Landslides geohazard map for Portland, Oregon, USA

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Abstract: After a large precipitation event, the 6th-9th of February 1996, when 20 centimetres of rain fell in four days in Portland, Oregon, our research team mapped 705 landslides in the area. This was a 100-year event climatically for landslides so we wanted to make sure we got a clear impression of the causes of the landslides. From the data of the survey we constructed a landslide hazard map that is now used in land use planning. Each landslide was described using 20 different criteria such as volume, dimension, scarp height, process, geology, soils, and slope angle. The landslides fell into mainly four zones. The West Hills Silt Soil Province had 374 landslides that were mainly earthflows less than 500 cubic metres in size because the parent material is mainly loess and ML soils. Mitigation of most of these slides was mainly from gabion walls, which have been very successful. The Fine-grained Troutdale Province of southeast Portland had 72 landslides that were mainly reactivations of larger earthflows and slumps. Movement occurred along clay and silt layers in these flat-lying fluvial deposits. Mitigation was difficult in most cases because the slides were so large. The Steep Bluffs Along Rivers Province produced 40 shallow translational slides. They occurred where there had been recent cutting of the trees, where recent dumping of soils onto the slopes had increased the driving forces, and where springs from Missoula flood deposits concentrated water on the slopes. Mitigation mainly focused on planning – getting people to stop dumping on the slopes, not cutting trees down, and putting drains where there were springs. The Debris Flows in Valley Bottoms Province is mainly in north Portland along the Columbia River. Debris flows were the main process that occurred in these bedrock streams. Over 45 debris flows were mapped. They occurred mainly where thick deposits of colluvium had been liberated in the heads of the streams and produced slurries that deposited on fans along the river. Mitigation mainly is by land use planning and prohibiting people from building along the channels and on the fans. The geohazard map is now used for building permits. A piece of property in one of the four zones has to be investigated by a Certified Engineering Geologist to make sure that the landslide dangers are not there.

Résumé: Après un grand événement de précipitation, le 6ème-9ème février 1996, quand 20 centimètres de pluie sont tombés en quatre jours à Portland, L'Orégon, notre équipe de recherche a tracé 705 éboulements dans le secteur. C'était un événement 100-année climatiquement pour des éboulements ainsi nous avons voulu nous assurer que nous avons obtenu une impression claire des causes des éboulements. Des données de l'aperçu nous avons construit une carte de risque d'éboulement qui est maintenant employée dans la planification d'utilisation de la terre. Chaque éboulement a été décrit en utilisant 20 critères différents tels que le volume, dimension, taille d'escarpement, processus, géologie, sols, et angle de pente. Les éboulements sont tombés dans principalement quatre zones. Les collines occidentales envasent la province de sol ont eu 374 éboulements qui étaient principalement des earthflows moins de 500 mètres cubes dans la taille parce que le matériel de parent est principalement loess et sols de ml. La réduction de la plupart de ces glissières était principalement des murs de gabion, ce qui ont été très réussis. La province à grain fin de Troutdale de Portland du sud-est a eu 72 éboulements qui étaient principalement des réactivations de plus grands earthflows et récessions. Le mouvement s'est produit le long des couches d'argile et de vase dans ces dépôts fluviaux à plat. La réduction était difficile dans la plupart des cas parce que les glissières étaient si grandes. Les bluffs raides le long de la province de fleuves ont produit 40 glissières de translation peu profondes. Ils se sont produits où il y avait eu découpage récent des arbres, là où récent vider des sols sur les pentes avait augmenté les forces d'entraînement, et où les ressorts de l'inondation de Missoula dépose l'eau concentrée sur les pentes. La réduction s'est principalement concentrée sur la planification - obliger des personnes à cesser de vider sur les pentes, ne coupant pas des arbres vers le bas, et mettant des drains où il y avait des ressorts. Les écoulements de débris dans la province des fonds de vallée est principalement à Portland du nord le long du fleuve de Colombie. Les écoulements de débris étaient le processus principal qui s'est produit dans ces jets de roche en place. Plus de 45 débris des écoulements ont été tracés. Ils se sont produits principalement où des dépôts épais du colluvium avaient été libérés dans les têtes des jets et des boues produites qui ont déposé sur des ventilateurs le long du fleuve. La réduction principalement est par voie de terre planification d'utilisation et des personnes d'interdiction de la construction le long des canaux et sur les ventilateurs. Un morceau de propriété dans une des quatre zones doit être étudié par un géologue machinant certifié pour s'assurer que les dangers d'éboulement ne sont pas là.

Keywords: inventory maps, susceptibility maps, landslides, databases, debris flows, earthflows

INTRODUCTION

The four days, 6th through the 9th of February 1996 will not be forgotten by the people of northwest Oregon and southwest Washington as a "rain on snow" climatic event caused extensive flooding with estimated river peaks ranging from 25 to 100 year recurrence interval events (Taylor, 1997). Most of the population was prepared for flooding (due to accurate weather forecasts by the National Weather Service), but the population was not ready for the many landslides that occurred over that time period. Comparing landslide distributions and damage to past climatic events, this series of landslides appears to have been a 100-year event. The effects of the landslides can still be felt in the region today.

