percentage of residents in the lahar-hazard zone is high for White (90% compared to 77% for the nation) and American Indian and Alaska Native (4% compared to 1.5% for the nation), low for Black or African American (2% compared to 13% for the nation), and equal for Asian (4%) and Native Hawaiian and Other Pacific Islander (both less than 1%). Race and ethnicity have been shown to influence individual sensitivity to natural hazards because of historic patterns of social inequalities within the U.S. that can result in minority communities lacking resources to prepare and mitigate (Cutter et al., 2003; Laska and Morrow, 2007) and being excluded from disaster planning efforts (Morrow, 1999). Seven percent of residents in the lahar-hazard zone are under the age of 5 and 11% are older than 65 years in age, which are both considered to be more vulnerable to sudden-onset hazards than other age groups because of potential mobility and health issues (Morrow, 1999; Balaban, 2006; McGuire et al., 2007; Ngo, 2003). Nine percent of households in the lahar-hazard zone are single-mother households, which are more likely to have limited mobility during an evacuation and fewer financial resources to draw upon to prepare for natural hazards (Enarson and Morrow, 1998; Laska and Morrow, 2007). Finally, 39% of the households in the lahar-hazard zone are renter-

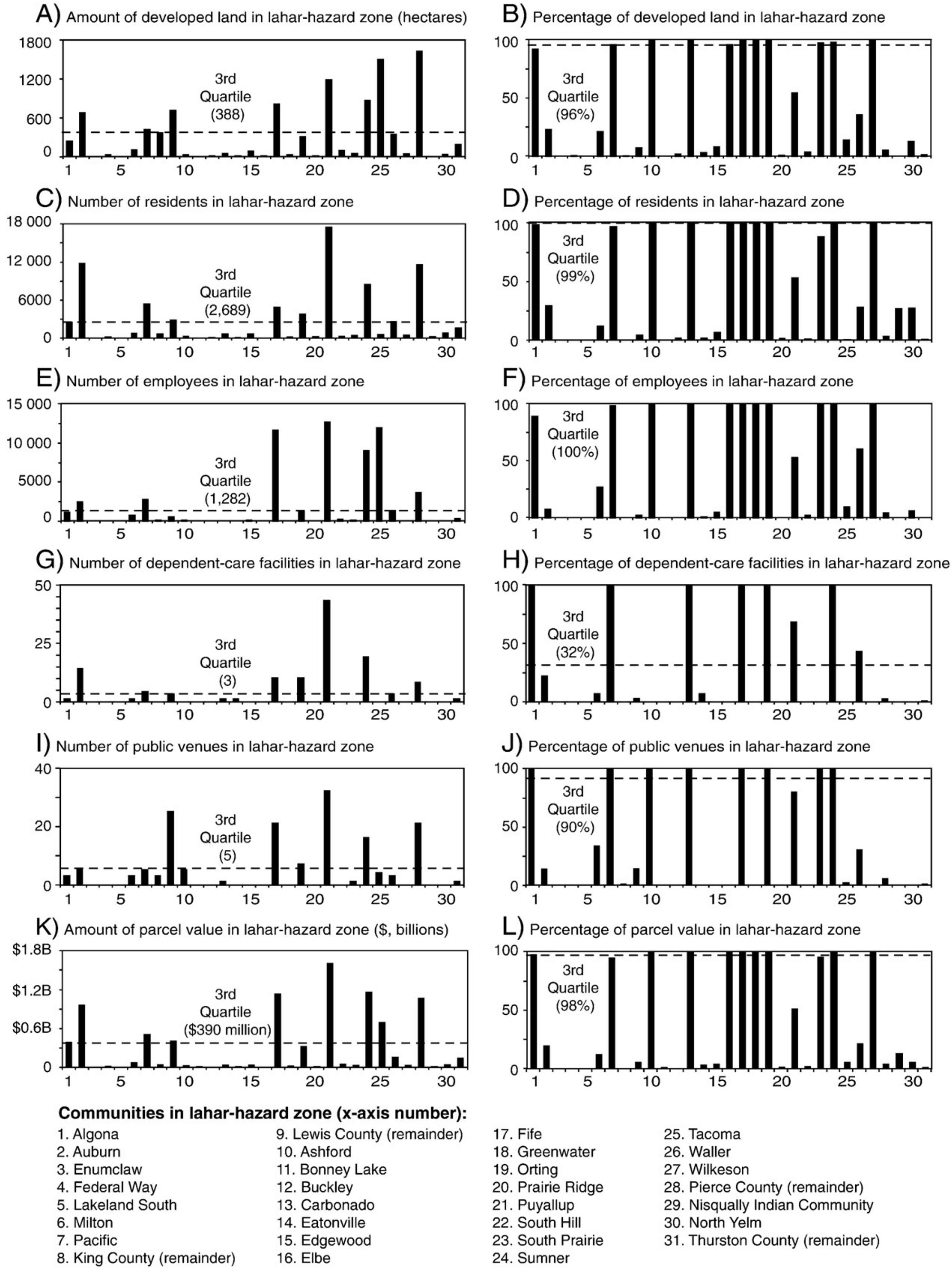


**Fig. 2.** Counts and percentages of community assets in the selected Mount Rainier lahar-hazard zone, including developed land (A and B), residents (C and D), employees (E and F), dependent-population facilities (G and H), public venues (I and J) and parcel value (K and L). Communities are arranged alphabetically along the *x*-axes, first by county (King, Lewis, Pierce, and then Thurston) and then by community within each county.

occupied, a demographic group that is less likely to be prepared for catastrophic events and may have less exposure to awareness campaigns than homeowners (Morrow, 1999; Burby et al., 2003).

Approximately 59 678 people work at 3890 businesses within the lahar-hazard zones, representing 4% of the total workforce in the four counties. Similar to residential populations, the number (Fig. 2E) and percentage (Fig. 2F) of employees in lahar-hazard zones vary across the study area. The City of Puyallup has the highest number of employees working within the lahar-hazard zone (12 603) and all of the employees of several communities (e.g., Fife, Orting) work within the lahar-hazard zone. Some communities have high numbers but low percentages of employees in the lahar-hazard zone (e.g., Tacoma), while others have fewer employees in these areas that represent an entire town's workforce (e.g., Pacific, Orting). The cities of Fife