



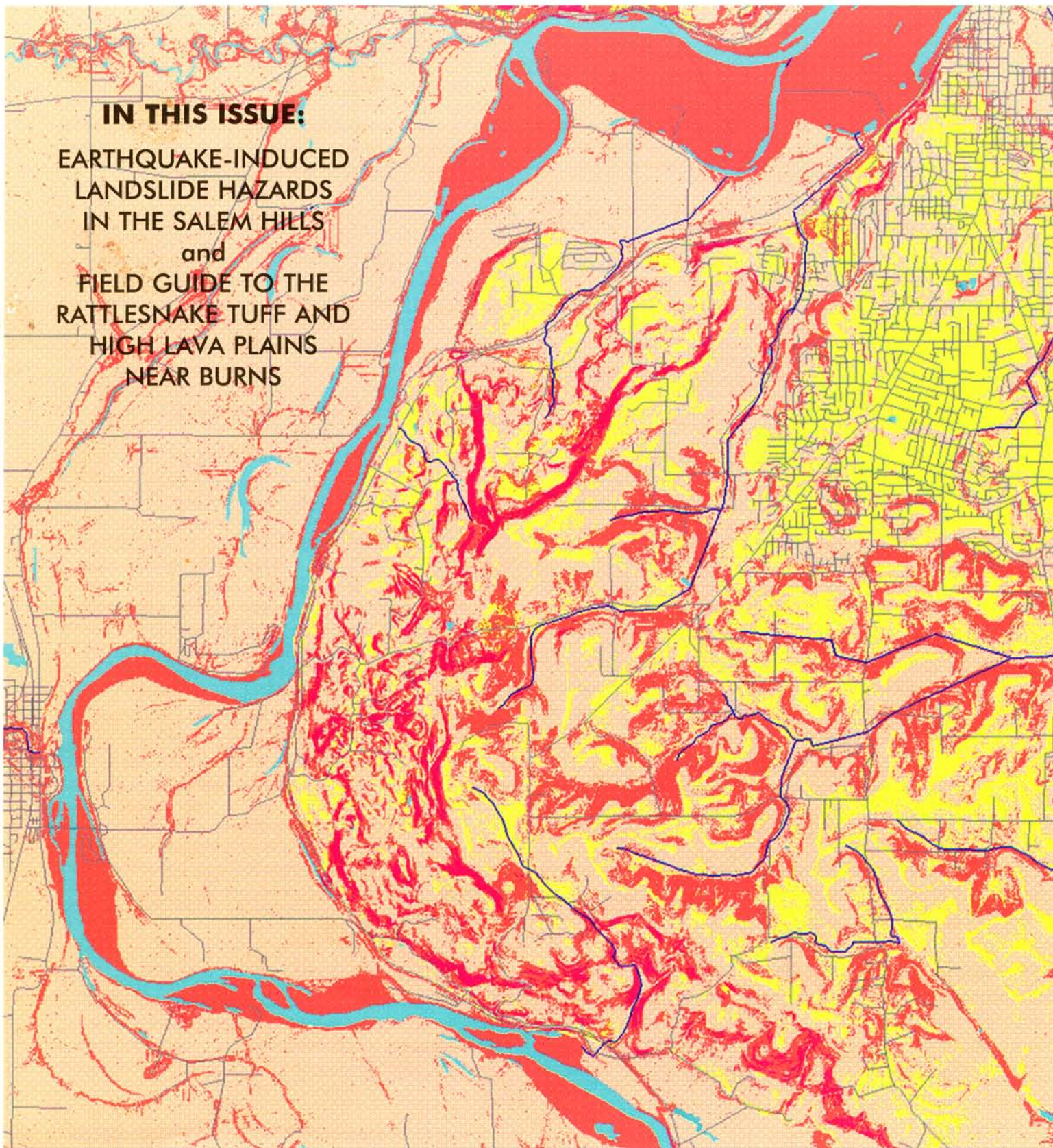
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Earthquake-induced slope instability: A relative hazard map for the vicinity of the Salem Hills, Oregon

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INTRODUCTION

Public and private agencies that create regional hazard maps can benefit from the use of a standardized regional hazard mapping methodology. The methodology should be uniform yet flexible enough to remain appropriate for, and verifiable across, vast and geographically diverse regions. The ideal is to produce the most accurate maps possible (that is, the best predictors of high-risk versus low-risk areas) in the least amount of time and at the lowest cost.

A recently-developed methodology by David Keefer of the United States Geological Survey (USGS) and Yumei Wang of the Oregon Department of Geology and Mineral Industries (DOGAMI) is aimed at this ideal in evaluating slope stability hazards on a regional scale (Keefer and Wang, 1997). Their methodology is specifically intended for implementation using Geographic Information Systems (GIS) and utilizes common methods for scientific and engineering analysis of slope stability.

The Salem study presented here is the second project employing that methodology. The first was a study for the Eugene-Springfield metropolitan area in Lane County, Oregon (Wang and others, 1998; Black and others, 1999).

This project had two primary objectives:

1. To implement and evaluate the methodology for assessing regional earthquake-induced slope instability by Keefer and Wang (1997) and to refine the method, where applicable, for subsequent regional mapping efforts in Oregon and elsewhere.
2. To create the most accurate and representative hazard map feasible for earthquake-induced slope instability in the Salem Hills vicinity, given the existing time and economic constraints.