A great loss of property resulted from this series of storms, followed by a few lawsuits. Local governments have current hazard maps for floods and earthquakes, but few for landslides, and these few have not been updated in the past 15 years. As the population grows and occupies land at a faster rate on hillslopes, more landslide activity can be expected in the future. Planners in the Portland region have asked for tools to help them reduce future vulnerability to landslides.

The region's planning authority, Metro, asked the geology department at Portland State University (PSU) to help them develop landslide susceptibility or geohazard maps for the Portland metropolitan area. A report, database, GIS layer and accompanying maps resulted (Burns et al., 1998).

This report summarizes the development of the resulting landslide inventory database, the inventory map and the resulting landslide susceptibility map for the region. We wanted to take advantage of this major event to produce a record that could be used in the future for planning.

The project was conducted from August 1997 to May 1998. The first part of the project was to collect data on all of the landslides that occurred in the Metro area from February 1996 until May 1998 from surface investigations and interviews. Data collected from each landslide included location, size, slope angle, geology, soils, hydrologic conditions, slide history, and probable cause factors. The data were then summarized into a database. The data were processed into an ArcView geographic information system (GIS), and a map of the landslide distribution was produced. After analysis of the data, four areas of landslide susceptibility were denoted, and a second landslide potential map was produced.

Of the 705 landslides studied in the Portland metropolitan area, approximately 25 homes were "red tagged" and 90 homes were "yellow tagged" (Burns, 1998). A house receives a red tag when it is determined that the house is not liveable until a problem has been fixed. A yellow tag is received when a house has problems, but the house is liveable without endangering its occupants. Most red and yellow tags were received from landslides either hitting the house or moving the ground underneath the house.

Climatic event leading to the storm

The climatic event that caused the many landslides and flooding in February of 1996 in Portland was a classic example of a "rain on snow event" (Taylor, 1997). The last similar major event in the Portland region occurred in December of 1964 and also caused extensive flooding. Two important precursors happened before February in the region. First, there was abundant precipitation in the fall of 1995, and the ground became saturated. Second, large snowfalls during the last two weeks of January led to mountain snowpacks 120% of normal by the 6th of February. Then, on February 6th, the "Pineapple Express" air mass and storm system arrived in the Pacific Northwest (Taylor, 1997). This moisture-rich air mass came from Hawaii and raised the temperature over 17 degrees Celsius in a day. The National Weather Service reported that 18 centimetres of rain fell on Portland from the 6th through the 9th of February (Taylor, 1997). (Some of the surrounding areas unofficially received between 20 and 25 centimetres of rain.) In the mountains, the rain melted the snow rapidly, and all of this water went into the streams. On Saddle Mountain in the Coast Range, a total of 86 centimetres of water drained into the rivers from the 48 centimetres of rainfall that fell and the melting of snow that was equivalent to 38 centimetres of precipitation (Taylor, 1997). Such large precipitation equivalents expressed by those numbers led to extensive flooding in the Tualatin River drainage basin.

George Taylor, Oregon State Climatologist, believes that we are now into a 20 year wet cycle after just having come out of a 20-year dry cycle (Taylor, 1997); the fact that 1996 was the wettest year on record this century supports his ideas. Many sites in the Portland area have "two strikes" against them already (geology that is susceptible to landslides and steep slopes), and that "third strike" comes when abundant storm water is not controlled on the site. Taylor (1997) believes that in the Portland area the two most important climatic factors that delivered the "third strike" causing the landslides were the precursor soil moisture and the intense rainfall over the four-day period of time.

Geology of the Portland Metropolitan area

The geology of Portland region is very simple and can be modeled as a large bowl or basin. The "bowl" is made of basalt called the Columbia River Basalt Group. It formed from flows that came down the ancestral Columbia River 14 million to 16 million years ago and solidified in the area (Beeson *et al*., 1991). Since that time the centre of the bowl has sunk in the middle, and the edges have uplifted to form the Tualatin Mountains (Portland's West Hills) to the west and the Cascade Mountains to the east. It has filled up with sediments (gravels, sands, silts, clays) that have come down the Columbia River and streams from the Cascade Mountains. In fact, the sediments are over $1.5x10^3$ metres thick in the deepest part of this basin near the Portland airport. This layer of sediments is called the Troutdale Formation (Beeson *et al*., 1991). Deposition of the Troutdale Formation occurred over a 12 million year period, ending about two million years ago (Beeson *et al*., 1991). In the eastern part of the Metro area the Troutdale Formation is mainly gravels, but in the southern portion of the basin, near Oregon City and the Clackamas River, it consists of mainly the "fine-grained facies" of sands, silts and clays. Where impermeable clay layers are exposed in this fine-grained formation on the slope, the slope is prone to landslides. Many devastating slides occurred in the fine-grained Troutdale Formation region during this period. From about two million years ago to about 92,000 years ago, many small volcanic vents occurred around the Portland area forming Mt. Tabor, Mt. Scott, Rocky Butte, and Mt. Sylvania to name a few. The basalts forming these hills are called the Boring lavas (Beeson *et al*., 1991).