and Sumner have both relatively high numbers and high percentages of their employees in the lahar-hazard zone. Based on employee distributions, the most common businesses in the lahar-hazard zone are manufacturing, retail trade, transportation and warehousing, wholesale trade, and construction (Fig. 3). Retail businesses attract local customers and tourists, whereas the other more industrial businesses will tend to have high numbers of employees, low numbers of on-site customers and tourists, and the potential presence of heavy machinery and hazardous materials.

Dependent-population facilities in the lahar-hazard zone include 63 school facilities, 30 child-day-care centers, 19 adult residential care centers, 4 outpatient-care facilities, and 1 correctional facility (Fig. 2G). Additional evacuation planning may be warranted for communities with high numbers of dependent-population facilities (e.g., Puyallup, Sumner) because of the limited mobility of certain groups, such as those in schools and nursing homes, and the limited time for evacuations (ranging from tens of minutes to hours depending on the community). In addition to unique evacuation and relief issues, many dependent-population facilities represent critical social services that, if lost, could slow community recovery following an extreme event. For example, the loss of child-day-care facilities or schools could keep some parents from returning to their jobs until suitable arrangements can be made for their children. In several communities (e.g., Algona, Pacific, Carbonado, Fife, Orting, Sumner), all of the dependent-care facilities are in the lahar-hazard zone (Fig. 2H).

Several public venues that likely attract high numbers of residents and tourists are in the lahar-hazard zone, including 78 religious organizations, 57 overnight-tourist accommodations, 7 libraries, 6 museums, and 1 casino. The highest numbers and percentages of public venues in the lahar-hazard zone are in Puyallup, Fife, and the unincorporated areas of Lewis and Pierce counties (Figs. 2I and J). Large numbers of visitors could be in danger if a lahar were to occur during a high-occupancy time (e.g., during a religious service or community fair). Visitors also may not be fully aware of evacuation procedures or even the potential for lahars if they are coming from areas with no history of lahars. The presence of public venues in the lahar-hazard zone, however, also presents an outreach opportunity for emergency managers to work with owners and employees of these public venues to educate local and tourist populations. Reaching tourists with risk awareness and evacuation materials is an ever-present challenge for emergency managers and public venues provide a gateway to this population group.