The resulting hazard map provides a rational basis for evaluating the spatial variability of landslide hazards within the Salem area. The calculations were performed with GIS tools and a 10×10 m grid spacing, and the final hazard map depicts zones of *Very Low*, *Low*, *Moderate*, and *High* potential for earthquake-induced slope instability.

The map is intended to help guide regional decisions by planners, emergency management officials, and others responsible for planning and implementing measures aimed at minimizing potential loss of life and property damage from future earthquake events.

BACKGROUND

Salem is the third largest city in Oregon. As population growth has expanded city boundaries, new development has spread into the marginal, steeper areas south of downtown Salem, including the Salem Hills area, and is expected to accelerate. Slope instability hazards are of particular concern in the area. Several rainfall-induced slides have recently caused damage to development in the study region. Extensive portions of the Salem Hills vicinity, particularly along the north and west flanks, are characterized by jumbled, "hummocky" terrain that resulted from major historical landslide events. These features are a noteworthy reminder that the area has been unstable in the past and that portions will inevitably move again in the future.

This project focuses on seismic slope stability hazards in the Salem study area. The Oregon Emergency Management Office has received funding from the Federal Emergency Management Agency (FEMA) for a complementary project to evaluate

rainfall-induced landslide hazards in the Salem Hills. That funding is being used by DOGAMI, the City of Salem, and Marion County to study the hazards in the Salem area and develop mitigation measures to reduce future losses. The characterization of precipitation-induced landslide hazards was contracted to Squier Associates, a geotechnical engineering firm based in Lake Oswego, Oregon. Results have been released as DOGAMI Interpretive Map Series map IMS-6 (Harvey and Peterson, 1998), a generalized hazard map depicting relative hazard zones from 1 to 6 (low to high susceptibility) and associated text outlining development recommendations for each zone (Harvey and Peterson, 1998).

The study region used for this study of earthquake-induced slope instability includes the area analyzed for rainfall-induced landslide hazards, and the two maps should serve as useful complements for evaluating critical hazard areas in the Salem vicinity.

This project builds upon previous earthquake hazard mapping in the Salem area published by DOGAMI in 1996 (Wang and Leonard, 1996). The Wang and Leonard analysis included an evaluation of ground shaking amplification, landslide, and liquefaction hazards in the Salem East and Salem West 7½-minute quadrangles. Those quadrangles overlap the northern portion of the region evaluated in this new study. The landslide hazard categories in the Wang and Leonard project were purely a function of calculated slope angles. In addition to expanding the geographic area mapped, the current study bolsters the slope stability portion of the earlier analysis by augmenting topographic data with soil property and other physical data to

further differentiate areas of relative hazard within the critical Salem Hills vicinity.

METHODOLOGY

The Salem Hills study area includes some challenging and complex geologic conditions that provide a unique opportunity to test the methodology introduced by Keefer and Wang (1997). Field evaluation by David Keefer of the USGS, Yumei Wang of DOGAMI, consulting geologist Robert Murray, and myself in March 1998 verified both the geologic complexity as well as the geographic importance of the study region.

Keefer and Wang methodology

The Keefer and Wang methodology uses three different methods to evaluate overall earthquake-induced slope stability hazard. The purpose in separating the analysis into three distinct facets is to account for the range of commonly observed modes of slope failure in earthquake events.

Steep slopes (generally rock) tend to fail as rock falls, rock slides, and debris slides (Keefer, 1984).

Moderate slopes (generally soil) most often fail as translational block slides and rotational slumps (Keefer, 1984).

For more gently sloping topography, the soil and rock slope hazards are usually lower, but in regions with saturated granular materials, liquefaction-induced lateral spread displacements can be significant.

The engineering and scientific methods differ depending on whether rock-slope, soil-slope, or lateral-spread hazards are evaluated.

Since all three hazards may be present in a regional study, different methods are selected for modeling each of these hazards. The choice also takes into account technical merit and applicability for regional GIS analysis.

For steep rock slopes, an empirical decision tree developed by Keefer (1993) is used. The method is based on empirical correlations between recorded landslide concentrations (number of landslides per km²) and material properties such as degree of weathering, cementation, fracture spacing and openness, and degree of saturation.

Moderate soil slopes are evaluated by means of a simplified Newmark sliding block analysis (Newmark, 1965) adapted for natural slopes by Jibson (1993).

For evaluating lateral spread hazard, an empirical relationship based on a regression analysis by Bartlett and Youd (1995) is used to establish relative hazard categories.

The results from these three methods of analysis are combined to create an overall relative slope instability hazard map.

Keefer and Wang proposed using slope groupings of <5°, 5°–25°, and >25° to differentiate between gentle, moderate, and steep slopes, respectively, and select the appropriate hazard analysis model. Table 1 summarizes the methods of analysis by slope group.

In the Keefer and Wang methodology, no analytical techniques are applied to mapped landslide areas, but these areas are assigned a "very high" hazard rating.

Application in the Salem Hills

The approach implemented in this study maintains the intent of the grouping into "gentle, moderate, and steep" slopes, but the methodology is slightly modified. Changes for the Salem study include the following:

1. A 6-percent (=3.4°) slope value is used to distinguish between "gentle" and "moderate" slope groups, rather than the 5° (=8.75 percent) break used by Keefer and Wang (1997). The 6-percent value corresponds to the maximum slope used in the regression analysis performed by Bartlett and Youd (1995).
2. The 6-percent slope value does not function as a strict cutoff between the Bartlett and Youd and simplified Newmark analyses. Lateral spread hazards may be significant on steeper slopes, particularly along cut banks in river and stream channels. Therefore, lateral spread hazard ratings are assigned to all susceptible sedimentary deposits, including those with calculated slopes of >6 percent.
3. The simplified Newmark analysis is used to evaluate all soil deposits, including some sites with slopes of <6 percent and some sites with slopes of >25°.
4. Steep-slope cutoff values are incorporated in the simplified Newmark analysis to ensure reasonably conservative hazard ratings in steep terrain.
5. Mapped preexisting landslide areas are assigned reduced residual strength values and are then analyzed with the simplified Newmark method. Large portions of the northern and western flanks of the Salem Hills have experienced movement in the past.