On top of the Troutdale Formation is a layer consisting mainly of silts and sands deposited 12,700 to 15,300 years ago from more than 40 gigantic floods that came down the Columbia River after a series of glacial dam breaks in Montana (Waitt, 1985; Atwater, 1984). These catastrophic floods are called the "Missoula Floods" and filled the basin with water to an elevation over 122 metres. The fine sediment settled out of the water as the flood waters receded, forming deposits that are more than 31 metres thick in some places. During previous glacial periods and after each of the floods, the sediment that was exposed in the floodplains was eroded by wind. These silts were blown onto the hillslopes surrounding Portland, especially the West Hills of Portland. This wind-deposited silt is called loess and has been named the Portland Hills Silt Formation (Beeson *et al*., 1991).

Landslides have always been an active process in the Portland area. The two most famous slides are located close to one another in the West Hills of Portland. One is where Washington Park in now located. This ancient slide was reactivated in 1894 when the city cut off its toe to build two reservoirs for the city water bureau (Clark, 1904). The problem was mitigated by installing dewatering tunnels throughout the slide in the late 1800's. Today, the slide moves as fast as a person's fingernail grows. The Portland Zoo, the World Forestry Centre and the Portland Children's Museum buildings are all built on Portland's other famous slide (Hammond and Vessely, 1997). This slide was also reactivated by humans cutting off the toe in the 1950's to widen Highway 26. It too has been slowed by installing dewatering tunnels, horizontal drains, and a buttress at the edge of Highway 26. Every winter small landslides are found along road cuts in the West Hills and along steep slopes in east Multnomah and Clackamas Counties, but they are not usually in the number and density characterized by this 100-year event.

Project methodology

The process of this study entailed two steps. First information on landslides needed to be gathered in the field. Second, the information needed to be organized into a database that could be presented graphically. These GIS maps, the GIS disk and the database could then be used by the public, consultants, and governmental agencies in making decisions related to land use.

Field methods

Locations of landslides were found through many methods. Our team used pre-existing databases from cities, counties, fire departments, and the Oregon Department of Transportation. The team also drove many of the streets in the landslide prone areas and found additional slides. Landowners with landslide problems also contacted us.

A standard landslide inventory form was used for the study. Many items were recorded on the sheet, but some items such as date investigated, landslide name, investigators, and photo number were not entered into the database. The following items for each slide are found in the database: landslide number; location; county; topographic quadrangle; city name (if outside of the city limits, the county name is given); and the landslide process based on the classification discussed below. Contributing factors, repair, landslide dimensions (including length, width, and volume), slope angle, dates of movement, and corrective actions were also documented.

The term landslide is a general term used to describe most mass wastage processes. The most common landslides found in the Portland area are what we call earthflows, earth slumps or just "slumps," debris slides, rockfalls, and debris flows. Don Easterbrook (1993), a well-known Pacific Northwest geomorphologist, defines these different landslides as follows. An **earthflow** is a downslope flow of unconsolidated, water-saturated material. It is generally slow moving and produces a well-defined scarp and a tongue-shaped debris deposit. This process is common in the loess of the West Hills of Portland. A **slump** is the downward slipping of a mass of rock or unconsolidated material along a concave-upward plane of failure, usually with backward rotation. Many times slumps have earthflows developing at the bottom of the slump, and we call them a **slump-earthflow**. Slumps (Figure 1) were most common in the fine-grained Troutdale Formation. A **debris slide** is a detachment and rapid downward movement of predominantly unconsolidated and incoherent debris. Generally, this slide occurs on a failure plane of weak rock, like clay or shale. We also mapped many of these thin slides on the steep bluffs above the rivers, and in their cases there was no failure plane (Figure 2). A **rockfall** is a free falling of newly detached rock from a cliff. Many times a pile of rocks, called talus, is found at the bottom of the cliff. A **debris flow** is a rapidly flowing mass of water-saturated debris. Most of the time debris flows occur in stream drainages. Debris flows have sediment content up to 70% and water content around 30% so they are very much like a slurry of wet concrete. In the valley bottoms these landslides scour the valleys, but when the debris flow leaves the constriction, the load is deposited on a fan.

Geology: The underlying geological formation is important. The units given by Beeson *et al* (1991) include: Portland Hills Silt (PHS), Columbia River Basalt Group (CRBG), Troutdale Formation, Boring Lava, Fill, stream alluvium (Qal), terrace deposits (Qt), Missoula Flood deposits (Qff/Qfc), marine sediments, Eagle Creek Formation (older volcanics in the Cascade Mountains), and Qes (undifferentiated aeolian silt).