Total land and content value for tax parcels in the lahar-hazard zone is assessed at approximately $8.8 billion, representing 2% of the total parcel values in the four counties. The amount (Fig. 2K) and percentage (Fig. 2L) of total parcel values in lahar-prone areas of each community vary considerably across the study area. The City of Puyallup has the highest total parcel value in the lahar-hazard zone ($1.6 billion) and several communities (e.g., Fife, Orting) have all of their parcel values within the lahar-hazard zone. Similar to the other datasets, there are several areas with high amounts but relatively low percentages of parcel value in the lahar-hazard zone (e.g., Auburn, Puyallup), while other areas have low amounts but high percentages of their parcel value (e.g., Orting, South Prairie). Only the communities of Fife and Sumner are above third-quartile values in both the amount and percentage of parcel values in the lahar-hazard zone.

### *4.2. Land-cover data as an indicator of community exposure*

Knowing the amount of lahar-prone land in a community is not a strong indicator of the number of people and assets in these areas. But knowing the percentage of a community's total land in a lahar-prone area provides some insight on the relative distribution of assets within that community. Linear regression analyses conducted to test the


**Fig. 3.** Percentage of employees, by business sector, in the selected lahar-hazard zone of Mount Rainier, Washington.

predictive power of land-cover data as an indicator of population distribution denote that most, but not all, relationships are significant (Table 1), based on criteria of $p<0.05$. The relationships between the amount of lahar-prone land in a community and the amount of employees and dependent-population facilities on that land are not considered significant ($p=0.63$ and $p=0.57$, respectively). The relationships are significant between the amount of land and the amount of developed land ($p<0.01$), residents ($p=0.03$), parcel values ($p=0.05$), and public venues ($p<0.01$); however, low explained variance ($r^2$) values for these assets (0.36, 0.16, 0.13, and 0.28, respectively) suggest that the relationships are statistically significant but weak. For tests concerning the percentage of a community's land and total assets in the lahar-hazard zone, all relationships are statistically significant ($p<0.01$). The $r^2$ values for tests related to percentages of assets are higher than those for tests related to the amount of assets, ranging from 0.41 for dependent-population facilities to as much as 0.98 for residents.

### 4.3. Composite indices of community exposure

Composite indices (one describing the amount and the other the percentage of assets in the lahar-hazard zone)—for each of the 18 incorporated cities, 9 unincorporated census-designated places, and the remaining portions of the four counties are the sums of normalized data in 6 categories—developed land, residents, employees, public venues, dependent-population facilities, and total parcel value. Six is the maximum possible value for the sum of these six factors. The City of Puyallup has the highest composite amount value (5.7), indicating that this community consistently has one of the highest amount of assets in the lahar-hazard zone. The communities of Carbonado, Fife, Orting, and Sumner have the maximum composite percentage value (6.0), indicating that they have the highest percentage of assets in the lahar-hazard zone for each of the six categories. Some communities (e.g., Tacoma, the unincorporated areas of Pierce County) have higher relative amounts than percentages, whereas others (e.g., Algona, Pacific, Ashford, South Prairie, and Wilkeson) have higher relative percentages.

A histogram depicting the number of communities with various composite amount and percentage values (in 0.5 increments) demonstrates that most communities have scores of 0 to 1 for the amount indicator (Fig. 4), suggesting that they have considerably fewer people and societal assets in lahar-prone areas than Puyallup. Composite percentage values have a bimodal distribution, indicating that there is one set of communities with consistently low percentages of assets in lahar-prone areas and a second set of communities with consistently high percentages (e.g., Fife, Orting, Carbonado, Sumner, Pacific, and Algona). This suggests that many communities face similar issues on the relative impact that lahars could have on their community's populations and economic assets, regardless of the absolute amount of assets in the lahar-hazard zone.

