Preliminary Evaluation of a Precipitation Threshold for Anticipating the Occurrence of Landslides in the Seattle, Washington, Area

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INTRODUCTION

Precipitation-induced landslides are a significant, recurring problem in the Seattle area. Major landslide events have been costly. Heavy precipitation at the end of December 1996 and in January and March of 1997 produced hundreds of landslides that resulted in loss of life and millions of dollars of damage (Baum and others, 1998; Coe and others, 2000; Laprade and others, 2000). Damage to City of Seattle facilities alone exceeded $34 million (Pageler, 1998).

Results of a comprehensive study of historical landslides in Seattle (using data that dates back to 1897, Laprade and others, 2000), show that a high percentage of reported landslides occurred in the November through April time frame (Figure 1). Precipitation in the form of rain, and occasionally snow, plays a major role in the occurrence of landslides. Cyclonic storms that develop over the Pacific Ocean and move inland account for much of the wet-season precipitation. Average November through April precipitation in the Seattle area is approximately 28.0 in. (711 mm), or 73% of the mean annual precipitation of 38.2 in. (970 mm).
In 1999, in response to the landslide hazard in the Seattle area, a U.S. Geological Survey project was undertaken to identify precipitation thresholds that might be used to anticipate or forecast the occurrence of landslides. Because the historical record indicates that a high percentage of landslides occur during the wet season, the study focused on the compilation and analysis of historical, wet-season landslide and climatic data. The effort resulted in the identification of an empirically derived 3-day and prior 15-day cumulative precipitation threshold for the occurrence of landslides in Seattle (Chleborad, 2000). The 3-day/15-day threshold (Figure 2a) is the basis of a prototype system for forecasting landslides in the Seattle area (http://landslides.usgs.gov/html_files/ofr-00-0469/seattlenet.html).

The threshold (Figures 2a and 2b) is based on an analysis of historical precipitation data associated with wet-season landslides that occurred during the period 1933-1997, in Seattle. In the initial part of the study, hourly rainfall data recorded at seventeen City of Seattle rain gauge sites, and daily climatic data (rainfall, snowfall and air temperature) from twelve National Weather Service sites in the Seattle area, were compiled and analyzed. Antecedent precipitation amounts were estimated using data from stations closest to the individual landslide locations. Information on location and time of occurrence was obtained in a search of City of Seattle landslide files, newspaper reports, geotechnical reports, USGS landslide project files, and personal field notes. The search yielded location and time of occurrence information on 187 historical landslides. Most of the landslides in the database of 187 landslides are shallow slumps, slides, or debris flows (estimated failure depths less than or equal to 10 ft (3.3 m)); however, the database also includes deep-seated landslides.

For the analysis, a level of activity of three or more landslides in a 3-day (72 hr) period was selected. It was assumed that, at that level of activity, precipitation played a major role in the development or triggering of the landslides. Further,
identification of a threshold for events that produce a specified level of activity is desirable for emergency response planning and preparedness. Inspection of the database revealed that 91 of the 187 slides could be shown to be part of landslide events with 3 or more landslides in a 3-day period. The approximate lower-bound precipitation threshold, defined by the equation $P_3 = 0.67P_{15} + 3.50$, was visually identified after constructing a scatter plot showing 3-day precipitation amounts ($P_3$) that occurred immediately prior to the landslides and antecedent 15-day cumulative precipitation ($P_{15}$) that occurred prior to the 3-day totals (Figure 2a). The precipitation threshold thus defined is interpreted as an approximate lower-bound threshold below which the specified level of precipitation-induced landslide activity does not occur or occurs only rarely and above which it may occur under certain conditions.

Additional data on 108 historical landslides that occurred in Seattle between 1950 and 1990 (Tubbs, 1974; Laprade and others, 2000), that were found to be part of 3-day events with three or more landslides, but were not part of the original 91 landslides used to define the threshold, were subsequently compiled and analyzed (Chleborad, unpub. data, 2002). As shown in Figure 2b, the additional data are consistent with the previously defined threshold; approximately 90% of the added data points (filled circles) fall on or above the threshold. In addition, the newly plotted data better define the threshold for conditions of 15-day cumulative precipitation greater than 3.0 inches.