Figure 1. A slump near Tigard, Oregon (Burns *et al.,* 1998, Slide #695)

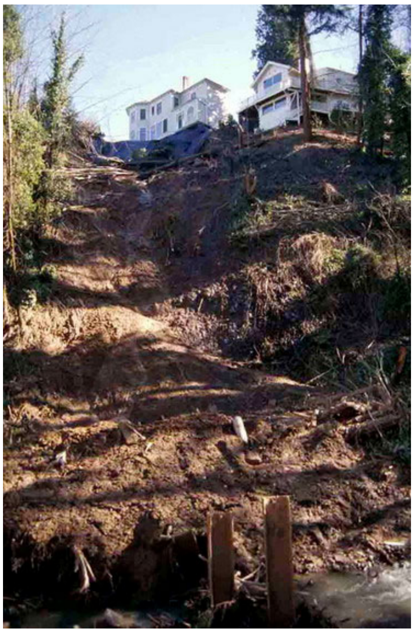

Figure 2. A debris slide resulting from a broken water line and saturated slope (Burns *et al*., 1998, Slide #302)

Mapping Methods

The data were all recorded into an EXCEL 4.0 database. The points plotted on the maps in the field were converted into a GIS database using ArcView 3.0. This database and resulting computer generated maps became part of Metro's RLIS (Regional Land Information System) database for the Portland metropolitan area.

RESULTS

Numbers of Slides

A total of 705 landslides were mapped during the project. This landslide inventory map is shown in Figure 3. It is likely that the majority of the failures that occurred near traffic routes have been mapped, but some of the landslides on private property remain unmapped.

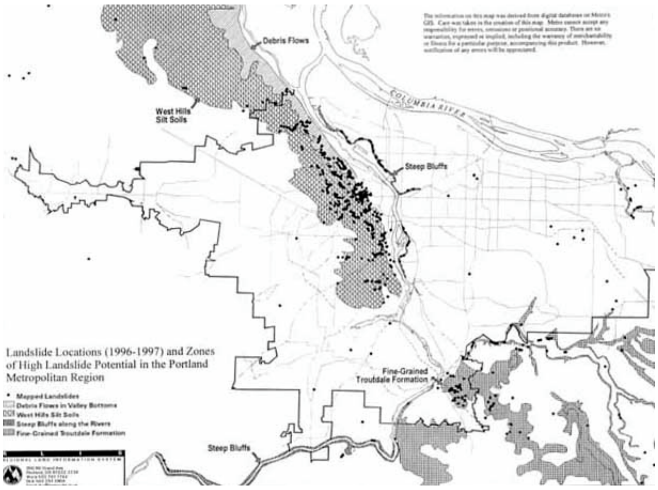

Figure 3. Landslide inventory map available from Metro

Geological Relationships

Most of the landslides (48%) surveyed in this study (Table 1) occurred in the West Hills within the Portland Hills Silt or loess. This material is very strong when it is dry, but the silt soils are very weak when they are saturated. Many of the failure planes were on palaeosols (old buried soil surfaces) in the loess. A significant number of landslides were recorded in the Troutdale Formation (12%). The majority of the landslides within Missoula Flood Deposits (Qff/Qfc) are along the steep slopes next to the Willamette and Clackamas Rivers. The common processes in areas of exposed basalt were rockfall and debris flows. A total of 15% of the landslides occurred in sidecast fill, and 60% of those fill sites used loess as the fill.

Table 1. Geology under the landslides

Geological Unit	Numbers	Percentage
Portland Hills Silt	334	48%
Fill	106	15%
Troutdale Formation	87	12%
Missoula Flood Deposits	58	8%
Columbia River Basalt	43	6%
Boring Lava	16	2%
Eagle Creek Formation	9	1%
Other	52	7%

Landslide Types and Mechanisms

Many types of landslides occurred in the Portland area (Table 2), but ones involving earthflows dominated the processes. Earthflows by themselves and in combination with slumps make up 69% of the landslides, mainly because so many of the failures occurred in the loess of the West Hills. Slumps and earthflows dominated the slide activity in the Troutdale Formation sites. Debris slides were the common mechanism along the steep cliffs along the rivers. The most dangerous type of landslide is the debris flow, and a total of 45 of them (found by themselves or in combination with other processes) occurred mainly in the steep valleys draining into the Columbia River and west of the Willamette River in northwest Portland. Only 4% of the sites had a rockfall, and those were associated with basalt outcrops around the Portland area.

