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Prototype landslide hazard map of the conterminous United States

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ABSTRACT: Landslides losses in the United States typically are excluded from private insurance policies because neither hazard nor loss can be quantified with current models. We present an empirical method to delineate areas with negligible landslide hazard as a first step towards quantitative hazard and risk assessment for insurance purposes. Economic and demographic data required for risk assessment are compiled within political boundaries, and so we depict landslide hazard using Zip Code Tabulation Areas (ZCTAs). Our prototype map combines topography from 90-m (SRTM) data with ~16,000 landslide point locations from inventories compiled for the States of Oregon; New Jersey; and New Mexico; for four counties in North Carolina; and for the San Francisco Bay region. About 30% of the conterminous US land area has some exposure to impact from landslides. The ZCTAs with negligible hazard are primarily located in the central US and along the Gulf and Atlantic coasts.

1 INTRODUCTION

The lack of private insurance for landslide damage in the U.S. results, in part, from the difficulty in estimating the probability of landslide occurrence at any particular location (Keaton & Roth 2008). Such estimates are complicated by the dependence of landslide occurrence on the probability of triggering events such as heavy rainfall or strong earthquake shaking. In addition, few landslide catalogs (e.g., Burns et al., 2011) are available for empirical or statistical analyses, and physically based prediction (e.g., Baum et al., 2010) is limited by the general paucity of geotechnical and hydrologic information on surficial materials. Keaton & Roth (2008) suggested that identifying that part of the country where the landslide hazard was essentially zero would be useful for private insurance. In those areas, insurance companies could include landslide damage coverage in “all-peril policies”, thereby creating an incentive to quantify the exposure, vulnerability, and hazard of areas with greater susceptibility. Such effort would improve the understanding of landslide hazard in general across the U.S.

Homeowner’s insurance policies generally cover common perils, such as fire and burglary, but also less common events such as aircraft impact and civil unrest. The risk of the latter two to residential property is essentially zero, and losses are frequently insured for zero additional premium, or cost to the insured. Insurance companies offer policies that cover perils with zero chance of occurrence because such policies provide a marketing advantage. When people buy insurance they want the broadest coverage possible. A method to define the parts of the country where landslide risk is zero would allow insurers to include landslides in an all-peril policy at zero additional premium. Defining such areas would also provide an incentive to develop engineering-based premiums for landslide damage in areas where the risk of landslides is non-zero. In current practice, the insurance premium rates for hurricanes, tornadoes, hail, flooding, and earthquakes are all based on engineering and science. In every case, there are geographic regions where the risk of these perils is zero according to scientific assessment, but homeowners still want the peace of mind these policies provide.

In this paper we use the term “hazard” in its restricted sense to describe the probability that an event or process of a certain magnitude occurs at a given place over a defined period of time. This usage is consistent with the U.S. National Seismic Hazard Maps (Petersen et al., 2008) that define earthquake hazards in terms of ground motions associated with a specific cumulative annual frequency or exceedence probability even in areas where the ground motions are negligible from a risk perspective.

In what follows, we describe an approach to define areas of the conterminous U.S. where the likelihood of landslide occurrence is negligible using landslide point locations and digital topography. To the first order landslide potential is controlled by topography (e.g., Taylor 1937, Savage 1994) and such data are available in a consistent manner at continental scale. We then use this map of locations where the probability of landslide occurrence approaches zero to identify ZCTAs with negligible landslide hazard. Although this is the simplest type of hazard map it can be used to identify areas where the risk from landslides is essentially zero. The maps depict two classes of landslide susceptibility and hazard and are small-scale prototypes created for the specific purposes described above. They are not intended for site-specific or regional landslide-hazard assessment.

