ABSTRACT

This paper describes geologic hazard quantification for the multi-hazard system vulnerability assessment of the Portland, Oregon’s water system. The two hazards that pose the greatest risk are earthquake (including ground motion, landslide, and liquefaction), and intense rain (including landslide, turbidity, and flood).

The primary supply (surface water) is transported to the city through three, 40 km-long conduits. The corridor is subject to earthquake and rain-induced landslides. The secondary supply (groundwater) is pumped from the Columbia River south shore well field which is founded on moderately liquefiable, silty sand. The final transmission segment crosses liquefiable material along the Willamette River. The supply system schematic is shown in Figure 1.

Earthquake ground motions are quantified considering crustal sources and an interface subduction source. Liquefaction vulnerability is based on recent site specific and regional studies. The landslide risk assessment relies on geologic mapping developed for the project, and landslide history along the corridor.

INTRODUCTION

Thirty-eight hazards were considered in the Multi-hazard System Vulnerability Assessment (SVA) of the Portland, Oregon, Bureau of Waterworks water system. The SVA project is summarized in *Multi-Hazard Risk Assessment For Lifelines Part 2 - Case Study For The Portland, Oregon Water Supply System* (Ballantyne, et al, 1999). This paper describes quantification of the geologic hazards for the SVA.

The 38 hazards were subdivided into four major hazard categories: natural, human/technological, transportation, and lifeline service. Table 1 presents a summary of the natural hazards analyzed and their risk-based ranking. Geologic hazards addressed in this paper are identified.

PROJECT APPROACH ISSUES

The intent of the project was to use hazard information developed for other projects when ever possible, and only to assess hazards in detail when no other resources were available. Such information had been developed for different purposes, and was often available, but in different formats. The project team included consultants addressing a range of hazards. Many of these consultants were selected because of their expertise with specific hazards in the region, but were not necessarily familiar with quantification of hazards in the form to be used in this risk assessment. Therefore, one of the significant project tasks was to put information into a useful common format. Hazards were ranked by supply and distribution systems, respectively, as described in the following subsections.
Table 1
Summary Of Natural Hazards And Rankings

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Discussed in this Paper</th>
<th>Very High</th>
<th>High</th>
<th>Moderate</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intense Rain on Snow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landslide (rain induced)</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbidity</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Fire in Watershed (Turbidity)</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Flood–Bull Run, Sandy rivers</td>
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<td></td>
<td></td>
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<tr>
<td>Flood–Columbia, Willamette rivers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Wind/Ice Storm (Power)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Winter Snow/Ice Storms (Structural)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Wind/Tree Fall (Structure Impact, Slope Destabilization)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Earthquake</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground Motion</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquefaction</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landslide</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Faulting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Seiche</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Volcanic Activity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandy River Lahar/Debris Flow</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash Fall (Turbidity, Electrical)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Land/Rock Slides/Debris Flow (non-rain induced)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Microbial Contamination</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Prolonged Freezing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Urban Firestorms, Forest Park Fires</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Supply Facilities

Hazard rankings for the supply facilities were categorized as follows: (1) preliminary categories were identified in the interview process and during SVA project meetings where the hazard matrix was reviewed; and (2) the potential effect of each hazard was evaluated as to whether it would affect one or multiple components at any time. Hazards with a recurrence interval of 1,000 years or less were considered in the project. A preliminary ranking was conducted for each hazard, estimating the level of risk considering the possible extent and consequences of damage, as follows:

- **Very High** – hazard events that could result in loss of overall system service because of damage to multiple facilities. In general, this group includes hazards that have the potential for making both the Bull Run surface water and groundwater system inoperable at the same time. Frequency-severity (also termed recurrence-intensity) relationships have been
developed for these hazards, and they are included in the system model to assess the probability of damage to multiple facilities.

- **High** – hazard events that could result in loss of service from either the Bull Run or groundwater supply; i.e., one or the other, not both. These hazards are examined but not modeled as they would impact only one supply at a time, allowing for continued service through redundancy in the system.

- **Moderate** – hazard events that could result in loss of service to limited supply areas, and/or cause significant damage to Bureau facilities, but without loss of the Bull Run or groundwater supplies.