In the analyses that follow, estimates of 3-day and prior 15-day cumulative precipitation and 6-hour peak rainfall intensity are based on data from City of Seattle rain gauges, National Weather Service (NWS) stations, or SchoolNet Automated Weather System (AWS) sites nearest the respective landslide locations (Figure 3). In some cases, where hourly rainfall data was not available from the nearest station or two stations were equidistant from the landslide or nearly so, data from an
additional station in the vicinity was included in the compilation. Because average hourly rainfall intensity over a 6-hour period ($I_6$) has been identified as a useful variable for developing a rainfall threshold for "shallow" landslide initiation in Seattle (Godt, report in review), $I_6$ was selected to examine relationships between rainfall intensity, 3-day and prior 15-day antecedent precipitation, and landslide occurrence.

In this report, the term landslide includes various types of slope failures on both engineered and natural slopes. Typically, the landslides exhibited one or more of the following types of movement involving earth or debris: translational slides, flows, rotational slumps, and topples or falls (see Cruden and Varnes, 1996). It should be noted that studies of landslide occurrence in the Seattle area often reveal a contributing human influence (such as placement of fill materials, improper drainage, leaking or broken water pipes, blocked culverts, excavation, etc.). In their comprehensive study of historical landslides, Laprade and others, 2000, state that "Some factor of human influence was reported for 84 percent of the landslides citywide in Seattle". However, the contribution of the human influence factors relative to other factors was not determined.

The purpose of this report is to present the results of the three-wet-season (2000 - 2001, 2001 - 2001, and 2002 - 2003) evaluation of the threshold, to present a newly developed rainfall history graph that allows a visual examination of relationships between rainfall intensity, 3-day and prior 15-day cumulative precipitation, and the precipitation threshold, and to briefly discuss the development of a prototype web-based landslide forecasting system for the Seattle area.
1 Period of record 1931 - 2002 (NWS SeaTac AP)

Data Limitations

The quality and completeness of information on landslides and associated precipitation, compiled for this report, is variable. Original source documents and reports were carefully examined in an effort to obtain the most accurate data on landslide timing and locations. Nearly all of the landslide locations were field checked and photographs of the sites were taken. However, the landslides were not studied in detail and only minimal descriptive information was obtained. The search yielded few eyewitness accounts. Times of occurrence are inferred based on available information from various sources. Sources include the City of Seattle database of landslides (unpub. data, 2001 - 2003), City of Seattle landslide specialists, geotechnical consultants, newspaper reports, and local residents.

Ideally, measurements of precipitation are made with recording devices located at the landslide sites. Because such measurements are rare or do not exist, data from City of Seattle rain gauge, NWS stations, and AWS stations located closest to the respective landslide locations were used for the analysis. In nearly all cases, the selected stations are located within a few miles of the respective landslides, and thus it is assumed that the data are sufficiently representative of conditions at the respective landslide locations.

Characteristics of the 2000 - 2001 Wet Season

The 2000 - 2001 wet season in the Seattle area was unusually dry. Cumulative precipitation for the six-month period (November through April) at SeaTac Airport (SeaTac AP) (fig. 4) totaled only 16.44 in. (417 mm) or 59% of the long-term average of 28.01 in. (711 mm). General conditions in the Seattle area relative to the 3-day and prior 15-day precipitation threshold are characterized in Figure.
using precipitation data from the National Weather Service station at SeaTac Airport. The threshold index (fig. 5) indicates conditions of antecedent precipitation relative to the threshold (positive values indicate conditions above the threshold).

The index is based on the threshold equation \( P_3 = 3.5 - 0.67P_{15} \) and is defined as:

\[
P_0 = P_3 + 0.67P_{15} - 3.5 \text{ where,}
\]

- \( P_0 \) is the threshold index,
- \( P_3 \) is the 3-day (72 hr) cumulative precipitation, and
- \( P_{15} \) is the 15-day cumulative prior to the 3-day

As shown in Figure 5, conditions did not approach the threshold during the 2000 – 2001 wet season. At the SeaTac AP location the 3-day/prior 15-day conditions were highest, relative to the threshold, on April 10 when an index value of -1.40 was reached (fig. 5). A maximum 3-day (72 hour) cumulative of 1.31 in. (33.2 mm) occurred on November 26 when the 15-day total prior to the 3-day was only 0.48 inches.