Table 1. Summary of hazard analysis methodology by slope group (adapted from Keefer and Wang (1997))

	Gentle Slopes	Moderate Slopes	Steep Slopes
Typical materials	Loosely-consolidated sediments	Semi-consolidated soils	Rock
Dominant hazard	Liquefaction-induced lateral spread	Soil slides	Rock falls, rock slides and debris slides
Analysis method based on:	Regression analysis by Bartlett and Youd (1995)	Simplified Newmark Sliding Block analysis adapted by Jibson (1993)	Decision tree analysis by Keefer (1993)

Grouping these regions into a uniform high-hazard category does not provide information on relative hazards within these extensive zones and would limit the usefulness of the final hazard map for planning and other uses. Incorporating a strength reduction factor and performing the simplified Newmark method allows the inclusion of other parameters, such as slope and material property variations, and the differentiation of the relative hazards within these important zones.

These modifications result in dual hazard analyses for some slopes, and as a result there is a less obvious differentiation between the three modes of slope failure being modeled. These changes, however, expand the applicability of the methodology and ensure that each area is analyzed for all potential hazards that may be relevant. Figure 1 presents a schematic flow chart of the Keefer and Wang methodology as modified for this study.

Four general steps are designated on the flow chart. The first step outlined is to select the applicable regions for each hazard type (lateral

spread, soil slide, and rock slope). This step involves a consideration of the types of materials that are susceptible to each of the hazard groups. It also requires an evaluation of the best and most appropriate sources of information for each method of analysis.

After gathering the information available for the study area, the next general step is to assign the corresponding input parameters for each of the three analytical techniques and perform the analyses. This is the most time consuming and difficult portion of the method and depends greatly on the nature and resolution of the data available within a given study region. For this study, a lateral spread analysis using equations developed by Bartlett and Youd (1995) is performed for all Quaternary sedimentary deposits delineated on a surface geologic map. The soil slide analysis, based on a simplified Newmark analysis (Jibson, 1993), is performed for all soil units contained in databases obtained from the Natural Resource Conservation Service (NRCS). The rock slope analysis, based on a deci-

sion tree developed by Keefer (Keefer, 1993), is performed for all bedrock units on the geologic map with calculated slopes $>25^\circ$.

The final steps outlined on the flow chart include translating the outputs from each analysis into relative hazard ratings, then combining the results to generate an overall hazard map. These steps require the application of good professional judgement and depend to some extent on the particulars of the region being analyzed. For this study, the three hazard types are first evaluated as separate data layers, then combined to create an overall map of earthquake-induced slope instability.

STUDY REGION

The size of the study region is approximately 13.5 km (8.4 mi) north/south by 12.3 km (7.6 mi) east/west. This region includes the southwest portion of the Salem urban growth boundary. Figure 2 is a map showing the location of the study area, and Figure 3 shows some of the local political boundaries. The Willamette River divides Polk County on the west from Marion County on the east. The