- **Low/Very Low** – hazard events with expected recurrence intervals significantly longer than 1,000 years and/or would result in limited damage and no loss of service.

**Distribution (Backbone) Facilities**

On review of the distribution facilities, it was concluded that the only hazard that could have an impact on multiple system components is an earthquake. (Note: although a power outage could impact multiple pump stations, in general pump stations have emergency power supplies.) Therefore, SAFENET, a proprietary post-earthquake network serviceability evaluation tool was used to model post-earthquake distribution system functions.

**INTENSE RAIN-ON-SNOW EVENT**

An intense rain-on-snow event is thought to produce the highest “water application rate” to the ground. This hazard category includes both rain-on-snow and intense rain. There are a number of sub-hazards that result from the intense rain-on-snow storms that are highly correlated, including (1) landslides, (2) turbidity events, and (3) floods on the Bull Run and Sandy Rivers, as shown in Figure 2. Other types of storm events including wind storms and ice storms, and longer periods or wider areas of rainfall that result in flooding on the Columbia River are not correlated to an intense rain-on-snow event. A fire in the watershed during the season before an intense rain-on-snow storm increases the probability of occurrence, and duration, of a turbidity event. We will focus on rain induced landslides, the geologic hazard in this group, with a brief discussion of related hazards. Some of the intense rain on snow hazards are correlated.

**Rain-Induced Landslide**

Landslides can be initiated by reduction in the strength of the soil as a result of being saturated, by rain, or from increased loading due to earthquakes. This section discusses landslides induced by rain. Landslides can occur in the watershed, along the conduit corridors, and to a lesser degree, at other locations within the system. Landslides can damage facilities as a result of impacting the facility with sliding debris, burying the facility, or the facility moving as part of the slide. Dam #2, the lower dam in the Bull Run watershed, is constructed on an ancient landslide. Washington Park Reservoir Nos. 3 and 4, the reservoirs serving the Portland central business district, are located at the toe of a large moving landslide. Landslides will occur in the watershed, exposing soils that can easily erode during heavy rains, increasing turbidity in the reservoirs. There is a very low probability that landslides will occur into the reservoirs that could result in a seiche and/or wave that could overtop a dam.
The project geotechnical consultant developed landslide probabilities based on historic data from landslides along the Bull Run corridor (Cornforth, 1998a). There was inadequate information on dates of occurrence to relate landslides directly with intense rain on snow, or rain events. It appears there is a correlation between intense rain and landslides, based on recent historical events. Therefore, the supply side hazard risk model assumes that landslides will occur during the 4-month rainy season, from November through February (the return period assumes 4 wet months and 8 dry months). The model also considers the sensitivity of the assumption that the landslides are directly correlated with intense rains, similar to turbidity events, and flooding on the Bull Run and Sandy Rivers.

The majority of landslide risk for the water supply system is associated with ancient landslide terrain located in the Bull Run corridor from the headworks to approximately 3 miles northwest of the Sandy River crossing. Within this area are three types of geologic terrain:

- **Ancient Landslide Terrain.** The majority of the Bull Run corridor is comprised of ancient landslide terrain that developed as the Bull Run River eroded through more resistant geologic units (Troutdale Formation) into softer geologic units (Sandy River Mudstone). This led to undercutting of the overlying more resistant layer, which eventually resulted in massive landsliding along both sides of the valley.

- **Historically Active Slide Terrain.** The historically active slide terrain includes 17 landslides that have occurred within the ancient slide terrain since the original construction of the conduits in the 1890s. Six of these slides have resulted in damage to the conduits, and seven others have come close to damaging the conduits. Nearly all of the slides have been remediated.

- **Stable Terrain.** Stable terrain consists of geologic units that show no evidence of landsliding and includes the majority of the conduit alignments west of the Sandy River crossing. In general, this material represents a very low risk for slide hazards.

Two types of landslides are considered for the Bull Run corridor:

- **Flow slides** occur during high intensity winter storms and are typically 20 to 200 feet in width. Downslope movement of a surficial layer occurs rapidly and can move tens to hundreds of feet.