No precipitation-induced landslide events were reported for the 2000 - 2001 wet season. However, earthquake-induced landslides occurred in the Seattle area at the time of the February 28, 2001, Mw 6.8 Nisqually earthquake. Three-day and prior 15-day cumulative precipitation totals on February 28, 2001, the day of the Nisqually earthquake, were particularly low (fig. 5). These data provide an empirical basis for the conclusion that the dryer-than-usual soil was probably less vulnerable to landslides that the earthquake might otherwise have triggered.

**Characteristics of the 2001 - 2002 Wet Season**
Departures of total and monthly precipitation from the norm during November - April of 2001 – 2002 are characterized in Figure 6 using data from the NWS station at SeaTac. Total cumulative precipitation at SeaTac AP during the period was 32.41 in (823 mm) or 15.7% above normal. As indicated in Figure 6, most of the above normal monthly precipitation occurred in the month of November. A series of frontal systems brought heavy rainfall to the Seattle area during the period November 13 to November 23 and again during the period December 13-16. General conditions relative to the 3-day and prior 15-day precipitation threshold during the 2001 - 2002 wet season are characterized using precipitation data from SeaTac AP and Sand Point (figs. 7 and 8). As shown in Figures 7 and 8, conditions were generally above the threshold between November 14 and December 19 of 2001. During the remainder of the wet season, at the SeaTac AP and Sand Point locations, conditions most closely approached the threshold on January 8 and February 23 of 2002 (figs. 7 and 8).

A database of 59 reported landslides was compiled for the 2001-2002 wet season analysis. Landslide locations and descriptive information are presented in Table 1. The database includes reported landslides that occurred on natural and engineered slopes in Seattle and neighboring areas. Landslides in the database that are part of events with 3 or more landslides in a 3 day period, in Seattle, are differentiated in a later section of the report. A high
percentage of the reported landslides are small, shallow slides or debris flows with estimated depths of less than 10 ft (~3 m). Five deep-seated failures with estimated depths greater than 10 ft (~3 m) were also reported. As used here, the term ‘human influence’ refers to factors such as blocked culverts, improper drainage, leaking or broken water pipes, placement of fill materials, or excavation that may have significantly affected slope stability and landslide timing. The presence of a human influence was noted for 9 of the slope failures (Table 1). To facilitate the analysis, landslide occurrences with a reported or identified human influence are also differentiated on Figures 9a and 9b (open triangles). The 2001 – 2002 slope failures resulted in numerous road closures, disrupted rail service between Seattle and Everett, Washington, and damaged homes, cars, yards, and retaining walls and rockeries in residential areas (Table 1).

Information sufficient to estimate 3-day and prior 15-day antecedent precipitation totals was compiled for 45 of the 59 slope failures (Table 2). Estimates of antecedent precipitation for the 45 landslides are plotted on Figure 9a. In cases where a range of values is given (Table 2), the average of the end members of the ranges are plotted as ‘best estimates’ of the 3-day and prior 15-day totals.
Error bars shown on Figure 9a depict the range of possible values associated with some of the estimates. The error bars are the result of limited precipitation data (e.g., hourly data missing or unavailable) and (or) uncertainty in exact time of landslide occurrence (e.g. day of occurrence may have been reported but not the exact hour). As indicated on Figure 9a, error bars for 11 of the plotted points cross the threshold (landslide no.s 7, 8, 16, 39, 43, 47, 48, 49, 50, 51, and 52, Table 2) indicating the actual location of those points could lie either above or below the threshold. Consequently, those estimates are not definitive and their usefulness in evaluating the threshold is limited. Therefore, they are not included in the analysis that follows. Note that some of the points plotted on the graph represent more than one landslide. Figure 9b shows the plotted points that remain after estimates with error bars that cross the threshold are removed.