Table 2. Landslide Types and Mechanisms

Process	Number	Percentage
Earthflows (EF)	354	50%
Slump-Earthflows (SEF)	135	19%
Slumps (SL)	67	9%
Debris Slides (DS)	78	11%
Debris Flows (DF)	45	7%
Rockfall (RF)	26	4%

Sizes and Volumes of Slides

Compared to the sizes of landslides in the Portland metropolitan area from this storm event to other well-known local large landslides such as the Zoo/OMSI and Washington Park landslides in Portland and the Cascade or Bonneville landslide in the Columbia Gorge, we find that these recent slides are mainly small to medium in size. Approximately 96% of the landslides studied in this report were less than 7.65×10^3 cubic metres in size and about 98.9% were less than 3.06×10^4 cubic metres (Table 3). Only two landslides were considered "large" or megalandslides (> 7.65×10^5 cubic metres in volume), of which one was a debris flow (Tumult Creek debris flow, Burns *et al.*,1998, slide #130) and the other a reactivation of an old palaeoslide (Dixie Mountain slide, Burns *et al.*, 1998, slide #657).

Table 3. Landslide volumes

Landslide Volumes	Percentage of Total Slides
< 76 cubic metres	18%
77 - 382 cubic metres	39%
382 - 764 cubic metres	14%
765 – 3.82×10^3 cubic metres	20%
3,823 - 7.65×10^3 cubic metres	6%
7.65×10^3 - 3.06×10^4 cubic metres	2.8%
3.06×10^4 - 7.65×10^5 cubic metres	0.9%
> 7.65×10^5 cubic metres	0.3%

This was a major climatic event that triggered a multitude of landslides, but only two “large” slides happened. This suggests that the large landslides found in the Portland metropolitan area have probably been triggered by other mechanisms than climatic events. Two non-climatic event trigger possibilities for the large landslides are large subduction earthquakes along the Oregon coast or saturated slopes failing as waters from the Missoula Floods left the Willamette and Columbia River valleys over 12,000 years ago (Waitt, 1985).

Excluding the two megalandslides, the volumes ranged from eight to 1.15×10^5 cubic metres, the average volume is 2.14×10^3 cubic metres, and the median size is 317 cubic metres. The low median reflects the large number of small landslides (Table 3). For comparison, a dumptruck carries a load that is approximately eight cubic metres.

Slope Angles

The majority of the landslides occurred on slopes with slope angles between 30 degrees and 50 degrees (Table 4). Relatively low angle slopes (<25 degrees) accounted for 8% of the landslides, most of which were in the Troutdale Formation on the toes of palaeoslides that had been reactivated. Also, some of the low angle failures were at sites with broken water lines. The failures that occurred on slopes above 66 degrees (4% of the total) were mainly rockfall.

Table 4. Slope angles of the landslides*

Approx. Degrees	Numbers	Percentage of Total Landslides
10	2	.3%
15 (30% slopes)	5	.7%
20	13	2%
25	35	5%
30	65	10%
35	123	19%
40	96	15%
45 (100% slopes)	116	18%
50	78	12%
55	28	4%
60	53	8%
65	13	2%
70	7	1%
75+	20	3%

* Note: not all landslides had slope angles recorded for them, especially the debris flows

Contributing Factors of the Landslides

The primary contributing factor to most of the landslides appears to have been the increased water in the soil system. Many of the sites were prone to failure (steep slopes and weak geological unit/soil under the site), and the addition of 18 centimetres of precipitation in four days on top of already saturated soils led to landslides. For 24% of the landslides we could not find any human action that could have increased the chances for the landslide occurring, hence these are called "natural slides." Human influence was noted in 76% of the landslides. The most common human factor was that 52% of the landslides occurred in cutbanks where humans had cut into the slope for roads or driveways. Failures along roads in the road prism (the fill) resulted in 15% of the slides.

In 9% of the cases, we could actually point to places where humans had influenced the concentration of storm water on the slopes. Broken water pipes, broken drainpipes, clogged gutters, and runoff from driveways and patios were examples of humans inadvertently helping the landslides. If the people at these sites had controlled the storm water, the landslides could have been prevented or at least decreased in severity. An example of a clogged gutter concentrating water on the slope below a house leading to a landslide is in Figure 4.

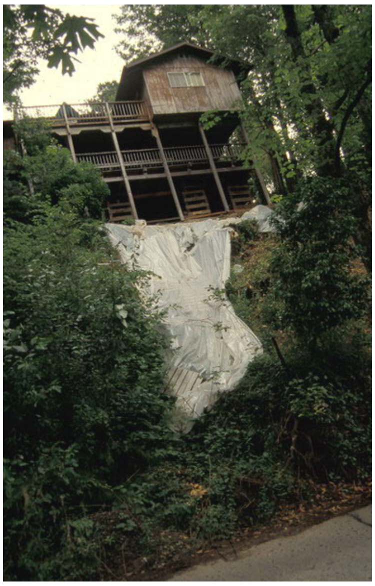

Figure 4. Earthflow in the West Hills began where a gutter deposited water (Burns *et al*., 1998, Slide #119)

