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Comparing population exposure to multiple Washington earthquake scenarios for prioritizing loss estimation studies

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A B S T R A C T

Scenario-based, loss-estimation studies are useful for gaging potential societal impacts from earthquakes but can be challenging to undertake in areas with multiple scenarios and jurisdictions. We present a geospatial approach using various population data for comparing earthquake scenarios and jurisdictions to help emergency managers prioritize where to focus limited resources on data development and loss-estimation studies. Using 20 earthquake scenarios developed for the State of Washington (USA), we demonstrate how a population-exposure analysis across multiple jurisdictions based on Modified Mercalli Intensity (MMI) classes helps emergency managers understand and communicate where potential loss of life may be concentrated and where impacts may be more related to quality of life. Results indicate that certain well-known scenarios may directly impact the greatest number of people, whereas other, potentially lesser-known, scenarios impact fewer people but consequences could be more severe. The use of economic data to profile each jurisdiction's workforce in earthquake hazard zones also provides additional insight on at-risk populations. This approach can serve as a first step in understanding societal impacts of earthquakes and helping practitioners to efficiently use their limited risk-reduction resources.

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Introduction

There have been more than 2.5 million fatalities from earthquakes around the world since 1900 and seismic risks continue to threaten communities (Centre for Research on the Epidemiology of Disasters, 2013). Although the exact location, magnitude, and impacts of the next earthquake cannot be predicted, public officials and private citizens can implement various structural and non-structural strategies to mitigate potential damages from plausible seismic sources. Hazard assessments that delineate the possible extent and magnitude of various earthquake-related processes (e.g., ground shaking, surface rupture, liquefaction, landslides, and tsunamis) can serve as a foundation for identifying where and what type of seismic risk-reduction strategies may be warranted.

Earthquake mitigation decision making is a difficult process given the uncertainty in sources, the spatial extent of a rupture, and the variability in local site conditions. In the United States, the Disaster Mitigation Act of 2000 (Public Law 106-390, hereafter referred to as DMA, 2000) provides the legal basis for hazard mitigation planning requirements for state, local, and Indian Tribal governments. Mitigation plans approved by the U.S. Federal Emergency Management Agency (FEMA) are required for receiving certain types of hazard mitigation grant funds and other non-emergency disaster assistance. Title 44 of the Code of Federal Regulations (CFR) related to this public law outlines requirements for local mitigation planning, including a risk assessment that contains a description of a jurisdiction's vulnerability to natural hazards that can affect it (44 CFR 201.6). An optional, but encouraged, element of this analysis is an inventory of the types and numbers of existing and future buildings, infrastructure, and critical facilities located in the identified hazard areas (44 CFR 201.6 (c)(2)(ii)(A)).

One of the most prominent and commonly used tools to help guide U.S. decision makers in seismic mitigation planning is Hazus

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(FEMA, 2012), which is software that uses geographic information system (GIS) tools to graphically and quantitatively estimate physical, economic, and social impacts of earthquakes (as well as floods and hurricanes). Loss estimates can be generated based on plausible scenarios to guide mitigation or on actual source parameters of a recent earthquake to guide response and recovery operations. Hazus provides users with the ability to identify the exposure of assets (e.g., people, buildings, and building value) to seismic hazards, which satisfies the inventorying requirement outlined in the vulnerability assessment section of DMA, 2000. Examples of other earthquake loss-estimation software with similar functionality include the Global Earthquake Model (Silva, Crowley, Pagani, Monelli, & Pinho, 2013), New Zealand's Riskscape project (Schmidt et al., 2011), and several others summarized in Erdik, Sesetyan, Demircioglu, Hancilar, and Zulfikar (2010).

The accuracy of Hazus or any loss-estimation modeling approach is determined by the accuracy of its input data and uncertainties can result from an incomplete understanding of earthquake source parameters or inaccurate inventories of the built environment, demography, or economic assets. Within the Hazus modeling framework, inaccurate societal inventories can result in loss-estimation uncertainties by a factor of two or more (FEMA, 2012). Other studies have documented uncertainties in social and economic losses by a factor as high as 14 compared to observed losses in past earthquakes due to variations in source parameters (Al-Momani & Harrald, 2003; Neighbors, Cochran, Caras, & Noriega, 2013; Price et al., 2010; Remo & Pinter, 2012). These sensitivity analyses demonstrate the need for including user-supplied data in Hazus analyses, instead of solely relying on default source, site, and socioeconomic data that are supplied by FEMA.