Characteristics of the 2002 - 2003 Wet Season

Total cumulative precipitation in the Seattle area during the 2002 - 2003 wet season was near normal. At SeaTac AP the November - April cumulative was 28.72 in.; monthly totals were highest in January and March of 2003 (fig. 10). There were no major storms or landslide events during the 2002 – 2003 wet season. General conditions in the Seattle area relative to the 3-day and prior 15-day precipitation threshold are characterized by precipitation data from the
SeaTac AP and Sand Point stations (figs. 11 and 12). At the SeaTac site conditions were at or slightly above the threshold briefly during the periods December 17-19, and 26-28, 2002, on January 31, 2003, and later in the wet season, during the period March 21-26 (fig. 11). At the Sand Point location conditions did not cross the threshold during the wet season. Similar to the SeaTac site, storms elevated the 3-day and prior 15-day totals to their highest levels during the months of December, 2002 and January and March of 2003 (fig. 12).

Information on seven reported landslides was compiled for the 2002-2003 wet season analysis (Table 3). The landslides occurred in Seattle (3), the Rolling Bay area on Bainbridge Island west of Seattle, and the Issaquah, Bremerton, and Kenmore, Washington areas (1 each). Six of the occurrences were shallow slides and(or) debris flows. One of the sites (landslide no. 2 in Table 3) was not visited and slide characteristics were not determined. A human influence was reported or identified for three of the slides (no’s 1, 4, and 7). The presence or absence of a human influence is undetermined for the remaining four slides (no’s 2, 3, 5, and 6 in Table 3). Reports of disruption and (or) damage caused by the landslides include destruction of a vacated home in the Rolling Bay area of Bainbridge Island, disruption of Amtrak Service due to debris on the track north of Careek Park in Seattle,
contamination of Salmon-bearing Issaquah Creek, and a brief highway closure near Kenmore, Washington (Table 3).

Antecedent precipitation totals associated with the 2002 - 2003 landslides are tabulated in Table 4. Estimates of 3-day and prior 15-day precipitation based on rain gauges nearest the landslide sites are plotted on Figure 13. As indicated on Figure 13, two of the slope failures (no.'s 4 and 7 in Table 4) have error bars that cross the threshold. Estimates for two of the five remaining landslides plot above the threshold and three below. A possible human influence is reported or identified for three of the slope failures (no.s 1, 4, and 7, Table 4).

Analysis of 2001-2002 and 2002-2003 wet season data

A total of 66 landslides were reported for the 2001 - 2002 and 2002 - 2003 wet seasons (Tables 1 and 3). The compilation yielded data sufficient for estimating 3-day and prior 15-day antecedent precipitation for 51 of the 66 slope failures. Because 13 of the 51 plotted points have error bars that cross the threshold, they are excluded, leaving a total of 38 for the analysis. Twenty-eight of the 38 remaining landslides are classified as shallow and four as deep-seated. There was insufficient information on depth of failure to classify six of the 38 slides as shallow or deep-seated. Ten of the 38 landslides have a reported or identified human influence. Basic statistics for estimates of antecedent precipitation associated with the 38 landslides are presented in Table 5.

<table>
<thead>
<tr>
<th></th>
<th>Number of landslides</th>
<th>3-day (72 hr) cumulative precipitation (inches)</th>
<th>15-day cumulative precipitation prior to 3-day (inches)</th>
<th>Number above threshold</th>
<th>Number below threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Range</td>
<td>Mean</td>
<td>Range</td>
<td>Mean</td>
</tr>
<tr>
<td>Shallow landslide</td>
<td>28</td>
<td>0.07-4.03</td>
<td>2.08</td>
<td>0.71-5.75</td>
<td>2.64</td>
</tr>
<tr>
<td>Deep-seated landslide</td>
<td>4</td>
<td>0.51-1.82</td>
<td>1.25</td>
<td>2.63-4.04</td>
<td>3.34</td>
</tr>
<tr>
<td>Landslide (depth not estimated)</td>
<td>6</td>
<td>1.08-3.17</td>
<td>2.13</td>
<td>0.91-6.50</td>
<td>2.93</td>
</tr>
<tr>
<td>Landslides with a reported or identified human influence</td>
<td>10</td>
<td>0.07-2.43</td>
<td>1.38</td>
<td>1.02-4.04</td>
<td>2.43</td>
</tr>
</tbody>
</table>