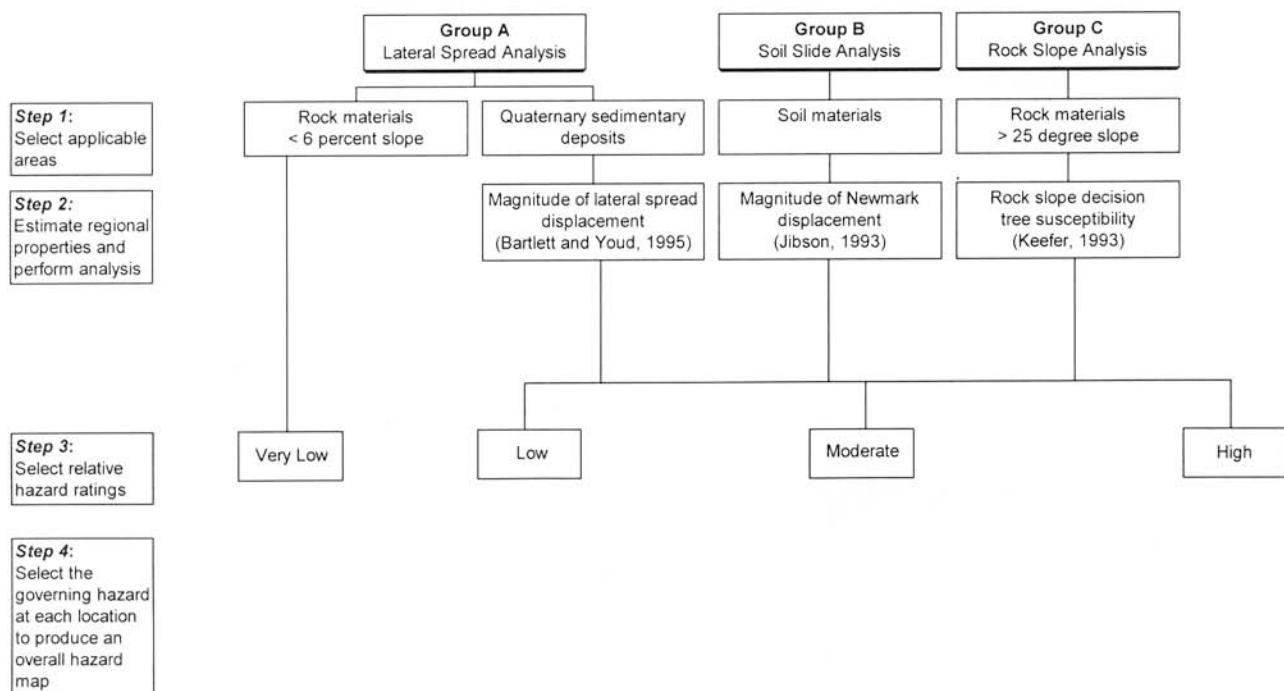


Figure 1. Flow chart showing method of hazard ratings as modified from Keefer and Wang (1997).

topography is predominately flat in the low-lying alluvial plains in the western portion of the study area, with moderate-to-steep slopes in the Salem Hills area to the east. Elevations range from approximately 38 m (125 ft) along the banks of the Willamette River to 345 m (1,130 ft) in the Salem Hills.



Figure 2. Vicinity map showing location of Salem Hills study area.

Extensive portions of the west and south sides of the Salem Hills are mapped as "landslide topography" by Bela (1981). The landslide terrain is distinguished by weathered headscarps, hummocky topography, mixed geologic materials, translated blocks of bedrock, interspersed sag ponds, and complex drainage patterns. The upslope topography of the eastern portion of the study area is marked by more regular topography and drainage patterns.

Active seismic setting

The Willamette Valley is located approximately 150 km inland from the Cascadia subduction zone, a convergent plate boundary where the Juan de Fuca plate is being subducted beneath the North American plate (Figure 4). Similar environments exist off the coasts of Japan, Mexico, Alaska, and Chile, where the largest earthquakes have occurred in recorded history. Three potential earthquake sources are associated with colliding tectonic plates: subduction zone, intraplate, and crustal events. Subduction zone earthquakes occur along the interface between the overriding North American plate and the subducting Juan de Fuca plate. Deep events

that occur within the subducting Juan de Fuca slab are referred to as intraplate events. Intraplate events are associated with internal deformation and volume changes due to high temperature and pressure gradients within the earth's crust. The third potential source for earthquakes in the Pacific Northwest is associated with deformation within the overriding North American plate. These events, referred to as crustal earthquakes, occur at shallower depths (typically 10 to 20 km) and are usually associated with fault zones within the crust.

In the Pacific Northwest, as in other similar settings, a great deal of uncertainty limits estimating the size and location of future earthquakes, because the events are infrequent and the mechanisms are not fully understood. Using the best available methods, this study includes estimates of probable magnitude (M) and source-to-site distance (R) to evaluate subduction, intraplate, and crustal sources that could affect the study area.

SOURCE DATA AND ANALYSIS

The Salem Hills study area was selected, in part, because of the range of available and usable geologic, topographic, and geotechnical data. In preparation for and throughout the analysis, a number of data sources

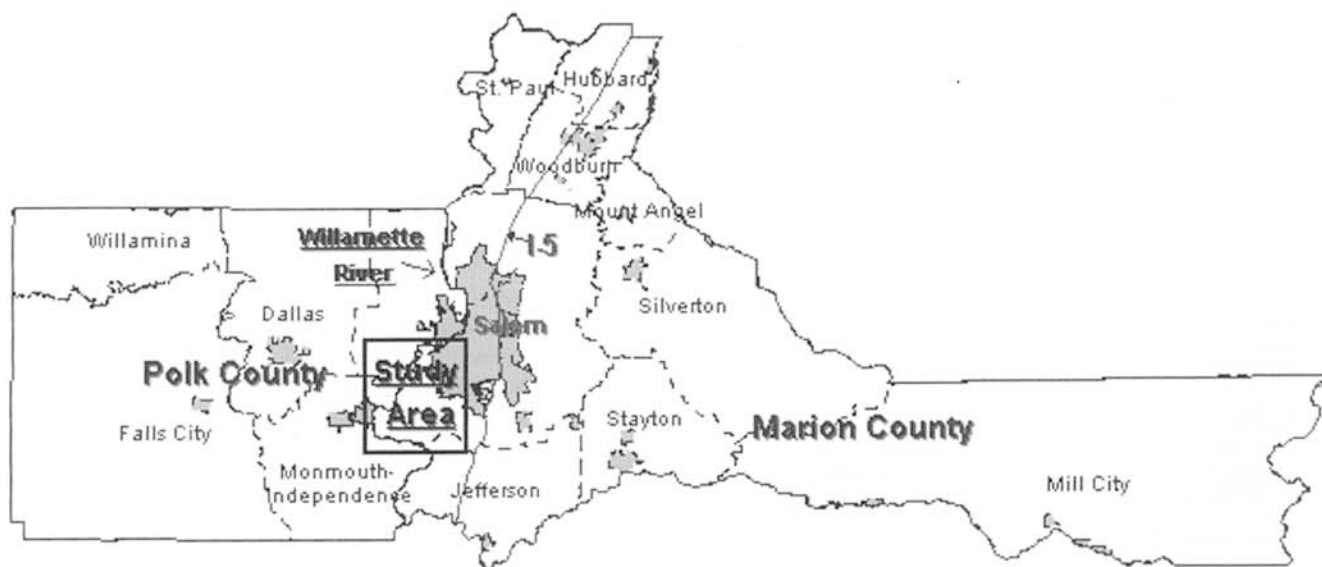


Figure 3. Outline of local political boundaries for the Salem Hills study area.