2 LANDSLIDE AND TOPOGRAPHY DATA

2.1 *Landslide inventories*

Landslide point locations were compiled from publicly available inventories and include landslides of all types. We used inventories from New Jersey, Oregon, California, North Carolina, and New Mexico. Other landslide inventory data are available, but generally cover sparsely populated areas and are of limited spatial extent. In aggregate, the inventories we used include about 16,000 point locations of landslides, many of which damaged public or private property. The New Jersey database includes point locations of 181 landslides and dates from the beginning of the 19th century (New Jersey Geological and Water Survey, 2010). Twenty-one fatalities have been attributed to landslides in New Jersey over this period. The Oregon data set includes point locations of more than 10,000 landslides that occurred throughout the state during the previous 160 years (Burns et al., 2011). These points were compiled from a variety of sources including previously published inventories and records kept by the Oregon Department of Transportation and the City of Portland. The San Francisco Bay region database includes point locations of 415 landslides that caused damage to private or public property in the region during the winter season of 1997–98 (Godt 1999). The New Mexico dataset contains the locations of 3410 debris-flow source areas and deposits mapped at 1:500,000-scale that presumably occurred over about the last 10,000 years (Cardinali et al., 1990, Brabb et al., 1999). The North Carolina dataset contains the locations of 2824 landslide and debris-flow source areas identified from historical aerial photography taken beginning in the 1940s, field mapping, and compilation of previous studies in Macon, Henderson, Watauga, and Buncombe Counties (North Carolina Geological Survey, 2008, 2009a, b, 2011).

The spatial accuracy of the landslide locations within and among the inventories varies and depends on the accuracy of the original source data, compilation method, and precision and accuracy of the conversion to digital format. Additional error in the analysis arises from changes in land surface morphology that might have occurred between the time the landslide was located and the period when the topographic data were acquired (February 2000). For example, the North Carolina inventory was compiled from historical aerial photography using modern geographic information system (GIS) techniques and tools and is appropriate for use at scales as large as 1:6000 (e.g., North Carolina Geological Survey 2011). In contrast the New Mexico inventory was compiled at 1:100,000 from 1:31,500 and 1:58,000-scale aerial photography using analog methods (Cardinalli et al., 1990) and later digitized (Brabb et al., 1999). However, sensitivity of the analysis to any spatial error in the landslide locations is presumably mitigated by the use of a ~1-km topographic database described in the next section.

2.2 *Topographic data*

We used a topographic database derived from Shuttle Radar Topography Mission (SRTM) elevation data (Farr et al., 2007, Verdin et al., 2007). The SRTM elevation data are available globally at 3-arcsecond resolution (approximately 90 m at the equator), but the summary topographic data layers were created at a reduced resolution of 30 arcseconds (approximately 1-km). Gaps in the SRTM data were filled using weighted scaling relations developed from the higher resolution (1-arcsecond) National Elevation Dataset (NED). Topographic slope was calculated in the steepest downslope direction using the full 3-arcsecond resolution accounting for the variation in cell spacing with latitude associated with data in geographic projection (see Verdin et al., 2007 for detailed description). Relief over each 30 arc-second cell was determined by differencing the highest 3-arcsecond elevation with the lowest. The 30-arcsecond database consists of 15 data layers describing the distribution of elevation and topographic slope. The data layers used in the hazard maps described below were the 99th quantile of topographic slope and relief. Computationally, the 30-arcsecond database for the conterminous US is readily manipulated using desktop digital cartographic software yet preserves the slope and relief values calculated from the 3-arcsecond data.

2.3 *ZIP-Code data*

ZIP Code Tabulation Areas (ZCTA) are geographic regions of the United States and territories produced by the U.S. Census Bureau for tabulating statistics from the 2010 census (U.S. Census Bureau 2011). They are representations of the ZIP Code service areas of the U.S. Postal Service. They vary greatly in spatial extent and are not available for unpopulated land areas and bodies of water. Because they are linked to the addresses of households and businesses, ZCTAs are a commonly used map unit in demographic and economic studies (e.g., Krieger et al., 2003).

3 TOPOGRAPHIC STATISTICS

The 99th quantile slope and relief for each landslide point were determined using the 30-arcsecond SRTM topography database. Figure 1a shows the cumulative frequency distribution of topographic slope, binned in two-degree increments, for the landslide points in the five regions. The OR and NC landslides generally occur on the steepest slopes and the NJ landslides on slopes with the shallowest gradients. The SF and NM landslides generally occur on slopes of intermediate gradient compared to the other regions. Relief of each of the landslide locations was binned in 10-m increments. As expected, the cumulative frequency distributions of relief (Fig. 1b) generally follow the same pattern; relief and topographic slope are highly correlated at the 30-arcsecond scale of the analysis.