After ordering the 31 areas (i.e., 18 incorporated cities, 9 unincorporated towns, and four counties) by their overall sum of normalized amount and percentage indicators (maximum possible value is 2.0 for this sum), we observe four community groups (Fig. 5). The first group includes the cities of Puyallup, Sumner and Fife (each with the highest values of approximately 1.6), where Puyallup's vulnerability arises from the amount of assets in lahar-prone areas and the vulnerability of Sumner and Fife have more to do with the high percentage of their assets in lahar-prone areas. The second group in Fig. 5 includes the next nine ranked communities (from Pacific to Elbe in Fig. 5) which have low amounts but high percentages of their assets in lahar-prone areas. The third group includes the medium to large communities of Auburn,

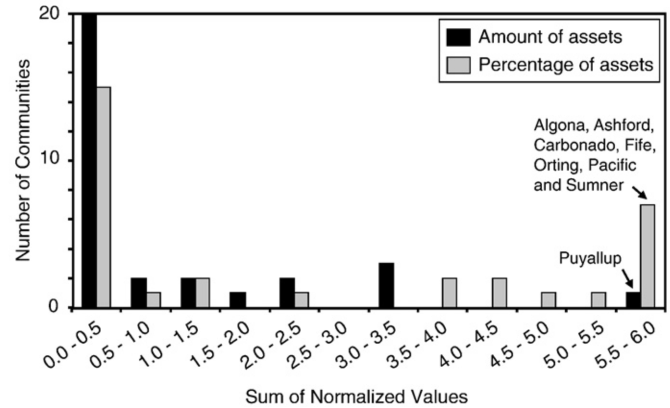


**Fig. 4.** Frequency histogram of the sum of normalized amount and percentage exposure indices for communities within the selected lahar-hazard zone of Mount Rainier, Washington.

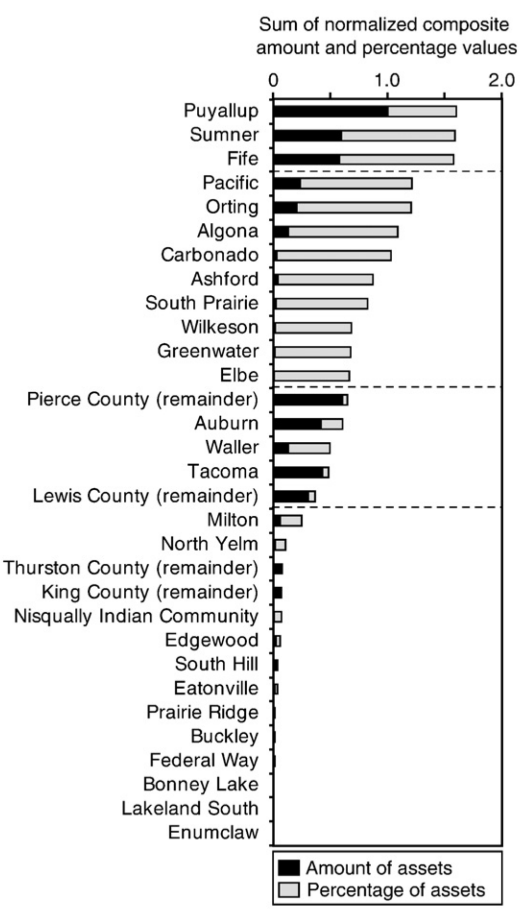


**Fig. 5.** Sum of normalized amount and percentage indices for communities in the selected lahar-hazard zone of Mount Rainier, Washington. Dashed lines indicate groupings discussed in the text.

**Table 1**
Statistical results comparing land data and community assets in the selected lahar-hazard zone of Mount Rainier, Washington.

| Regression significance between all land and: | Amount in lahar-hazard zone | | | Percentage of community total in lahar-hazard zone | | |
|---|---|---|---|---|---|---|
| | $r$ | $r^2$ | $p$ | $r$ | $r^2$ | $p$ |
| Developed land | 0.60 | 0.36 | 0.00 | 0.98 | 0.96 | <0.01 |
| Residents | 0.40 | 0.16 | 0.03 | 0.99 | 0.98 | <0.01 |
| Employees | 0.09 | 0.01 | 0.63 | 0.97 | 0.94 | <0.01 |
| Total parcel values | 0.36 | 0.13 | 0.05 | 0.98 | 0.96 | <0.01 |
| Dependent-population facilities | 0.11 | 0.01 | 0.57 | 0.64 | 0.41 | <0.01 |
| Public venues | 0.53 | 0.28 | 0.00 | 0.75 | 0.57 | <0.01 |

Waller, and Tacoma, and the remaining unincorporated land of Pierce and Lewis counties. In this third group, the areas have relatively low composite values (approximately 0.5) that are largely because of the amount of assets in lahar-prone areas. The fourth group includes the remaining 14 communities which have very low composite values (approximately 0.2 and less).