- **Translational slides** are much larger in size and deeper, and move at a much slower rate (inches per year or less). They typically exhibit creep-like movement during winter, and zero or very slow movement in the summer.

Landslide hazard curves were developed for each geological terrain by estimating the probability of a significant landslide anywhere along the conduit run for recurrence intervals of 10, 50, 100, 500, and 1,000 years. In this context, significant landslides include only those landslides judged large enough to result in failure of one or more conduits. The probabilities reflect the geologic conditions as they currently exist, and can be affected by man-made activities such as excavations, logging, and surface water management.

The landslide probabilities for stable terrain and ancient landslide terrain were developed based on historical data over the past 100 years and extrapolated based on experience and judgment. The probabilities for flow slide failures took into consideration that the more susceptible flow slide areas have probably failed already, and that creeping slide terrain could be slowly stressing.
the conduits in undetermined locations. Table 2 lists the probability of conduit slides for the three geologic terrains and two slide types. The probabilities refer to the likelihood of a landslide occurring anywhere along the length of the slide terrain. Note that the slide probabilities do not include the probability of earthquake-induced landslide, which is addressed in the earthquake hazard section.

Table 2
Estimated Probabilities Of Conduit Landslide Damage During 4-Month Rainy Period (Rain Induced)

<table>
<thead>
<tr>
<th>Item</th>
<th>Probability of Conduit Landslide Damage for Given Return Period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Remediated Flow</td>
<td>0.00</td>
</tr>
<tr>
<td>Remediated Translational</td>
<td>0.01</td>
</tr>
<tr>
<td>Ancient Flow</td>
<td>0.60</td>
</tr>
<tr>
<td>Ancient Translational</td>
<td>0.01</td>
</tr>
<tr>
<td>Inactive</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Based on these results, we have used a 10-year recurrence interval for a landslide that damages one or more conduits occurring somewhere in the Bull Run corridor. The majority of the alignment is in ancient landslide terrain. Flow slides, the most likely to move, occur rapidly, with widths that would be damaging to the conduits. In subsequent analyses, the probability of failure is distributed by length of corridor, where the corridor may contain Conduits 2 and 4, Conduit 3, or Conduits 2, 3, and 4.

Related Hazards

The water quality from Bull Run unfiltered water supply must be maintained at an acceptable level for drinking. To continue use, the turbidity must be kept below 5 turbidity units. Intense rains result in localized erosion in the watershed which increase turbidity. If a significant fire were to occur in the watershed, the turbidity would be worse during subsequent rains.

Intense rains may cause flooding in local rivers, including the Bull Run and Sandy. Flooding may cause scour/bank erosion along the river damaging the conduits adjacent to the river and/or foundations of the conduit bridges crossing the river. Extreme flooding could result in hydraulic loading on the conduit bridge decks. Flooding could result on the Columbia River from of a number of occurrences: (1) the dikes could fail, (2) the dikes could overtop, and (3) stormwater pumps could lose power for an extended period. The Willamette River submarine crossings could be damaged due to scour. This risk would be increased during periods of high flow.

Wind or ice may be associated with intense storms. These hazards may result in damage to power lines, disrupting electrical power supply to system facilities. Disruption of power to the groundwater system is of particular concern because it has no emergency power supply, and portable generators would be too small to drive the large pumps.
Correlation of Intense Rain Sub-Hazards

It is important to consider the correlation of hazard events, including geologic hazards, with other hazards. Some hazard events, such as earthquakes, will impact multiple facilities during the same event, potentially rendering the entire system inoperable. There may be correlated hazards that impact different facilities during the same period, resulting in loss of system service.

By definition, correlated events have a higher probability of occurring during the same period compared to uncorrelated events. For example, high turbidity in the Bull Run and rainfall-induced landslides are closely correlated.

Uncorrelated events are, in general, not a concern. For example, an intense rain-on-snow event and an earthquake event are uncorrelated. That is, probabilistically, there is no relationship between occurrence of an earthquake and occurrence of an intense rain-on-snow event. The probability of concurrently having a significant earthquake and a significant rain-on-snow event is very low. The probability is the product of the probabilities of the two independent events.