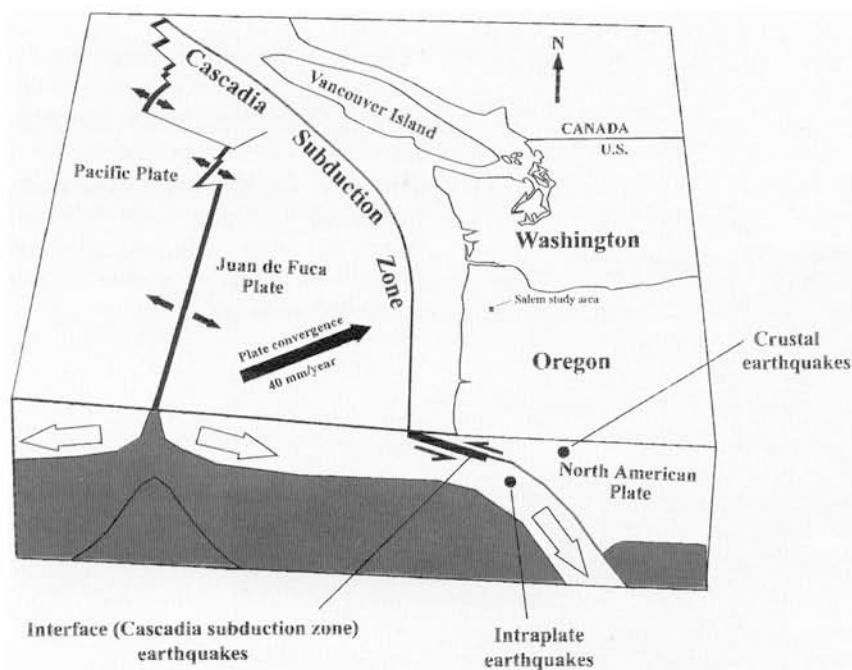


Figure 4: Schematic of the Cascadia subduction zone showing typical locations for the three types of earthquake sources in the Pacific Northwest.

was utilized. These are summarized below, organized by subject. Solid bullets (●) indicate that information from these sources was either available in digital form or was converted to digital form.

Topographic data

- 1:24,000-scale USGS 7.5-minute topographic map series (10-ft contour interval)
- DOGAMI 10-m Digital Elevation Model (DEM¹)
- USGS 30-m DEMs

Geology/soils

- 1:24,000-scale DOGAMI geologic map GMS-18
- Geologic information in Burns and others (1992), McDowell (1991), Crenna and others (1994), and Wang and Leonard (1996)
- USDA Soil Conservation Service [now Natural Resource Conservation Service] map of Polk County (Knezevich, 1982)

- USDA Soil Conservation Service map of Marion County (Williams, 1972)
- Oregon Water Resources Department water-well database
- Borehole and laboratory data collected by DOGAMI

Other sources

- U.S. Army Corps of Engineers Color Infrared (CIR) photographs, scale 1:30,000, taken September 11, 1979
- Black-and-white aerial photographs, scale 1:48,000, taken April 6, 1986
- Geotechnical consultant reports collected by DOGAMI

For this project, the Keefer and Wang (1997) methodology, modified as described above, was implemented mainly with the GIS application MapInfo. GIS applications are specifically designed for working with geographic databases and manipulating spatial data. With the GIS application, various layers of information can be overlaid, combined, and analyzed accurately and efficiently. The combination of spatial data, databases, and analytical tools allows for convenient updat-

ing and modifying of spatial databases within one environment.

Several other applications were used in conjunction with MapInfo, including Vertical Mapper, 3D Mapps, ArcView, and IDRISI (Eastman, 1990,1993).

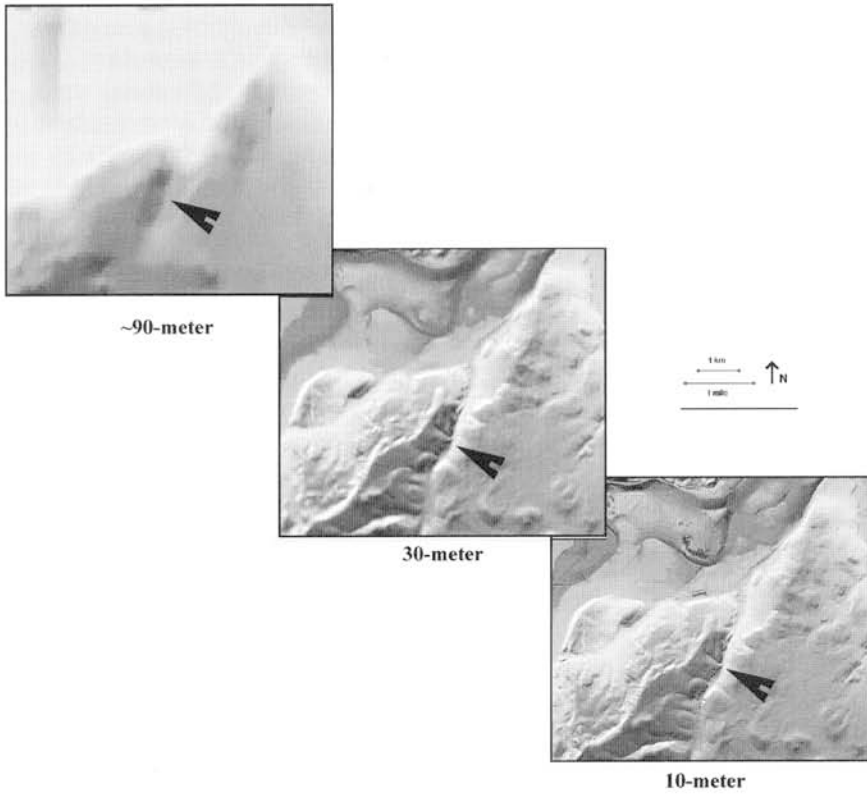
For working with digital spatial information within a GIS, resolution of the data is an important consideration. For the topographic data, DEM with a 10-m grid spacing was used. An illustration of the significance of resolution is shown in Figure 5, where 10-m, 30-m, and approximately 90-m DEMs of the same area are shown side by side. A superimposed arrow points out a southwest-northeast-trending drainage ditch that is visible in the 10-m DEM, but is difficult to distinguish in the 90-m elevation file due to the larger sample spacing.