DISCUSSION

Geological provinces of greatest landslide occurrence

Landslides were concentrated in certain geological provinces of the metropolitan area and are mapped as a geohazard map or landslide susceptibility map. Of the 705 landslides that were documented, most were concentrated in the West Hills that are covered with loess. We have called this province the **West Hills Silt Soil Province.** Quite a few landslides were concentrated on the steep slopes along the Willamette, Clackamas and Sandy Rivers in a region we call the **Steep Bluffs Along the Rivers Province**. Some large landslides also occurred in southeast Portland on slopes of the Troutdale Formation. This province was given the name the **Fine-grained Troutdale Province.** The most devastating and dangerous landslides were the debris flows that developed along bedrock streams feeding into the Columbia and lower Willamette Rivers. This province was called the **Debris Flows in Valley Bottoms Province.** The few exposures of basalt cliffs that could lead to rockfall were not mapped. These four provinces are shown in Figure 5. A good portion of Portland is flat and those areas were practically devoid of landslides.

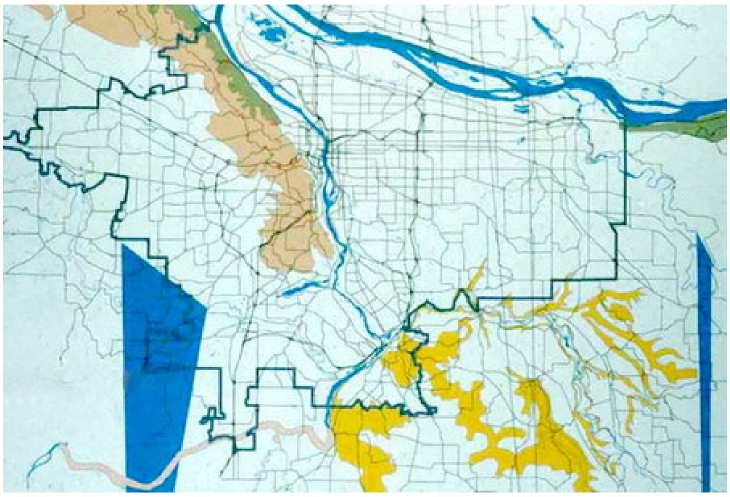

Figure 5. Landslide susceptibility or geohazard map for Portland, Oregon
*The West Hills Silt Soil Province is in light blue; the fine-grained Troutdale Province is in yellow; and the Debris Flow in Valley Bottoms Province is in green

The West Hills Silt Soil Province

The greatest concentration of landslides in Portland was in the West Hills in the wind-blown loess of the Portland Hills Silt Formation. A total of 374 slides were mapped in this province with 84 occurring in the area where the West Hills Silt Soil Province overlaps the Debris Flows in Valley Bottoms Province. The loess varies in thickness from 0.3 metres to over 31 metres at the crest of the Tualatin Mountains. Most of the failures occurred on steep slopes in the loess. Most of the failures were earthflows, but there were a few slumps, and the sizes were relatively small, being mostly in the range of 19 to 382 cubic metres. The greatest concentrations of slides in this province were found along the following roads: Fairview, Fairmont, West Burnside, Cornell, Skyline, Germantown, Humphrey and Thompson.

Even small landslides in this province can cause great destruction and inconvenience. An example of a small earthflow (637 cubic metres) at the 800 block of Broadway Drive (Burns *et al*, 1998, slide # 597) that destroyed a complex of seven condominiums on 8th of February. Another small earthflow destroyed the home in the 4000 block of SW Fairvale (Burns *et al*., 1998, slide #124, 595 cubic metres) in Glencullen when a 12 metre high cliff of loess collapsed into the back of the house.

Many of the failure planes of the earthflows and slumps in this province occurred along palaeosols in the loess. A palaeosol is an old weathering surface of a layer of soil, and it tends to be clay rich and holds up water that is trying to pass through it. There are anywhere from one to four palaeosols in the loess between the modern soil surface and the palaeosol resting on the basalt bedrock. Two examples of failures on palaeosols are located on SW 16th between Elm and Laurel (Burns *et al.*, 1998, slide #599) and in the 2700 block of SW Fairmont (Burns *et al.*, 1998, slide #611). One can see these palaeosols in the slope (exposed by a landslide) in the northwest quadrant of the intersection of SW Terwilliger and Barbur Blvd (Burns *et al*., 1998, slide #66).