Inspection of Table 5 reveals the following: Precipitation estimates for 26 of the 38 landslides (68%) fall above the threshold. Seven of the 12 landslides that fall below the threshold (Table 5 and Figures 9b and 13) have an identified human influence, suggesting that, for the purpose of threshold identification, landslides with a significant human influence should be considered separately from landslides that occur under natural conditions. For example, human influence factors such as improper drainage, plugged culverts, and broken water lines may result in local concentrations of groundwater that raise soil pore pressures to critical levels despite relatively low amounts of antecedent 3-day and prior 15-day cumulative precipitation that occur below the threshold. Shallow landslides occurred under a wide range of 15-day cumulative totals, whereas the four deep-seated landslides occurred when 15-day prior estimates were relatively high (Table 5). Similar results were obtained with the previous analysis of 198 historical Seattle landslides (Chleborad, 2000) which showed a high percentage of deep-seated landslides associated with 15-day cumulates in excess of 2.5 in. (63.5 mm) (Figure 2b).
Additional study is needed to verify the apparent relationship and examine possible causes.

As previously mentioned, the 3-day and prior 15-day threshold is based on an analysis of 91 historical landslides that were part of events with 3 or more landslides in a 3 day period in Seattle (Chleborad, 2000). It was assumed in the initial study that, at that level of activity, precipitation played a major role in the development or triggering of the landslides. In the database of 66 landslides compiled for this analysis, 42 occurred in Seattle and 24 occurred in neighboring areas outside the city. Twenty-one of the slope failures that occurred in Seattle can be shown to be part of events with 3 or more slides in a 3 day period (Tables 1, 2, 3, and 4). A plot of antecedent precipitation totals for the 21 Seattle landslides that meet the original criteria indicates two of the plotted points have error bars that cross the threshold and thus are not definitive (Figure 14). Of the remaining 19 estimates, 89% (17 of 19) plot above the threshold (Figure 14). The high percentage of occurrences above the threshold is consistent with results of previous analyses based on the original database of 91 landslides (Figure 2a) and the expanded database of 198 historical landslides (Figure 2b). The lower percentage of landslides (68%) that fall above the threshold in the dataset of 38 landslides (Table 5) may be explained, in part, by the inclusion of landslides that are not part of events with 3 or more landslides in a 3-day (72 hr) period.

**Cumulative Precipitation, Rainfall Intensity, and Landslide Occurrence During the Period November 13 - 26, 2001.**

Most of the slope failures that occurred during the 2001 - 2002 and 2002 - 2003 wet seasons (Tables 1 and 3) are associated with storms that impacted the Seattle area between November 13 and December 16 of 2001. As indicated in Figures 7 and 8,
conditions were generally above the threshold from November 13 to December 19, 2001. Nine of the slope failures (no.s 6, 10 through 14, 20, 22, and 23 in Table 1) occurred in northeast Seattle within 2 mi. (3.2 km) of City of Seattle rain gauge no. 2. 

Figure 15 shows the history of cumulative rainfall and rainfall intensity in northeast Seattle during the period November 13 - 26, 2001 (color coded line) in relation to landslide occurrence (triangles) and the 3-day and prior 15-day cumulative precipitation threshold for landslides (dashed red line). Rainfall intensity categories are shown in the table of color coded values on the right side of the graph. Arrows indicate rainfall intensity and 3-day and prior 15-day cumulative totals at the beginnings of the indicated days. Color-coded line segments between arrows indicate intensities that occurred during the successive 24 hr periods. Time scale (not shown) varies along the color-coded line. Rainfall intensities and 3-day and prior 15-day antecedent precipitation indicated by the trajectory are based on hourly rainfall data from City of Seattle rain gauge no. 2 (Figure 3).