We arbitrarily chose the 10% cumulative frequency of both topographic slope and relief as the boundary between "negligible" and "some" landslide susceptibility. Figure 2 shows the 10% cumulative frequency of these two topographic variables for each of the five regions. A straight line between these five points can be described by the equation $y = 0.19x–0.16$, where y is topographic slope and x is relief. Obviously, this relation is valid only over this narrow range of topographic variables. The upper limit of slope values in the SRTM database for the conterminous US is about 80°, whereas slopes less than a few degrees generally are not prone to non-earthquake-induced sliding. Relief over approximately1-km^2 scale has an upper limit of about 1000 m in the conterminous US. The simple linear relation provides a means to scale topographic slope across the various landforms of the US to define regions that have negligible susceptibility to landsliding.

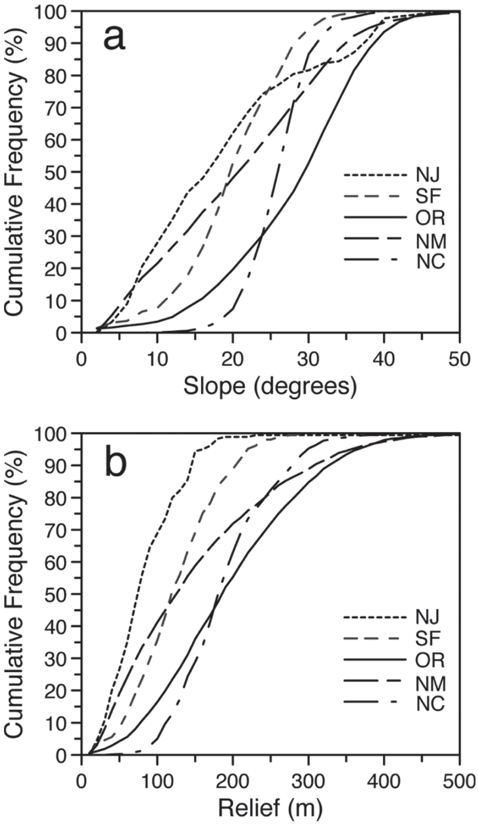

Figure 1. Cumulative frequency of (a) topographic slope binned at 2° intervals and (b) relief binned at 10-m intervals for the landslide locations in the five inventories, New Jersey (NJ), San Francisco Bay region (SF), Oregon (OR), New Mexico (NM), and North Carolina (NC).

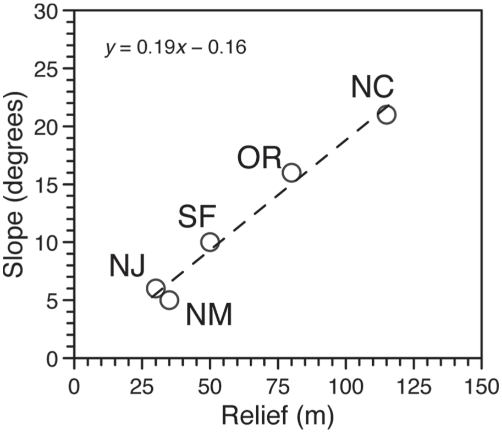

Figure 2. The 10% cumulative topographic slope and relief for the landslide locations in the five inventories and the best-fit linear relation.

We use the NJ and NM 10% cumulative slope frequency of 6° as the lower limit and choose an upper limit of 21°, consistent with the NC data. For slopes that fall within this range, we established a threshold based on relief using the linear equation above. We then compared this threshold with the 99th quantile slope from the SRTM dataset on a cell-by-cell basis. Cells with topographic slopes greater than the threshold were then classified as having "some" landslide susceptibility, and cells with topographic slopes less than the threshold were classified as having "negligible" susceptibility to landslides. For example, a 1-km grid cell with a relief of 50 m and a 99th quantile slope of 9° was classified as having negligible landslide susceptibility, as was any grid cell with a 99th quantile slope less than 6° regardless of relief. If the 99th quantile of slope for the same 50-m relief grid cell was 10°, that cell was classified as having some landslide susceptibility. Any cell with a slope greater than 21°, irrespective of the relief, was also a susceptible cell.

Landslide hazard for each ZCTA was then defined based on the presence of one or more susceptibility cells within the ZCTA boundaries; ZCTAs with no susceptibility cells have negligible landslide hazard. Because the ZCTAs vary greatly in size, the relative area covered by a single susceptibility grid cell varies greatly too. Thus, some large hazard ZCTAs may be classified as hazardous by the presence of relatively small regions of susceptibility.