While the 90-m and 30-m DEMs are USGS products that have been produced for most of the United States, 10-m DEMs are not as widely available. For the Salem study area, DOGAMI funded the creation of a 10-m DEM from the 10-ft contour interval topographic quadrangles of the USGS. A shaded-relief map derived from the DOGAMI DEM is shown in Figure 6.

With the 10-m DEM as basis, the GIS program Vertical Mapper was used for the generation of a slope map (Figure 7). The calculated slope values are stored at the same grid points as the original DEM. The slope map, then, served as the database used for reporting hazard values. It was overlaid on both the geology and soils map layers, and the properties associated with each were assigned to the slope map grid points. A schematic of the GIS overlay operation to create a single database with slope, geology, and soils data stored at grid points is shown in Figure 8. The subsequent hazard analyses outlined in the following sections were performed on this combined data file, with values stored at a 10-m grid spacing throughout the study area.

(Continued on page 62)

¹ A DEM is a regularly spaced series of points (a grid) with an elevation value and geographic coordinates (e.g., latitude, longitude) stored for each point. Grid spacing is the distance between the points.



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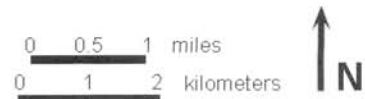
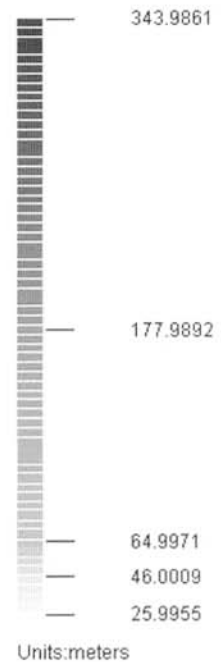
Figure 5: Resolution comparison between a USGS 1:250,000-scale (~90-meter grid spacing), USGS 1:24,000-scale (30-M=meter) and the 10-meter DEM used for the Salem Hills study. The arrows mark a drainage ditch that stands out in the 10- and 30-meter DEMs but is barely visible in the 1:250,000-scale USGS file.

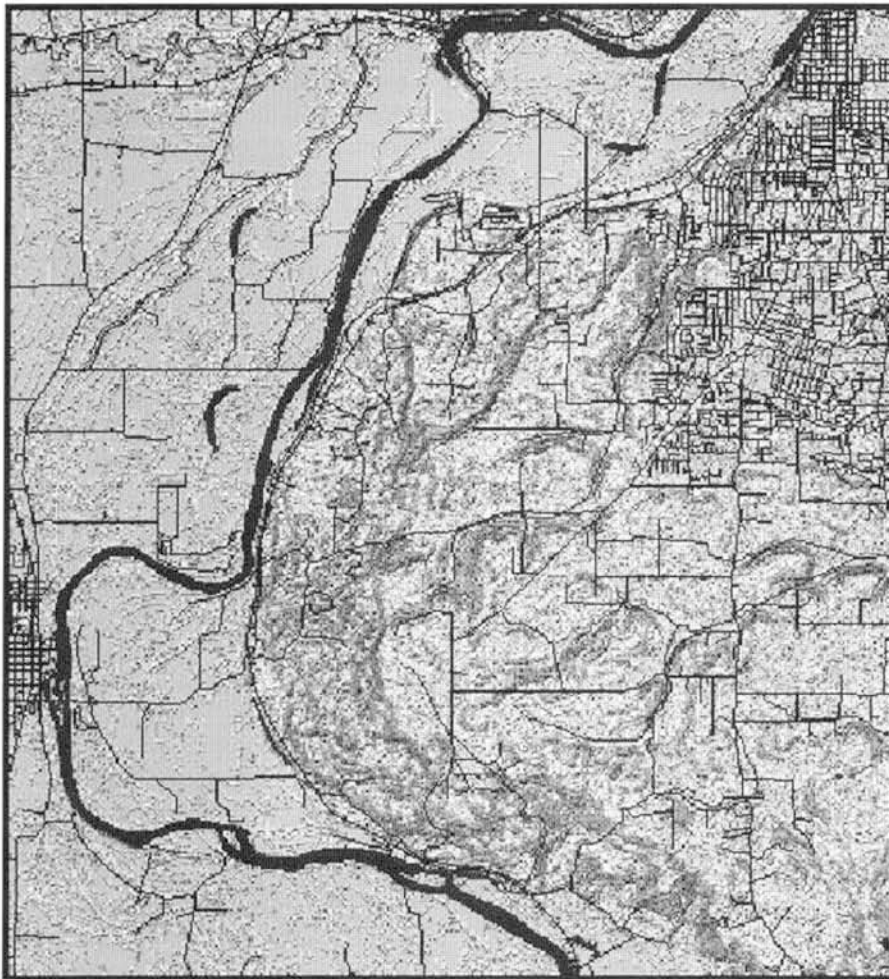
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Figure 6: Shaded relief map from the 10-meter DEM used for the Salem Hills study area.