We concluded that there are strong correlations between sub-hazards affecting different components of the Bull Run supply, but there are no correlations between pairs of hazards that would affect the Bull Run and groundwater supplies at the same time.

The most significant question becomes whether these sub-hazards are correlated events that impact the Bull Run supply and the groundwater supply; i.e., is there a pair of any of the intense rain-on-snow sub-hazards that affect both the Bull Run supply and the groundwater supply? Table 3 shows a summary of this correlation.

### Table 3
Correlation Of Intense Rain-On-Snow Sub-Hazards

<table>
<thead>
<tr>
<th>Hazard Event</th>
<th>Turbidity</th>
<th>Landslide</th>
<th>Flood on Bull Run and Sandy Rivers</th>
<th>Flood on Columbia River</th>
<th>Flood on Willamette River</th>
<th>Ice and Wind Storms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landslide</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flood on Bull Run and Sandy Rivers</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flood on Columbia River</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flood on Willamette River</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ice and Wind Storms</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

There are some intense rain-on-snow sub-hazards that are correlated, and some that are not correlated. Intuitively, turbidity and landslide have a high degree of correlation. It is believed that when a 500-year intense rain-on-snow event (0.002 annualized) occurs, there is a high probability of having a flood event on the Bull Run and Sandy Rivers, a turbidity event, and a landslide along the conduits. From a system modeling perspective, it has only limited significance because the three sub-hazards events impact the same system, the Bull Run supply. The turbidity event is significant at a 5-year recurrence interval, the landslide event at a 10-year recurrence interval, and the flood event at a 100-year recurrence interval. For a 500-year event, they are all significant.
The hydraulic characteristics of the Columbia River drainage basin, and the Bull Run and Sandy river drainage basins are significantly different; therefore, flooding in these basins should not be correlated. The Columbia basin covers all of eastern Washington, and extends into southern British Columbia, Idaho, and eastern Oregon. Further, stream flow is controlled by a series of dams. The Bull Run drainage basin is much smaller. While there are two dams, during the periods when peak stream flows are expected, the reservoirs behind the dams would likely be full, and would have little impact on stream flow.

Flooding on the Willamette River may be related to flooding on the Columbia River because of the hydraulic backwater effects at the mouth of the Willamette River. In addition, the Willamette River drainage basin is considerably smaller than the Columbia River drainage basin, and is more likely to receive rain from the same storms that impact the Bull Run basin. However, flooding on the Willamette River does not affect either the Bull Run or the groundwater supplies. Therefore, the correlation of the Willamette River flooding with other intense rain-on-snow sub-hazards is not a concern.

Intense rain-on-snow events, and ice and wind storms, have different characteristics, and are not correlated. While every ice storm was accompanied by moderate to high wind speeds, none had excessive precipitation. Only one of the storms produced more than 2 inches of precipitation. Thus, the likelihood of significant flooding at Bull Run is quite low during such storms, and the probability of power outage from an ice storm coinciding with a problematic flood at Bull Run appears to be quite low.

**EARTHQUAKE**

The earthquake hazard is subdivided into the following categories: fault rupture, strong ground motion (or shaking), landslide, and liquefaction hazards. The initiating event for this hazard is a fault rupture, which releases accumulated strain energy. The release and transmission of energy causes ground shaking. Shaking can then cause liquefaction or landslides to occur.

**Regional Seismicity**

Seismic hazards in the Portland area are dominated by two sources: deep earthquakes along the Cascadia subduction zone occurring at the interface between the subducting Juan de Fuca Plate and the North American Plate, and shallow crustal events within the North American Plate. There is geologic evidence that subduction earthquakes occur approximately every 500 years, the most recent being in 1700. The USGS has included a third earthquake source zone in the Seattle area but not in the Portland area, even though the two areas arguably have a similar tectonic structure.

The USGS currently believes that the Pacific Northwest is under north-south compression, possibly relating to the geometry associated with the northwest movement of the Pacific Plate relative to the North American Plate. This north-south compression is occurring within the North American Plate. Earthquakes that occur within this plate are called crustal earthquakes. Crustal faults resulting from compressive forces are often thrust (reverse) faults, similar to that which caused the Northridge Earthquake.