4 PROTOTYPE HAZARD MAPS

Figure 3 shows the extent of landslide susceptibility in the conterminous United States. Landslide potential covers much of the western US and the Appalachian region. Large regions of negligible susceptibility in the western US are generally confined to the broad inter-montane valleys. East of about Longitude –105° the area of negligible landslide susceptibility increases abruptly. Here, landslide susceptibility is present primarily only along the slopes of river valleys that drain to the east and in isolated upland areas.

The negligible hazard ZCTAs (shown in black in Fig. 4) generally mirror the location of areas of negligible susceptibility mapped using topography (Fig. 3). Few ZCTAs in the western U.S. lie entirely in areas with negligible landslide susceptibility relative to the ZCTAs in the central and eastern US. This is a result of both the relatively greater spatial extent of the susceptibility and the relatively larger size of ZTCAs in the west. Because much of the western US is sparsely populated, the ZTCAs there tend to be large compared to the eastern US. Broad regions of negligible hazard ZCTAs are present in the central US and along the Gulf and southeastern Atlantic coasts. Scattered negligible-hazard ZCTAs are present throughout the region east of about longitude –85°.

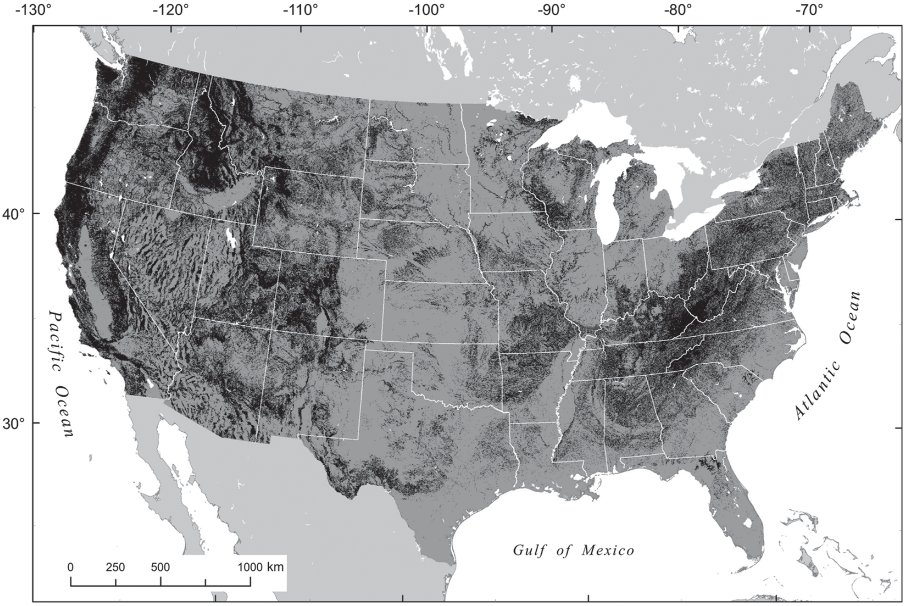

Figure 3. Prototype map showing areas of the conterminous U.S. with negligible (gray) and some (black) susceptibility to landslides.