Several groupings of communities are also evident when one compares the composite amount and percentage index to estimated lahar arrival times from time of initiation at source (Fig. 6), which range from approximately 30 min (e.g., Ashford) to more than 2 h (e.g., Tacoma) (Pierson, 1998). If Mount Rainier exhibited unrest or eruption, scientists would be monitoring the volcano and lahar notification could occur shortly after initiation. For lahars that occur without precursory volcanic activity, communities in the Puyallup and Carbon Rivers are served by the Mount Rainier lahar warning system. Warning of lahars detected by the system would be communicated approximately 30 min after initiation. Lahar arrival times are based on the fastest estimated times of a lahar with volumes from 10 to 100 million $m^3$. Actual times may be faster as lahar flows may have higher volumes on the order of 200 million $m^3$; however, there are limited data on behavior of these larger volume lahars (Pierson, 1998; Pierce County GIS Data Express 2009). Communities in Fig. 6 are also classified by their size (represented by the total amount of developed land within a community), allowing us to comment on relationships between community size and their vulnerability to lahar hazards.

A comparison of composite indices, lahar arrival times, and community size suggests three community clusters. Cluster A in Fig. 6 includes seven small communities (Ashford, Carbonado, Elbe, Greenwater, Orting, South Prairie, and Wilkeson) that have relatively less developed land, lower total parcel values, and fewer residents, employees, public venues, and dependent-population facilities in lahar-prone areas compared to the other communities but may have difficulties evacuating given the quick arrival time (between 0.5 and 1.2 h) and high percentages of their assets in lahar-prone areas. The five, primarily medium-sized, communities in cluster B (Fife, Puyallup, Sumner, Pacific, and Algona) have the highest relative amounts and percentages of assets in lahar-prone areas and also have greater lead times to evacuate ahead of an event, ranging from approximately 1.6 h in Sumner to 2.0 h in Fife. The majority of the remaining fifteen communities in cluster D are relatively large communities, have relatively low amounts and percentages of assets in lahar-prone areas and have the greatest amount of time prior to lahar inundation.

## 5. Discussion

An integral part of reducing and managing volcanic risk is for officials and the public to understand their vulnerability to volcanic hazards, strategies for how to modify this vulnerability, and how to react if an event occurs. To be most effective, a risk characterization should focus on a salient problem, such as minimizing life loss, economic loss, or impacts to ecosystem services (e.g., water quality, biodiversity), and not simply be an exhaustive summary of all available data that attempts to cover all aspects of vulnerability. All-encompassing assessments of societal risk to volcanic hazards are unrealistic because of the diverse, multi-scalar and multi-temporal aspects of socioeconomic systems. Some risk issues lend themselves to map-based and probabilistic assessments (e.g., structural and economic loss), while others require qualitative and subjective assessments (e.g., preparedness levels and adaptive capacity). Indicators for addressing life loss will be different than those for regional economic impact and it is questionable whether attempts to address multiple objectives in a single analysis or map help officials or distract them with disparate information. Time is an important factor when assessing risk—what matters most in the first 72 h of an event may not matter three years later when an area is still a disaster zone because of an ineffective recovery. Because of the inherent complexity, multiple scales, and multiple time horizons, an effective risk characterization should be designed in collaboration with decision makers to provide answers to officials and involved public so they may make informed decisions on specific issues (Stern and Fineburg, 1996).