The 1993 magnitude 5.6 Scotts Mills Earthquake, and the 1962 magnitude 5.2 Portland earthquakes were crustal events. The USGS and other researchers have identified shallow (crustal) faults and lineaments in the Portland area, the most pronounced of which is the Portland
Hills Fault paralleling the Willamette River through downtown Portland. The Portland Hills Fault is modeled with a slip rate of 0.1 mm/yr, with a characteristic earthquake of magnitude 7.0 with a return period on the order of 10,000 years. With this low slip rate/long return period, the fault has little effect on 500-year return probabilistic ground motions.

**Strong Ground Motion**

Strong ground motion is a significant hazard to Bureau facilities, whose vulnerability varies depending primarily on the type of construction and the earthquake criteria to which the facility was designed.

Strong ground motion can be characterized in two ways:

- **Probabilistically**, where a hazard curve is developed for a site, expressing the probability of various levels of PGA due to all sources,

- **Scenario**, where peak ground acceleration (PGA) is determined at a site or sites given a specified earthquake occurrence; i.e., magnitude and epicentral location are uniquely defined.

The USGS provides probabilistic seismic hazard curves for virtually any location in the United States (Frankel, 1996). For a distributed system such as the Bureau’s water system, however, the use of probabilistic curves may generate overly conservative results. Therefore, PGA hazard curves were developed for this assessment based on scenario events in such a manner as to be generally consistent with the 1996 USGS National Seismic Hazard Maps.

**Earthquake-Induced Landslide**

In earthquakes, the soil resistance to sliding remains constant but the loading increases. If an earthquake occurs during the rainy season when the ground is saturated, there is a higher probability of a landslide than if the earthquake occurs during the dry season.

Cornforth Consultants developed probabilities for damaging slide movement for earthquakes with return periods of 100 and 500 years, summarized in Table 4 (Cornforth, 1998b).

The vulnerability of a slope to earthquake-induced ground motions depends on several factors including slope angle, slope material type, groundwater conditions, and level of ground shaking. Materials most susceptible to landsliding include rockfalls and soil debris slides. Slides are more susceptible to earthquake-induced movement during the wet season when groundwater tables are elevated.

In the Bull Run corridor, the material most at risk to earthquake-induced slope failures is colluvium on steeper portions of the ancient landslide terrain. This material can be predominantly rocky or can have significant portions of silt, clay, and sand mixed with rocky material, and is identified below as Ancient Landslide Terrain. Flow slides (or debris slides in drier material) have the highest hazard ratings. Translational landslides consist of a larger reactivation within ancient landslide terrain than flow/debris slides. Translational slides in the corridor typically have base shear zones in clay. These slides may be marginally stable and can be creeping small amounts without detection or noticeable distress to the conduits. These slides are less susceptible to earthquake ground motions.
Hazard ratings for historically active slide terrain that have been remediated are generally moderate. Most have been remediated using rock fill buttresses. During an earthquake, the outer layer of the rockfill may ravel down the slope, but should not damage pipelines embedded in native ground below the rockfill. Remediated translational slides have been assigned a higher hazard rating than remediated flow slides due to their larger size and lower factors of safety.

Geologic terrain not previously impacted by landslides includes areas of locally steep topography where conduits traverse small creeks and streams. These areas have been assigned a moderate hazard rating for seismically-induced landslides.

Individual facilities are also vulnerable to landslides, where were quantified in a similar manner.

**Liquefaction**

The Groundwater Pump Station (GWPS) and the Willamette River pipeline crossings are vulnerable to liquefaction.

- **Groundwater Facilities.** There has been no liquefaction study focusing on the dikes along the Columbia River. The Groundwater Pump Station/Interstate Facility Seismic Vulnerability Study (Dames & Moore, 1996) made a conservative estimate that permanent ground deformations of up to 2 feet may occur during a maximum credible earthquake (MCE). The ground motion used for an MCE was 50 percent greater than for a 500 year return event. The Army Corp of Engineers (COE) indicated that because of the large dike cross-section, that even if liquefaction were to occur, the dikes would remain competent.