Developing better site condition and societal data for earthquake loss-estimation studies can be resource intensive and difficult to achieve for resource-poor jurisdictions. Practitioners with resource limitations therefore need ways for determining and prioritizing where and for which seismic scenario(s) to conduct more-detailed, loss-estimation studies and where to focus their resources for improving input data. For U.S. jurisdictions, this is difficult to do with Hazus software currently for several reasons. First, Hazus analyses focus on defined study areas that do not acknowledge jurisdictional boundaries within a study area (e.g., cities within a county or across a State). If a study area with a specific seismic source contains multiple jurisdictions, a regional analysis may mask local hotspots that could benefit from local studies; yet this can only be remedied by running the software for each individual jurisdiction, which can be cumbersome and time consuming. Second, if there are multiple seismic sources across a study area, then public officials may not know which scenarios are most relevant to their jurisdiction and Hazus would need to be run multiple times, which may be cost- or time-prohibitive. Third, social impacts are primarily described in Hazus in terms of fatalities and injuries to select population types (typically resident due to data availability); however, emergency managers may wish to also know the full spectrum of population and business types that are in hazard zones to help develop targeted risk-reduction strategies that better reflect local needs and conditions. An emphasis on reporting fatalities also may eclipse the discussion of other, less fatal but more likely impacts that may be experienced by communities. For example, a scenario earthquake may be perceived as insignificant and dismissed by public officials if a loss study reports low fatalities, even though the event could significantly impact the quality of life or community functioning in a large, metropolitan area.

In light of the limitations and challenges in only using loss-estimation models to describe earthquake impacts, there have been many efforts to use population distributions relative to recorded or estimated seismic intensity. A near-real-time example of this approach at the global scale is the Prompt Assessment of Global Earthquakes for Response (PAGER) tool which integrates ambient population models and recorded earthquake intensity data to rapidly estimate the number of people exposed to various levels of ground shaking and potential fatalities (Allen et al., 2009; Earle et al., 2009; Jaiswal & Wald, 2010; Wald, Jaiswal, Marano, Bausch, & Hearne, 2010, p. 4; U.S. Geological Survey, 2014). Coarse, global population data and seismic intensity have also been used as elements in multi-criteria impact analyses that are based on historic earthquakes (Armas, 2012; Chen, Chen, Liu, & Chen, 1997). To support pre-earthquake, risk-reduction planning and mitigation at national and regional levels, there have been several efforts to characterize variations in population exposure to seismic intensity scales related to probabilistic seismic hazard maps (Nojima et al., 2013) and individual earthquake scenarios (Badal, Vazquez-Prada, & Gonzalez, 2005; Suzuki & Hayashi, 2010). Nojima et al. (2013) summarizes a national assessment in Japan of population exposure to earthquake hazards based on estimated seismic intensities and residential data inventoried in 500 m^2 cells. Suzuki and Hayashi (2010) use a similar approach but focus on just one metropolitan area (Tokyo, Japan), one earthquake scenario, and include coarser (1 km^2) residential and business data. While other efforts provide tabular and mapped inventories, Suzuki and Hayashi (2010) also qualitatively propose regional zones of similar population exposure to seismic hazards in their study area.

Previous efforts to characterize earthquake impacts using population exposure provide great insight, either as near-real-time support for response and relief operations (e.g., PAGER) or as the basis for national-level, earthquake mitigation planning (Nojima et al., 2013). However, lacking from these efforts is the ability for managers and policymakers to characterize population exposure to earthquake hazards across multiple scenarios, among multiple jurisdictions, and that includes non-residential data. Managers and especially state and federal policymakers require this level of understanding if they are to develop effective risk-reduction strategies that also efficiently use their limited mitigation resources.

The objective of this paper is to present a GIS-based approach for comparing earthquake scenarios and jurisdictions in terms of population exposure to seismic hazards. This process can help public officials understand the scope of seismic issues across a region and prioritize where to focus limited resources for scenario-based, loss-estimation studies. To demonstrate this approach, we compare population exposure in multiple jurisdictions for 20 earthquake scenarios developed for the State of Washington in the U.S. Pacific Northwest (Washington State Department of Natural Resources, 2011). We begin by demonstrating the impact of various approaches for describing earthquake ground-shaking hazards on population-exposure estimates. Second, we illustrate how spatial scale impacts the interpretation of a regional population-exposure assessment by comparing residential exposure for the 20 earthquake scenarios at the state, county, and community level. Third, we use one earthquake scenario to demonstrate other aspects of population vulnerability to earthquake hazards that can be examined to guide loss-estimation studies. Approaches and applications described here support emergency managers in their efforts to prioritize and conduct earthquake-risk assessments that yield actionable information for risk reduction.

Study area

The State of Washington (USA) has a 2010 population of 6,724,540 residents (U.S. Census Bureau, 2013a) living in 628

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