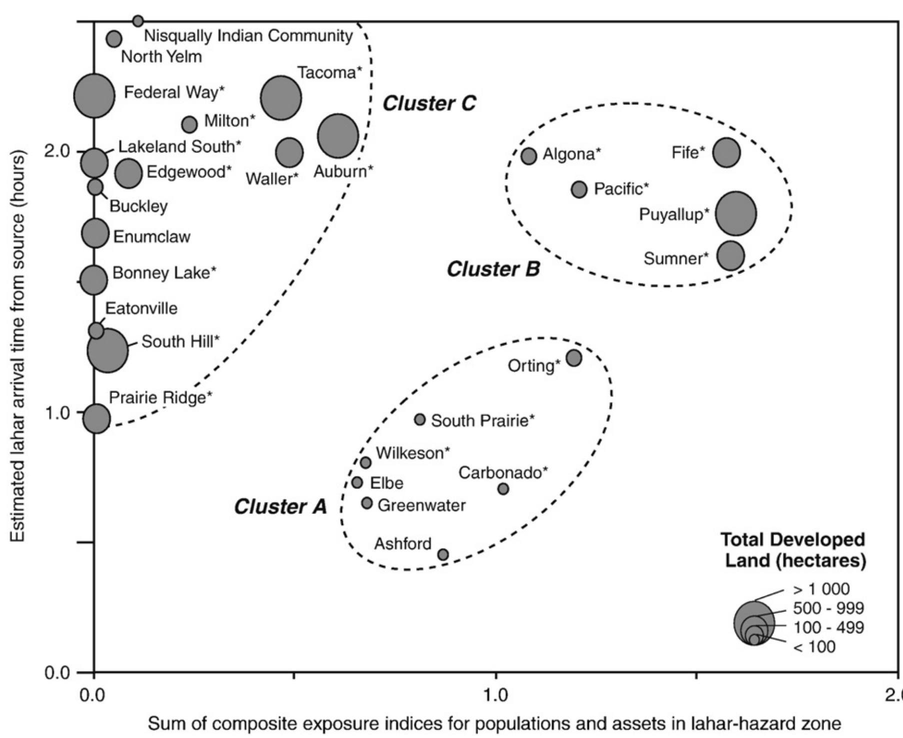


**Fig. 6.** Comparison of estimated lahar arrival times from time of initiation at source and sum of normalized amount and percentage indices for communities in the lahar-hazard zone of Mount Rainier, Washington. Communities are also identified by their total amount (in hectares) of developed land, regardless of the lahar-hazard zone. Communities with asterisks are served by the Mount Rainier lahar warning system and warning of lahars detected by the system would be communicated approximately 30 minutes after initiation.

Our choice of population exposure and related indicators described in this paper is based on discussions with State-level emergency managers to support local lahar warning, evacuation planning and education efforts. Emergency managers wished to better understand where exposed population concentrations in lahar-hazard zones were greatest and what kind of people were in these zones.

Our study indicates that population exposure varies considerably, both in terms of space and type, across the study area. The histogram of composite index scores (Fig. 4) shows that a few towns have many assets in the selected lahar-hazard zone (e.g., Puyallup, Fife, and Sumner) but there are several towns with high percentages of their assets in this area. Regardless of size, towns such as Algona, Ashford, Greenwater, Orting, and Pacific may experience similar relative impacts. Although Puyallup, Fife, and Sumner have the highest numbers of individuals in lahar-prone areas, these towns may have more than an hour to evacuate people and smaller communities with fewer people (e.g., Carbonado, Greenwater, Ashford, and South Prairie) may be at higher risk because of the short window of time they will have to evacuate (Fig. 6). Of the three community clusters in Fig. 6, we imagine the greatest difficulties in evacuating people may be in the moderately-sized communities of cluster B and the small communities of cluster A. The small communities in cluster A have high percentages of people and assets in lahar-prone areas; therefore, they will need to initiate community-wide evacuations in a short amount of time and could have no place to return to after an event. The communities in cluster B have more time to evacuate than cluster A communities, but evacuations will be challenging because of the large, mixed populations (i.e., residents, employees, dependent populations, and tourists) in the lahar-hazard zone. Emergency managers in these communities will have to contend with congestion issues to evacuate the large numbers of people and with the unique needs and challenges of a mixed population. In allocating limited risk-reduction resources and attention prior to an event, emergency managers, policymakers, and the general public must decide where to focus their energy—to the communities with high loss potentials or to communities that will have less time to evacuate their entire community and may have difficulty recovering because of the loss of significant percentages of their assets. Results reported here provide a foundation upon which additional studies of adaptive capacity can be conducted and decisions based on values and priorities can be made.

There are also significant differences among communities in the types of people that are in lahar-prone areas. The communities of Puyallup, Fife, and Sumner have high numbers and several types of people in lahar-prone areas. However, other communities with high numbers of people in these areas vary in the type of people, such as residents (e.g., Auburn), employees (e.g., Tacoma), dependent-care facilities (e.g., Puyallup), public venues (e.g., unincorporated portions of Lewis County) and residents and public venues (e.g., unincorporated areas of Pierce County). The ability of individuals to prepare for future events and take protective actions when a lahar is imminent will vary across these population groups and targeted risk-reduction strategies may be warranted to address each group's unique education and preparedness needs. The ability of public officials to quickly evacuate an area prior to lahar inundation will be influenced by whether the at-risk population is primarily homeowners trained in evacuation procedures, tourists at a public venue unaware of the potential for such events, or a special-needs population that is unable to evacuate without assistance.