  Further, there is a low probability that an earthquake and flooding will occur at the same time. The COE indicated that the Columbia River only reaches flood stage once every 5 years. In the most extreme years, it has remained at flood stage for approximately 2 months. A more likely duration is estimated to be 15 days every 5 years, or 3 days per year. That is, the river is expected to be at flood stage approximately 1% of the time (0.01). To be conservative, that percentage might be doubled, allowing time for dike repair should they be damaged, so that the probability of the Columbia River being at flood stage is 0.02 per year. Multiplying 0.02 times the probability of a 100-year earthquake, 0.01, is 0.0002, or a 5,000-year return event, which is beyond the planning horizon for this study. In Sewer...
Collection Facilities Seismic Vulnerability Assessment, a study for Portland Bureau of Environmental Services (BES) (Dames & Moore, 1997), Fujitani Hilts estimated that permanent ground deformations (PGD) in a 100-year event might only be 15% of that in a 500-year event (approaching an MCE). That would result in expected PGDs of 4 inches, which should have minimal impact on the function of the dikes.

- Willamette Crossings. Liquefaction/lateral spread PGDs for the Portland Quadrangle were obtained from the Oregon Department of Geology and Mineral Industries (DOGAMI) maps, Earthquake Hazard Maps of the Portland Quadrangle, Multnomah and Washington Counties, Oregon and Clark County, Washington (GMS-79). These PGDs were developed for a magnitude 8.5 subduction earthquake, representing a 500-year return earthquake. In the same BES study cited above, Fujitani Hilts used procedures similar to DOGAMI to estimate PGDs outside the Portland Quadrangle. They also recommended multiplying displacements for an M8.5 event by 0.15 for an estimate of PGDs for a magnitude 6.0 crustal event, representing a 100-year return earthquake. Additionally, Fujitani Hilts estimated the percent of area that would liquefy within each liquefaction zone. The results, modified for this study, are shown in Table 5.

<table>
<thead>
<tr>
<th>Liquefaction Region</th>
<th>PGD (inches) for an M8.5 Earthquake</th>
<th>Percent of Area to Liquefy in an M8.5 Earthquake</th>
<th>PGD (inches) for an M6.0 Earthquake</th>
<th>Percent of Area to Liquefy in an M6.0 Earthquake</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>12-24</td>
<td>2</td>
<td>2-4</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>24-36</td>
<td>5</td>
<td>4-6</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>36-48</td>
<td>10</td>
<td>5-7</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>&gt;48</td>
<td>40</td>
<td>&gt;7</td>
<td>8</td>
</tr>
</tbody>
</table>

None of the river crossings are located in the most liquefiable material. The Clay St., Mill Street (abandoned), and Ross Island crossings each have some portion in Region 2, highly liquefiable material, and the most likely to fail. The other three crossings all have some portion in Region 4, moderately liquefiable material. It is estimated that three crossings will fail in an earthquake with a 500-year return period. For a 100-year return event, it is estimated that there is about a 50% chance that one crossing may fail.

Surface Fault Rupture

Surface faulting is not a concern in the Portland area. Fault rupture associated with a subduction earthquake would be located off the Oregon coast, and should be of no consequence to Bureau facilities. Thrust or reverse faults that may result from north-south crustal compression typically do not reach the surface. By comparison, the San Andreas and Hayward strike slip faults in California have a very significant surface expression, and are considered when design facilities cross them. There is no evidence of surface faulting in the Portland area over the last 10,000 years.
VOLCANIC ACTIVITY

The Bull Run watershed is immediately west of Mount Hood, and active volcano in the Cascade Mountain range. Debris flow and ash fall hazards were both considered.

Sandy River Debris Flow

A debris flow along the Sandy River valley would result in the destruction of the conduit bridges crossing the river, and, thus, all three conduits. Debris flows generated by volcanic activity produce a phenomenon referred to as a lahar, a rapidly moving mud flow. The lahar could also damage Bonneville’s Troutdale substation, which is one source of electrical power for the GWPS.