The Fine-Grained Troutdale Formation

A total of 72 landslides have been mapped in the fine-grained Troutdale Formation of southeast Portland. Landslides are not very common (other than rockfall) in outcrops of the coarse-grained Troutdale Formation. Rainfall percolates into the soil and moves through the alluvial (river) sediments until the water intercepts a clay layer, the finest-grained layers of the Troutdale. On slopes where this clay layer daylights, one generally finds a spring. If the clay layer is dipping out of the slope, it can become the failure plane for a slump or slump-earthflow when the pore water pressure has built up to a critical value on top of the clay layer. These landslides are most common in this type of geology, but occur on slopes of lesser values, with some being in the range of 15 to 30 degrees. The sizes of the slides range from 38 to 1.22×10^5 cubic metres. Most of the slides along the Clackamas River were in the Troutdale Formation. Landslides in the Troutdale Formation generally are slower to react to storm events than the slides in the loess. Therefore, some failures did not start their movement until the 20th of February.

Many palaeolandslides (ancient landslides) dot the landscape in southeast Portland in the Troutdale Formation, and some of these ancient slides reactivated after the storm. Movement on some of these slides ranged 0.3 to 0.6 metres. The Bruin slide (Hinkle Road, Burns *et al*., 1998, slide #679, 1.28×10^4 cubic metres) and the Jacobs slide (Burns *et al*., 1998, slide #680, 5.12×10^3 cubic metres) caused little destruction, but the reactivation of the Matthew Court (Burns *et al*., 1998, slide #263, 2.04×10^4 cubic metres) and 401 Warren Street (Burns *et al*., 1998, slide #279, 6.8×10^3 cubic metres) palaeoslides disabled and destroyed two homes (Figure 6). A scarp of 1.5 metres high developed across five lots of the Beaver Lake subdivision (Burns *et al*., 1998, slide #704) when this ancient landslide started moving again. Reactivation of the palaeoslide on Holly Lane (Burns *et al*., 1998, slide #272) destroyed four homes with a one metre drop at the headscarp in February, 1996 and then another drop of one metre the following winter (Figure 7). These palaeolandslides can be identified by locating ancient headscarps and the hummocky topography (rolling hills) of the slide surface (Figure 8).

Figure 6. Toe of ancient landslide moves 0.3 metres laterally and causes distress for house (Burns *et al.*, 1998, slide #263)

One of the greatest concentrations of landslides in the Troutdale Formation is found in the 2.43×10^6 square metres of Newell Canyon next to Oregon City. The canyon is bisected by Highway 213 which has had yearly landslide problems since it was built. A total of 53 older landslides were mapped in the canyon in 1993 (Burns, 1993), and 17 new earthflows and slumps were discovered after February 1996. The largest earthflow occurred in the northwest corner of the canyon just off of Alden Street. The first day of the slide, it was approximately 153 cubic metres in size. After two months, it was 1.15×10^3 cubic metres and had developed into a debris flow that had moved over 46 metres down the valley at the base of the slope. After the rains of November and December 1996, the slide had enlarged to 3.41×10^4 cubic metres.

Figure 7. Ancient landslide in the Troutdale Fm drops one metre (Burns *et al.*, 1998, Slide #272)

Figure 8. Hummocky topography, one cannot see any new movement (Burns *et al.,* 1998, Slide #272)

The Steep Bluffs Along the Rivers Province

Forty landslides were mapped along the steep bluffs on the Willamette, Clackamas and Sandy Rivers. The geology of these sites is mainly Missoula Flood sediments which are sometimes fine-grained (Qff) and sometimes coarse-grained gravels (Qfc) (Beeson *et al*., 1991). These sediments fail mainly as shallow earthflows and debris slides. Many slides were recorded above Mocks Bottom and along NE Greeley Avenue at the base of Overlook Park in north Portland. Another large number of landslides could be found surrounding Oaks Bottom. Most of these slopes are over 50 degrees. Most of the slides were less than 765 cubic metres. Two exceptions to the small size are the $1.20\text{x}10^5$ cubic yard Gill slide (Burns *et al*., 1998, slide #696) in Newberg and the mobile home park along the Clackamas River (Burns *et al*., 1998, slide #230, $2.54\text{x}10^4$ cubic metres) which is discussed below.

Many landslides in this province were aided by humans who over the years had dumped soil and yard debris over the edge of the cliff thus increasing the driving forces by adding weight to the tops of the slopes. The worst earthflow occurred at the end of Ramona Street (Burns *et al*., 1998, slide #69, $1.76\text{x}10^3$ cubic metres) above Oaks Bottoms where a home received a red tag. The slide got within one metre of the house. The house had to be moved back on the lot.

Where the slope was in contact with the river, undercutting occurred and caused the slope to fall into the river. These slides were especially common in the meander bends of the rivers. There were 14 lots of a mobile home park undermined in the meander bend of the Clackamas River just west of where Highways 212 and 224 merge (Burns *et al*., 1998, slide #230). The only death during the storm in the Portland area occurred when the Sandy River undercut the bank of the home of Harold and Jacqueline Jank on the Old Columbia Highway in east Troutdale (Burns *et al*., 1998, slide #162). The landslide carried their home into the Columbia River.