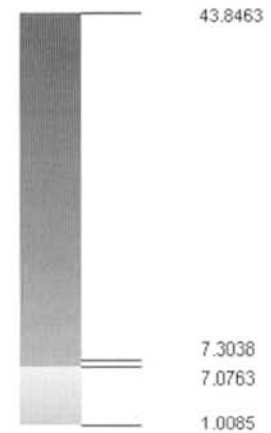


Salem Hills Digital Elevation Model (DEM)





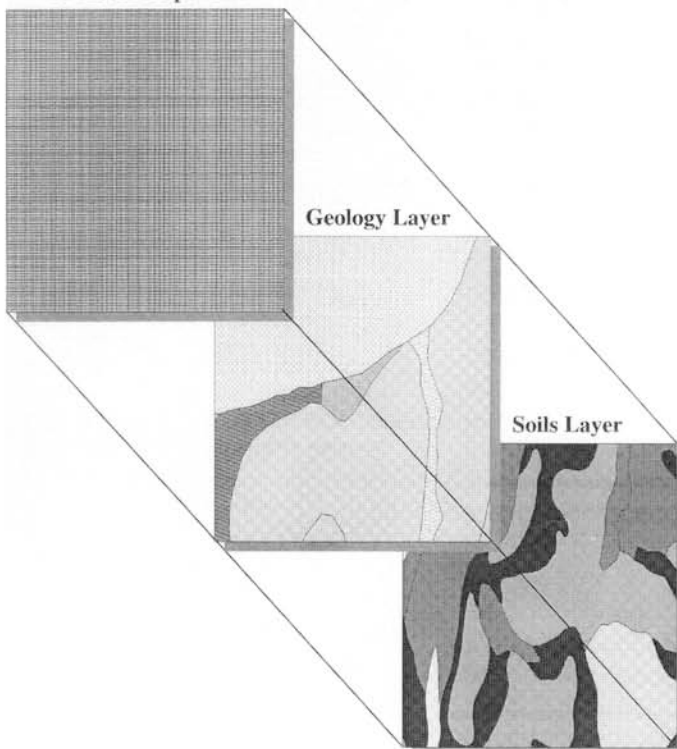
Salem Hills Slope Map



(Units: Degrees)



10-meter Slope Grid



↑ Above:

Figure 7: Slope map for the Salem Hills study area.

← Left:

Figure 8: Schematic of the GIS overlay operation to create a single database with slope geology and soils data stored at grid points with 10-meter spacing.

Database with Slope and Material Properties

Global_ID	Slope_deg	Geo_Unit	Geo_Modifier	Soil_Unit	Total_Stress	Effective_Stress	Cohesion	Phi_Angle
1	2.5333	Qm		21	46.3324	20.9162	22.5036	0
2	4.6442	Qm	LS_Slope	20	51.053	24.8897	28.728	0
3	2.2225	Qm		25	46.0036	24.1731	22.5036	0
4	3.4444	Qm		77A	48.19	28.7544	28.728	0
5	1.3342	Qm		14	48.2496	48.2496	28.728	0
6	2.6528	Qm	LS_Slope	20	51.053	24.8897	28.728	0
7	3.6643	Qm	LS_Slope	33	46.8143	25.4412	22.5036	0
8	2.8736	Qm		20	51.053	24.8897	28.728	0
9	1.6278	Qm		77A	48.19	28.7544	28.728	0
10	1.9962	Qm		45	47.5783	47.5783	28.728	0
11	2.0023	Qm		20	51.053	24.8897	28.728	0
12	2.4567	Qm	LS_Slope	77A	48.19	28.7544	28.728	0
13	2.8892	Qm		20	51.053	24.8897	28.728	0
14	3.0356	Qm		20	51.053	24.8897	28.728	0
15	3.6723	Qm		3	47.3416	23.4209	28.728	0
16	3.9818	Qm		3	47.3416	23.4209	28.728	0
17	4.0561	Qm		20	51.053	24.8897	28.728	0
18	3.8714	Qm		3	47.3416	23.4209	28.728	0
19	3.5912	Qm		20	51.053	24.8897	28.728	0

(Continued from page 59)

A more detailed discussion of analyses performed and equations used for the analyses of lateral spread, soil slide, and rock slope is found in the respective sections of DOGAMI Special Paper 30 (Hofmeister, 1999).

SUMMARY OF RESULTS

The relative hazard map of earthquake-induced slope instability of the Salem Hills vicinity (shown in Figure 9) is the combination of the lateral spread, soil slide, and steep slope analysis maps. The overall map delineates hazard zones, using a simple, relative scale from "Very Low" to "High." The hazard ratings in the Salem Hills portion of the study area are governed primarily by the soil slide and the rock slope susceptibility ratings. For the more gently sloping alluvial deposits in the low-lying areas, the hazard ratings primarily reflect the lateral spread hazard ratings.