As indicated by the trajectory, an initial storm front brought rainfall to the area during the period November 13 - 15. During that interval the 3-day cumulative rainfall total rose above the threshold to 3.3 inches (84 mm). The 6-hour mean rainfall intensity reached a high of 0.13 in/hr on the afternoon of November 14. Landslides (triangles) occurred in northeast Seattle on November 14 and 15. All but one of the slides occurred when the 3-day/prior 15-day cumulative rainfall totals were at or above the threshold. The initial storm ended November 15 and little or no rain fell between November 16 and 19. On November 19 the 3-day cumulative had dropped to zero and the prior 15-day cumulative total had risen to nearly 4 inches.

A series of storm fronts brought additional rain to the area during the period November 19 - 23. As shown on the graph, the 3-day cumulative total rose to 2.1 inches and the prior 15-day rose to over 4.5 inches. Six-hour mean rainfall intensity
reached a maximum of 0.11 in/hr on November 22. Landslide activity occurred on November 21 and 23 and during the weekend of November 24-25 when conditions were above the 3-day/prior 15-day precipitation threshold and rainfall intensities were less than or equal to 0.06 in./hr (1.52 mm/hr).

**Summary and Discussion**

Compilation and analysis of Seattle area precipitation and landslide data for the 2000 - 2001, 2001 - 2002, and 2002 - 2003 wet seasons has revealed the following: 1) consistent with previous findings, a high percentage (89%) of Seattle landslides in the evaluation that were part of events with 3 or more landslides in a 3-day period occurred when conditions were above the threshold. 2) a lesser percentage (68%) of landslides in a dataset that includes all landslides in Seattle and surrounding areas, regardless of associated level of landslide activity, occurred when conditions were above the threshold, 3) a majority of landslides that occurred below the threshold had a reported or identified human influence; suggesting that, for the purpose of threshold identification, landslides with a significant human influence should be considered separately from landslides that occur under natural conditions, 4) the rainfall history graph developed in this study (Figure 15) is useful for visually examining relationships between landslide occurrence, 3-day and prior 15-day antecedent rainfall, rainfall intensity, and the precipitation threshold. Generation of similar graphs based on real-time or near real-time rainfall data are potentially useful as part of a web-based landslide advisory or early warning system. Also, construction of similar graphs for other historical landslide events combined with statistical analysis of related antecedent precipitation and rainfall intensity may be useful in efforts to determine probabilities of landslide occurrence relative to the threshold.

Distances between landslides and corresponding rain gauges (Tables 2 and 3) have a mean value of 2.9 mi. (4.6 km), and a standard deviation of 2.2 mi. (3.5 km). However, the issue of rainfall spatial variability has not been addressed in this study and it is unknown whether or not variability over the distances involved can significantly affect estimates of 3-day and prior 15-day precipitation. In addition, variability and possible errors associated with rain gauge type have not been examined. For example, snowfall and wind conditions may significantly affect data accuracy. Landslide prone areas in Seattle and vicinity have been mapped or identified in numerous studies and landslide recurrence intervals for the areas have
been estimated (e.g. Tubbs, 1974; Laprade and others, 2000, Baum and others, 1998; and Coe and others, 2000). If variability with distance is a significant factor, deployment of rain gauges in known landslide-prone areas or areas with a high frequency of landslide occurrence could significantly reduce distances between future landslides and rain gauges used to estimate amounts of antecedent precipitation and rainfall intensity, thus improving the rainfall estimates.

Development of a web-based landslide forecasting capability

Currently, near real-time updates on conditions in the Seattle area relative to the 3-day and prior 15-day threshold are provided on the web (http://landslides.usgs.gov/html_files/ofr-00-0469/seattlenet.html). A link to the National Weather Service, Seattle web site allows users to easily access standard, short-term precipitation forecasts for the Seattle area. The combination of current updates relative to the threshold and the NWS precipitation forecasts provides users with a crude method of anticipating future conditions relative to the threshold. However, numerical precipitation forecasts are needed to adequately project future conditions. A web-based numerical weather forecast (MM5) for areas of the Pacific Northwest is currently provided by the University of Washington’s Department of Atmospheric Sciences (http://www.atmos.washington.edu/mm5rt). Future work plans related to this study include an investigation to examine the possibility of integrating the numerical forecasts with precipitation measurements in the Seattle area in order to forecast conditions relative to the precipitation threshold.

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