Gravel mining in the Clackamas River floodplain by the Clackamas Sand and Gravel Company upstream of Barton Park created a large gravel pit and separated it from the river by a human-made levee. During the flood the levee breached causing the river to reroute through the centre of the gravel pits on the old point bar. The gravel pits had captured the stream, and the new stream undercut the banks of the pit causing a slide to occur under the offices of the operation (Figure 9). Today, the condemned office sits precariously perched on the alluvium of the old flood plain (Darienzo, 1997, Burns *et al*., 1998, slide #615).

The Debris Flows in Valley Bottoms Province

Debris flows are the most dangerous of the landslides because they move so rapidly, have so much force, and often come unannounced. A total of 45 debris flows were mapped in the study area, primarily along the Columbia River and the northern Willamette River. Debris flows occur in bedrock stream bottoms and on the alluvial fans at the ends of those canyons. Most of them occurred when debris slides, slumps or earthflows in the upper reaches of the streams blocked the streams by forming a dam. A lake formed in back of the landslide dam, but because of the high precipitation rates, the dam breached, and the landslide deposit was turned into a slurry that rushed down the stream valley. The debris flow would erode and scour the valley bottom to the basalt bedrock. Volumes ranged from 765 cubic metres to millions of cubic metres.

The two most famous debris flows occurred on Thursday, February 8th at Dodson, 56 kilometres east of Portland in the Columbia Gorge (Powell, 1998). At the west end of Dodson, a slow moving debris flow (moving at about eight kilometres per hour) half buried the 50 year old homestead of Carol and Hersh Royse (Figure 10) (Burns *et al*., 1998, slide #128). A fast moving debris flow came down Tumult Creek (Burns *et al*., 1998, slide #130) at a rate estimated to be 48 kilometres per hour. Both of these debris flows crossed I-84 and the Union Pacific Railroad tracks. The highway was closed for three weeks. Resident Mark Chandler of Dodson reported that the Tumult Creek stopped flowing for a while just before the first debris flow came rushing down.

Figure 9. Clackamas River undercutting slope along the Rivers Province (Burns *et al*., 1998, Slide #685)

Figure 10. Debris flow buried the Royse homestead, Dodson, Columbia River Gorge (Burns *et al.,* 1998, slide #128)

The stoppage probably was created by debris slides upstream blocking the creek; the debris flow originated when the debris dam was breached. Estimates of the volume of the debris flow deposits range from $7.65x10^5$ to $1.91x10^8$ cubic metres (Powell, 1998). The area around Dodson received 33 centimetres of rain in the four-day event.

These debris flows are not a new phenomena. The last major one was in 1918. Carol Royse remembers playing as a child on her land on a buried tractor that was lost in that event. Smaller debris flows also occurred in 1964, 1972, and 1974 (Wickwire, 1996). Dodson and the neighboring town of Warrendale are on an alluvial fan at the bottom of the basalt cliffs at the edge of the Columbia Gorge. That fan has formed in the past 12,700 years, the date of the last Missoula Flood (Waitt, 1985). The Missoula Floods scoured the gorge; the fan is a result of debris flows since that time building it back up. These are natural phenomena.

Other Significant Landslides Outside of the Provinces

Outside the four provinces, 174 other landslides were mapped around the Portland region; 26 rockfall events were recorded at some of the outcrops of basalt in the region, but these were too dispersed to make up a province. Most of the other failures fell into three categories of slides. First, and probably foremost, was the reactivation of old landslides. Most of the landslides at the northern and western ends of Washington County were in reactivated palaeolandslides such as Dixie Mountain and Scoggins Reservoir in the Yamhill Formation. Second, fill failures resulted from improper drainage possibly caused by poor maintenance. An example of one of these failures occurred below Salmon River Road in Welches destroying one house and causing over $150,000 (125,938 Euros) of damage to another (Burns *et al*., 1998, slide #197, $9.8x10^4$ cubic metres). Third, where water was uncontrolled, low angle slopes could fail.

CONCLUSIONS

We mapped 705 landslides, resulting from the 6^{th} to the 9^{th} of February 1996 storm systems affecting the Portland metropolitan area, along with more recent storms. The mapping area extended beyond the Metro boundaries to get a better feeling for the landslide activity in the region. Most of the landslides were earthflows and slumps, with the majority of them occurring in the loess soils of the West Hills of Portland. The most dangerous and devastating slides were the debris flows that developed in bedrock streams along the Columbia River and lower Willamette Rivers. Based on the abundance of the landslide activity, it was estimated that this was probably a 100-year event for landslide recurrence. The slides caused significant damage to over 100 homes in Portland alone. Up to 10% of the damage could have been reduced or prevented if humans had controlled the water on the sites. Human activities were contributing factors to 76% of the landslides.

Analysis of these landslides and the compilation of an inventory map and the resulting susceptibility map has been important. We now have one of the most complete databases for a major landslide event promoted by a major storm event. Use of these maps will help prevent future landslide activity and will aid planners in their decision making.

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