The relative nature of the hazard ratings needs to be emphasized. Developing the scale of hazard zones includes using potential earthquake scenarios and includes a number of regional assumptions. The extent and severity of slope instability that occurs during an actual earthquake depends on the size and location of the event. A hazard rating of "high" does not necessarily mean that a slope will fail in any earthquake, and a rating of "very low" does not mean that there is no potential for movement. In a large earthquake event, there may, in fact, be instability in zones of moderate, low, and very low hazard as well as in a high hazard zone. In small earthquakes, only slight damage may occur even in zones of high hazard. In general, however, one would expect a higher percentage of earthquake-induced ground failures in "high" zones than in the "moderate," "low" and "very low" zones in any given earthquake event.

While a relative hazard map cannot serve as a replacement for site-specific studies in critical areas, it can, and should, serve as a useful tool for estimating the regional impact of fu-

ture earthquake events. Creation of a regional hazard map is an initial step, which ideally is followed by hazard mitigation programs that focus efforts on the higher risk areas. Realistic evaluations of relative hazards are vital for planning and development, for emergency response management, as inputs for damage and loss estimations, and in making informed land use decisions. Potential users may include public policy makers, land use planners, civil engineers, developers, insurance adjusters, public safety officials, home owners, and home buyers, to name a few.

The Salem area is growing at a rapid rate; some predict it may soon surpass Eugene to become Oregon's second-most-populated urban area. In recent years, residential and commercial development has steadily expanded southward, and this study covers an area that is likely to experience increased development in the near future. This map is intended to be used in conjunction with other available resources to make informed decisions regarding regional development as well as retrofit or other mitigation measures to limit loss of life and property damage in future earthquake events.

The Keefer and Wang (1997) methodology, slightly modified for this study, proves to be one of the most promising approaches available for the accurate mapping of earthquake-induced slope instability hazards within reasonable time and cost limits. The successful completion of this study advances the ongoing efforts by DOGAMI to map hazards in major population areas statewide. A mapping project is now underway in Klamath Falls, and future studies are expected in Klamath and Tillamook Counties.

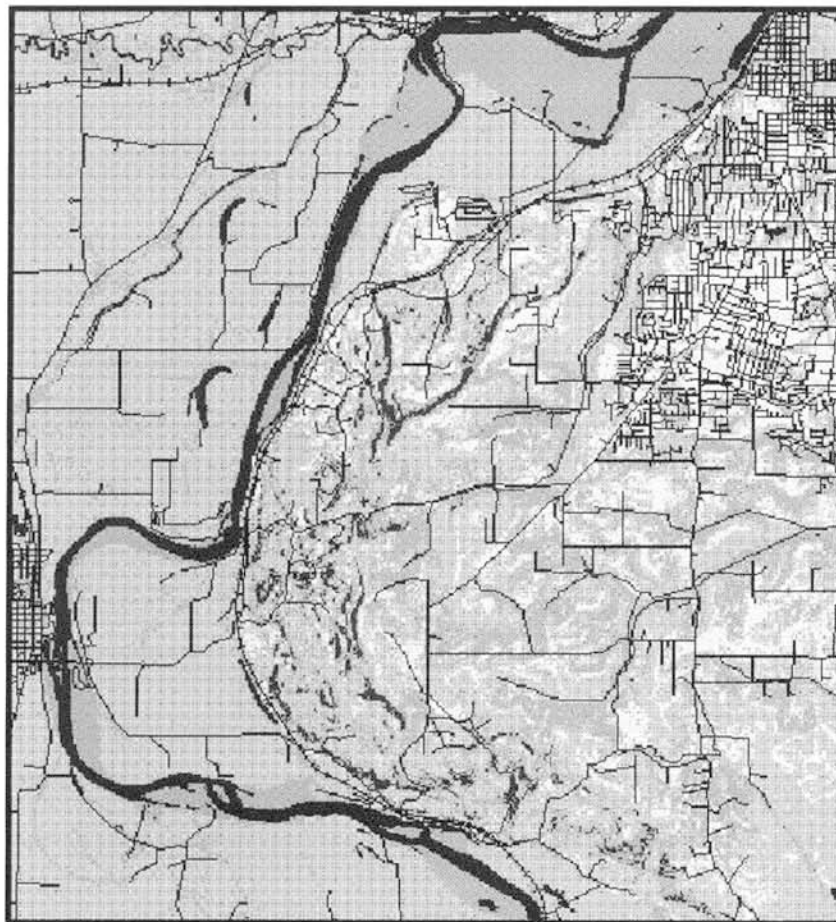
ACKNOWLEDGMENTS

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Relative Earthquake-Induced Slope Instability Hazard Map of the Salem Hills Vicinity, Oregon 1998

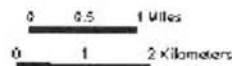
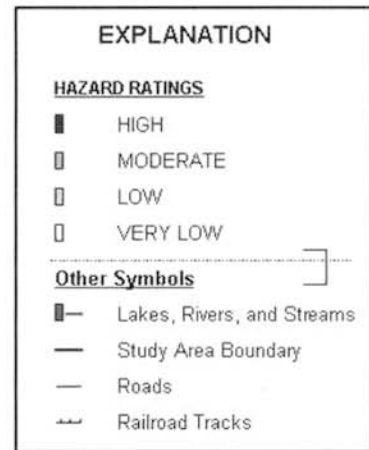


Figure 9: Overall hazard layer for the Salem Hills study area, with gray shades instead of color for ratings in original map.

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