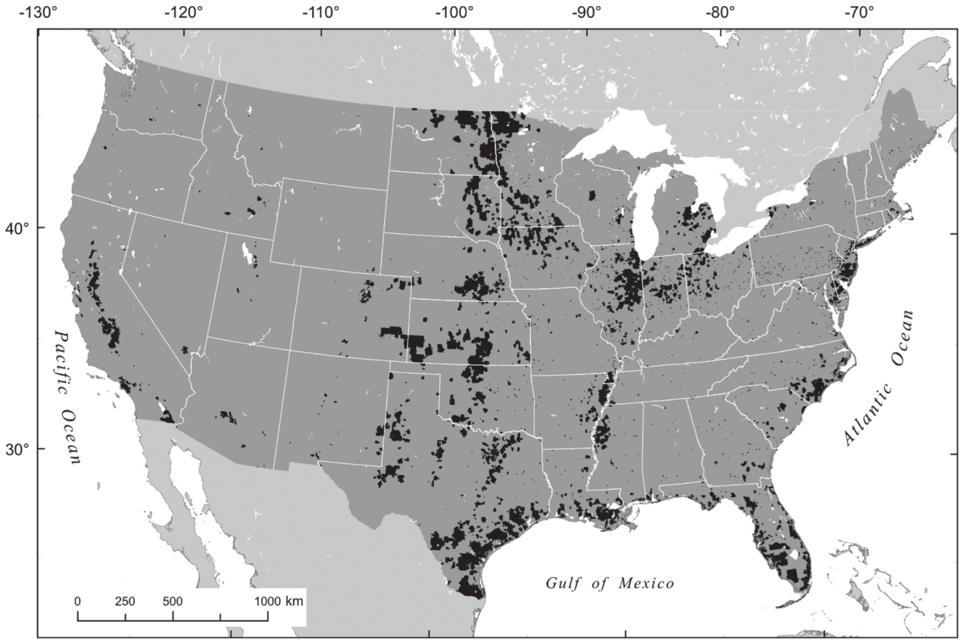

Figure 4. Prototype map showing Zip Code Tabulation Areas (ZCTAs) in the conterminous U.S. with negligible (black) landslide hazard.

5 CONCLUDING DISCUSSION

We described a consistent, objective approach to map landslide hazard at national scale. The map is the simplest form of hazard map in that it separates areas where landslide occurrence is possible from those areas where the likelihood of landslide occurrence, under any conditions, is negligible. Because it defines the regions where landslide hazard is essentially zero, it also defines the region of zero landslide risk. This method is based entirely on topography neglecting any explicit variation in landslide susceptibility as a function of groundwater conditions, geologic materials, tectonics, weathering, glacial history, climate, or land-use factors. Topographic slope and relief are the primary variables controlling the distribution of gravity-induced forces that tend to drive landslide occurrence. The other variables, save groundwater, generally describe the spatial variation in the forces resisting landslide occurrence. Including their effect would tend to reduce the overall susceptible area counter to our purpose of identifying zones of negligible landslide hazard.

The landslide susceptibility map (Fig. 3) is broadly consistent with previous efforts to map landslide incidence and susceptibility (Radbruch-Hall et al., 1982; Brabb et al., 1999). Areas with "moderate" or "high" landslide incidence on the Radbruch-Hall map generally correspond with susceptible areas shown in Figure 3. However, our map generally identifies much more of the U.S. as having some landslide susceptibility. Our map is generally consistent with the Brabb et al., (1999) national debris-flow hazard map as well, which was created in a similar manner to that described here using an earlier, globally available dataset (GTOPO30) derived from topographic contour maps.

The hazard map potentially could be improved by using higher-resolution topography, which would better identify steep slopes in low-relief landscapes. However, higher-resolution topography would also make results more sensitive to positional error of landslides in the inventories. Additional landslide inventory data are needed, particularly in the low relief areas of the central and southeastern U.S. Such data would help better define the lower bound of topographic slope where landslides present a hazard, and improve portrayal of landslide susceptibility along the shores of the Great Lakes, in urban areas such as Cincinnati, Ohio, and along the lower Mississippi River valley and east Texas where landslides have occurred on gentle slopes.

Our approach neglects any explicit description of the frequency or likelihood of triggering events such as heavy rainfall or earthquake shaking. Incorporating these factors to quantify the frequency of landslide occurrence requires moving from an empirical to a physically based approach. Although conceptually possible, application at national scale is hampered by the lack of geotechnical and hydrologic data. Clearly, landslide frequency and magnitude varies greatly across a range of scales within the "some" landslide susceptibility and hazard categories. Further work is needed to define hazard levels within this category and discriminate amongst them across the nation. In addition, the maps do not explicitly account for coastal erosion, which potentially affects any ZCTAs that border bodies of water. Finally, for clarity in presentation and limitations in the topographic data at very high latitudes, we chose not include the States and Territories outside the conterminous U.S. Nonetheless, because of generally steep terrain (e.g., Hawaii, Puerto Rico) or sparse population (Alaska) of these areas few ZCTAs there would fall into the negligible hazard category.

Refinements to our prototype hazard map will result in several zones with progressive levels of landslide hazard, similar to early earthquake hazard maps. Refinements will require improved methods to quantify landslide intensity and frequency at finer spatial scales, and to quantify the performance of structures and buried utilities impacted by slides. Additional loss data, such as those collected in the San Francisco Bay region (Crovelli and Coe, 2009), also are needed. We suggest that the ZCTAs will be useful for transforming landslide hazard into landslide risk because building inventories and demographic data are compiled using these map units.

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