The evaluation of volcano hazards is based primarily on information contained in Open-File Report 97-89 published by the USGS “Volcano Hazards in the Mount Hood Region, Oregon.” This report concludes that the probability of Mount Hood generated lahars affecting the Sandy River is between 1-in-15 and 1-in-30 during the next 30 years. This translates to an event with a mean recurrence interval of between 435 and 886 years. Such an event would probably not be the result of a volcanic eruption with associated magma and ash. Lahar flows from Mt. Hood would more likely result from sudden failure of a glacier.

A lahar flow could occur as the result of a volcanic eruption, which could produce ash. The USGS believes that such an event has a recurrence interval longer than this project’s planning horizon.

It is expected that a debris flow would not be correlated to a regional earthquake event that would impact the other power supplies. Similarly, it is not expected that a debris flow is correlated to other hazard events that would impact other Bureau facilities within the project planning horizon. Therefore, this is considered to be an independent event, and is not included in the model.

A flood on the Sandy River could have the same impact on the system; i.e., loss of the Sandy River bridges. The probability of occurrence of the debris flow and flood on the Sandy River are combined when considering the priority of replacement of the Sandy River bridges with tunnels.

Ash Fall

The Bull Run watershed is susceptible to volcanic activity, and associated ash fall (tephra) from either Mt. Hood or Mt. St. Helens. Tephra is fragmented, solidified lava that rises into the air, is carried by winds, and falls back to the ground. Tephra falls can result in water supply turbidity, arcing on high voltage electrical insulators, and damage to rotating equipment if the ash is allowed to get inside bearings and cylinders. While Mount Hood has historically produced only moderate tephra falls, other volcanoes in the Cascade range, most notably Mount St. Helens, have produced large amounts of tephra. The USGS report indicates 30-year probabilities of tephra fall from all Cascade sources for two levels of accumulation. For the Bureau’s area, 1 cm or more of tephra accumulation can be expected about once every 4,500 years, and 10 cm can be expected about every 9,000 years.

The Bonneville Power Administration has expressed concern about arcing. This could result if there was a light rain at the time ash fall occurred, resulting in a buildup of ash on insulators. As discussed elsewhere, the BPA system has a high level of redundancy.
Since the probability of occurrence of tephra fall is relatively small, and the consequence of damage is also likely to be small, tephra fall can be considered to have negligible effect on the reliability of the system. In general, tephra fall is beyond the 1,000-year planning horizon.

**CONCLUSION**

Of the 38 hazards evaluated, the Portland water system is most vulnerable to intense rain on snow events, and earthquakes. Volcanic activity which can produce debris flows and ash falls are high and low risk hazards, respectively.

One of the most significant consequences of rain on snow is landslides along the Bull run conduit system. The vulnerability of this hazard was quantified by mapping geologic formations, and relating results of detailed evaluations of similar materials to formations along the conduit corridor. Other intense rain-on-snow event hazards are correlated, including turbidity events, and flooding on the Bull Run and Sandy rivers. These could disrupt service to the Bull run supply, but should not impact the groundwater system operation.

Both the Bull Run surface water and groundwater systems are vulnerable to earthquake ground motion, liquefaction, and landslides. Ground motion information was developed using earthquake source zone information from the USGS, and modeled for selected epicenter locations. Liquefaction probability information was used from previous studies of Portland Water Bureau, and Environmental Services Bureau facilities. Landslide probabilities were developed for the Bull Run conduit corridor, considering information developed for rain-induced landslides, and relating the sites to similar formations that had been evaluated in detail in the Portland area.

Mount Hood volcanic activity can result in debris flows on the Sandy River, which can destroy pipeline bridge crossings. The USGS has estimated a recurrence interval for such an event in the order of 500 years. Ash fall from Mount Hood or other volcanoes in the region can disrupt the power system due to arcing across insulators, and causing turbidity in the surface water supply. Ash fall event recurrence intervals are longer than the 1000 years considered in this project.

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**REFERENCES**


**Abbreviations:**
CD = Conduit  TR = Trestles  BR = Bridges  LND = Landslide

**Figure 1**
Supply System Schematic
Figure 2
Bull Run and Sandy Rivers, with Mt. Hood in the distance, looking east from Portland (4X vertical exaggeration).