Assessing where and what kind of people are in lahar-prone areas helps officials to determine the placement of warning signage and technology, to tailor the format and delivery of education efforts to reach different populations (e.g., residents, tourists, commuters, individuals who cannot speak the primary language) and to understand who may need special assistance during an evacuation (e.g., elderly populations). For example, a risk awareness and evacuation education effort designed for local residents could be implemented through existing social networks (e.g., neighborhood groups, church groups, parent–teacher associations, chamber of commerce), can rely somewhat on residents' familiarity with the area, and can include sustained training drills. In contrast, education efforts for tourists are typically limited to static information available at public venues and evacuation procedures that emphasize easily-identifiable physical landmarks. Education and preparedness training at dependent-care facilities would focus on the caregivers and their ability to move their dependents out of harm's way. Helping others will also play a large part in education efforts for employees at businesses with customers (e.g., retail trade), where employees will assume the on-site role of emergency manager to tourists likely unaware of lahar risks. Employees in the lahar-hazard zone may themselves be unaware of lahar hazards or proper evacuation strategies if they do not live in lahar-prone areas themselves, are not well connected to the community, and are reliant on business owners for information. Risk awareness and education efforts for employees at industrial businesses (Fig. 3) would ideally address the potential for hazardous materials or infrastructure (e.g., powerlines, cranes) that could obstruct or constrain an individual's ability to evacuate before an imminent lahar. Industrial businesses (e.g., manufacturing, transportation and warehousing, wholesale trade, and construction) are the primary types of businesses in the lahar-hazard zone (Fig. 3) and these worksites are likely to house heavy equipment.

Differences just within the residential population may also warrant targeted preparedness and education efforts. For example, 21% of the exposed population may miss community-based risk-reduction strategies because they live outside of the 18 incorporated cities and 9 unincorporated towns. Communities with high percentages of renter-occupied households in the lahar-hazard zone (e.g., 75% in the City of Fife) may want to identify and work with landlords and renters to ensure that they understand the potential for lahars and how to evacuate if warned. Communities with high percentages of individuals over the age of 65 years in age in the lahar-hazard (e.g., 18% in both the town of Waller and the unincorporated areas of Lewis County) may want to conduct training drills so that older residents practice evacuation routes and understand where to go if an event occurred. Practicing evacuation procedures is also helpful for communities with high numbers of dependent-care facilities (e.g., schools, day care centers).

Although there are differences in how communities are vulnerable to lahar hazards, there is some consistency across the study area with regards to development. The lack of correlation between the amount of land and the number of people in lahar-prone areas (Table 1) indicates that two communities with the same amount of lahar-prone land have, for whatever reason, made different land-use decisions on what kind of development (e.g., residential, commercial, industrial) is in these threatened areas. The same amount of lahar-prone land in two communities may be occupied by a series of homes (reflected in high residential numbers) in one community and by a manufacturing plant (reflected in high employee numbers) in the other. However, the strong correlative relationships between land and population percentages ($r^2$ values of 0.94 to 0.98; Table 1) suggest that while communities may vary in the type of development in these areas, they are not varying in the proportion of development in these areas. Regardless of community size, communities with similar percentages of land in lahar-prone areas have similar percentages of their assets in these areas. This suggests that development is fairly distributed within communities and that the lahar-hazard zones have not inhibited development. If communities were actively avoiding development in lahar-prone areas, then we would expect to see lower correlative relationships between the percentage of land and of population levels in lahar-prone areas.

## 6. Areas for future research

Although methods described in this paper provide insight on understanding population exposure and sensitivity to lahar hazards, they should be considered only first-order approximations of overall vulnerability. To complement this study, follow-up studies are needed on the adaptive capacity (or resilience) of individuals and communities to lahar hazards. With other conditions of exposure and sensitivity remaining the same, greater adaptive capacity lowers a community's vulnerability to extreme events (Turner et al., 2003; Polsky et al., 2007). For example, if two communities have the same number and types of people in lahar-prone areas, but one has a lahar education program, a well-rehearsed evacuation plan, redundant critical infrastructure, and a holistic post-disaster recovery plan, then that community is believed to have greater adaptive capacity. This capacity could result in more-efficient response operations and shorter recovery times after the extreme event. Despite similar distributions of assets in lahar-hazard zones, the same extreme natural event could mean a short-term crisis in the more resilient community and a longer-term disaster in less resilient community.

The adaptive capacity and post-disaster resilience of an individual is influenced by his or her risk perception and the degree to which someone has taken proactive actions to reduce this risk (Mileti, 1999; Slovic, 2002; Paton et al., 2008; Gaillard and Dibben, 2008). To date, there has been little work to gauge hazard perceptions and preparedness to Mount Rainier lahar hazards. Results of a 2006 survey of Orting and Puyallup residents indicate that although the majority of participants perceived lahars to be credible threats to their safety, less than one-third of them feel prepared, believe local managers are prepared, or have translated risk knowledge into risk-reduction actions (Davis et al., 2006). A 2006 survey of secondary-school students from Orting and Sumner indicates that a high percentage of students also perceived lahars as credible threats to their safety, yet only 36% of students stated their families have emergency plans (Johnston et al., 2006). These studies provide a baseline to guide further education efforts of residents in lahar-prone areas, such as the perceptions of individuals in moderately-sized communities with significant numbers of people in lahar-hazard zones (cluster B in Fig. 6) and small communities with lower exposure but smaller evacuation windows (e.g., communities in cluster A). Although the number of individuals in lahar-prone areas of cluster A communities is lower than those in Puyallup, Fife, and Sumner, the short amount of time for evacuations in these small communities requires that all individuals fully understand the hazards and risks associated with Mount Rainier lahars and how to take protective measures if a warning issued or they recognize natural cues of an imminent flow.

A second area that lends itself to further research is the distribution of tourists in lahar-prone areas. Although public venues and hotels were identified (Fig. 2) and give some insight to tourist locations, day-travel tourists are a significant issue for the region. The majority of lahar-prone land is classified as undeveloped (e.g., forest, shrub/scrub, open-space, grassland, wetlands), and these areas can attract significant numbers of recreationists, including local residents as well as tourists, who could be impacted by a lahar associated with Mount Rainier. One example is the Puyallup Fairgrounds in the City of Puyallup (Fig. 1), where daily attendance at the annual 17-day Puyallup Fair can exceed 100 000 people (Puyallup Fair & Events Center, 2009)—more than the total number of residents in the lahar-hazard zone (Fig. 2C). Twenty-five percent of Fair attendees come from outside of the four counties (Puyallup Fair & Events Center, 2009) and may not be well educated about Mount Rainier lahar hazards or prepared to react if one occurred. Another example is Mount Rainier National Park, which attracts almost two million visitors each year (Driedger and Scott, 2008). With the limited time available to evacuate and the remoteness of some lahar-prone areas, hikers and other outdoor recreationists will need to recognize natural cues indicative of an approaching flow and to take protective actions without official technology-based warnings. The U.S. National Park Service therefore provides visitors to Mount Rainier National Park (USA) with lahar-related information (e.g., printed material, wayside displays, and trailhead signs) that explain, with words and pictures, what lahars are, the sounds they make, and what to do when flows are seen or the sounds are heard (Driedger et al., 2002). Surveys of tourists to gauge hazard awareness and protective actions could help park rangers understand the likelihood of tourists being able to evacuate and the effectiveness of their education efforts.

## 7. Conclusions

This study defines and measures the types of people that occupy lahar-prone areas whether they are residents, workers, or tourists and how communities vary within lahar-prone areas of Mount Rainier. Results presented here illustrate that lahars are regional hazards that will impact communities in different ways and therefore a more regional comparative approach to assessing societal vulnerability to volcanic hazards is warranted in future efforts. Results indicate that communities vary in their exposure and sensitivity to Mount Rainier lahar hazards—some may experience great losses that reflect a small portion of their community and others may experience relatively small losses that devastate them. The dominant population type in lahar-prone areas varies across the study area—residents in some communities, employees in others, and tourists at certain public venues. Further research is needed to capture the magnitude and spatial distribution of day tourists and to gauge perceptions and preparedness levels of at-risk populations. The goal of these efforts is to better understand who is at risk from future lahars so that emergency managers can effectively educate these individuals to prepare themselves before an event and to take protective measures when warned.

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